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Research into, and development of, smart boxing gear for the

measurement and analysis of boxing related biomechanical parameters.

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Thank you from the bottom of my heart!

Table of contents

List of abbreviations

1RM	One repetition maximum
2-DOF	Two degrees-of-freedom
A	Surface area
α	Smoothing factor
ADC	analogue to digital converter
AHRS	Attitude and Heading Reference System
AIBA	l'Association Internationale de Boxe Amateur
ASCII	American Standard Code for Information Interchange
BABA	British Amateur Boxing Association
BC	Before Christ
BF	Muscle Biceps Femoris
BMA	British Medical Association
COP	Center of pressure
cf	Confer
CF_S	Calibration function sensor
CMC	Carpometacarpal
CNS	Central Nervous System
CNTs	Carbon Nanotubes
CTE	Chronic Traumatic Encephalopathy
DOMS	Delayed Onset Muscle Soreness
ε	Poisson's ratio
EMG	Electro Myograph
ES	Effect size

F	Force
F_a	Coriolis acceleration
F_C	Coriolis force
FFB	French Boxing Federation
FIBA	la Fédération Internationale de Boxe Amateur
FOG	Fiber-Optic Gyroscope
F_S	Final sensor force
FSR	Force Sensing Resistor
G	Conductance
GDP	Gross Domestic Product
Ge	Germanium
G_S	Sensor conductance
HIC	Head Injury Criterion
HRG	Hemispherical Resonator Gyroscope
IBF	International Boxing Federation
I	Electric current
IDC	International Data Corporation
IDE	Integrated Development Environment
K	Gage factor
L	Length
LED	Light-emitting diode
MARG	Magnetic Angular Rate and Gravity Sensor
Mx_0	Moment for COP movement in X direction
My_0	Moment for COP movement in Y direction

MEMS	Micro Electro Mechanical systems
mmHg	Millimetre of mercury
mTBI	mild Traumatic Brain Injury
N	Newtons
NCBI	National Center for Biotechnology Information
NPCR	Negative pressure coefficient of resistance
p	Specific electrical resistance
PDMS	Polydimethylsiloxane
PPCR	Positive Pressure Coefficient of Resistance
PVC	Polyvinyl chloride
R	Electrical resistance
RF	Muscle Rectus Femoris
R_F	Resistor factor
RLG	Ring Laser Gyroscope
RMSE	Root Mean Square Error
RPM	Revolutions per minute
R_{REF}	Sensor reference resistor
SD	Standard deviation
S_G	Sensor conductance
Si	Silicon
SQUID	Superconducting Quantum Interference Device
V	Constant of proportionality
VO_2 max	Maximal Oxygen Consumption
y_i	perpendicular distance in y direction from the origin

VL	Muscle Vastus Lateralis
VM	Muscle Vastus Medialis
V_S	Sensor Voltage
V_{IN}	Input Voltage
V_{Ref}	Reference voltage
w	filter weighting parameter
WBA	World Boxing Association
WBC	World Boxing Council
WBO	World Boxing Organization
WOS	Web of Science
WSTC	Wayne State Tolerance Curve
ψ_B	Body Coordinate Frame
ψ_I	Inertial Coordinate Frame
x_i	perpendicular distance in x direction from the origin

List of figures

List of tables

Abstract

Research into, and development of, smart boxing gear for the measurement and analysis of boxing related biomechanical parameters.

Much development work and scientific research has been conducted in recent years in the field of detecting human activity and the measurement of biomechanical performance parameters using portable sensor technologies, so-called wearable systems. As one of the oldest and most popular sports throughout the world, millions of people participating in the sport of boxing and martial arts these days. Despite the fact that boxers participating in one of the most vigorous and complex disciplines of all sports, it is one of the disciplines where no noteworthy, advanced performance analytic tools are used for training neither for competition purposes worldwide. Therefore, this research aimed to develop a comprehensive boxing monitoring system for the measurement and analysis of sport specific biomechanical parameters. The developed sensor system demonstrated high accuracies of up to R^2 = 0.99 for punch force, acceleration and further data, compared to laboratory measuring instruments like a force plate and a motion capture camera system. The system was subsequently applied and tested to detect and analyze kinetic as well as kinematic data in a non-laboratory condition throughout the conducted studies.

The presented research work has not only revealed new fields of research in the sport of martial arts, but moreover provides new information in terms of sensor application, fist activity, center of pressure distribution, expert versus non-expert performance exertion and much more.

This research provides the fundamental framework for necessary research and data acquisition in the sport of boxing and martial arts to obtain information about the performance parameters by use of instrumented sport equipment.

Keywords: Instrumented sport equipment, boxing monitoring system, punch force, strike trajectory, punching technique

Abstract

Research into, and development of, smart boxing gear for the measurement and analysis of boxing related biomechanical parameters.

In den letzten Jahren wurde viel Entwicklungsarbeit und wissenschaftliche Forschung auf dem Gebiet der Erfassung menschlicher Aktivität und der Messung biomechanischer Leistungsparameter mit Hilfe tragbarer Sensortechnologien, so genannter "Wearable Systems", betrieben. Als eine der ältesten Sportarten in der Geschichte partizipieren heutzutage Millionen von Menschen im Box- und Kampfsport. Trotz der Tatsache, dass Boxer in einer der anspruchsvollsten und komplexesten Disziplinen aller Sportarten partizipieren, stellt diese Sportart eine der Disziplinen dar, in der weltweit keine nennenswerten, fortschrittlichen leistungsanalytischen Systeme für das Training oder den Wettkampf eingesetzt werden.

Ziel dieser Forschung war daher die Entwicklung eines ganzheitlichen Sensorsystems zur Messung und Analyse von sportartspezifischen biomechanischen Parametern im Boxsport. Das entwickelte Sensorsystem zeigte eine hohe Genauigkeit von bis zu R^2 = 0,99 für die Schlagkraft, Beschleunigung und weiterer Messvariablen im Vergleich zu Labormessgeräten wie einer Kraftmessplatte oder einem Motion-Capture-Kamerasystem. Das System wurde in der Folge im Feld eingesetzt, um sowohl kinetische als auch kinematische Bewegungsdaten unter laborunabhängigen Bedingungen im Rahmen der durchgeführten Studien zu erfassen und auszuwerten.

Die vorgestellte Forschungsarbeit hat nicht nur neue Forschungsfelder im Kampfsport aufgedeckt, sondern liefert darüber hinaus neue Informationen in Bezug auf Sensoranwendungen, Faustaktivitäten, Kraftangriffspunktverteilung, sowie Leistungsdeterminierenden Schlagvariablen von Experten und Novizen.

Diese Forschung bietet den grundlegenden Rahmen für die notwendige Forschung und Datenerfassung im Box- und Kampfsport, um Informationen über die Leistungsparameter durch den Einsatz von instrumentalisierten Sportgeräten zu erhalten.

1. Introduction to wearable technology in boxing

Sport is a phenomenon of the modern world. Millions of people participating in different activities with different motivation as recreational, amateur or high-performance athletes.

As one of the oldest and most popular sports throughout the world, more than 6.5 million people participating just in the United States of America, in the sport of boxing these days (Statista, 2019a).

Martial arts and combat sports have a long history. Especially boxing has one of the longest histories of all martial arts performed in mankind´s history. Because its nature is not only the execution and exhibition of athletic performance but to a greater degree the natural instinct of self-defense and the natural mechanism of survival in archaic times by striking an opponent with the fist. It takes little imagination to picture how the rudimentary nature of punching turned into training activities for both hunting and warfare, evolving ultimately to an organized sport like boxing.

One of the first documented boxing fights can be back traced to Sumer, the southern Mesopotamia and modern day south of Iraq 5,000 years before Christ (BC) (Seltzer, 2000). In 688 BC the sport of boxing appeared for the first time as a formal Olympic match in the 23rd Olympic games performed with less rules and more vicious than it is exerted in modern times. The sport of boxing evolved in mankind’s history continuously. In the 17th and 18th century the sport experienced a high popularity especially in England where it was indicated as “the novel science of defence” as it was called by James Figg, an Englishman (Kordi et al., 2009, p. 193). Regular boxing events were held in the Royal Theatre of London from 1698. This era was called “the bare-knuckle era” as all fights were fought without gloves or protective equipment and solely with bare hands (Poliakoff et al., 2020). Almost 200 years later the first significant change occurred with the introduction of the Queensbury Rules in 1867. The Queensbury Rules were named after the two inventors and initiators of the new era, the eighth Marquess of Queensberry, John Douglas Sholto and John Graham Chambers (Poliakoff et al., 2020). For the first time in boxing history a point system was introduced to award each boxer with points after every round, to determine a winner in the case if no knock out occurs, within the new set of limited rounds by the establishment of the Queensbury Rules. Furthermore, the sport of boxing became a gloved sport to reduce the severity of injuries that occur in competition. Thirteen years later the first "Amateur Boxing Association" was founded in 1880 in England (Kordi et al., 2009). With the established rules the sport became more popular and has been part of the modern Olympic Games since the Olympic Games of St. Louis back in 1904. The sport of boxing has been on the program of the Olympic Games without interruption since 1920 (Kordi et al., 2009).

Amateur and professional boxing is unlike other sports organized by individual organizations. Amateur boxing matches are organized by the l'Association Internationale de Boxe Amateur (AIBA) (AIBA, 2019a). Whereas prominent professional boxing events are organized by one of the four major boxing associations, the World Boxing Association (WBA), the World Boxing Council (WBC), the International Boxing Federation (IBF) or the World Boxing Organization (WBO). Boxing events hosted by the professional boxing associations are these days the highest remunerated single sport events worldwide. Already two fights in the professional boxing history have reached an estimated revenue of 500,000,000 US dollar. These two boxing matches were fought by Floyd Mayweather Jr. versus Manny Pacquiao on May 2nd, 2015 and two years later again by Floyd Mayweather Jr. against Conor McGregor on August 26th, 2017 (Bojan, 2017; Isidore, 2015). In terms of TV ratings and therefore passive participation, boxing is one of the most popular sports worldwide. In 2016, boxing was ranked as the third most popular sport event in television, with 24% in terms of TV ratings in Germany (Statista, 2019c).

All this shows that sport is more present in our society than ever before. The modern sport as it is performed nowadays has changed drastically not only in terms of people participating but also in the professionality the sport is performed. Therefore, the level of competition has been improved. This evolution of the sport has reduced the discrepancy among athletes for professional as well as for amateur athletes (Nusser & Senner, 2010). As a result of this progression, even a small advantage can make the difference between victory and defeat in a competition. This phenomenon is particularly evident in professional sports (Umek et al., 2017).

As a result of the advanced number of participations as well as the level of competition, the interest of the sporting goods industry has been expanded to develop consistently new and modern sport apparel and equipment with state-of-the-art technologies.

In so doing the offer ranges from health care applications such as biosensors for heartbeat tracking, personal assistance such as navigation tools, to performance analysis tools for training periodization and optimization purposes, high-tech sportswear, such as movement tracker, to training equipment like upgraded sports equipment as optimized balls to performance enhanced rackets. The use of high-tech equipment in the field of sport and exercise have increased exponentially (Higgins et al., 2009). This led to an interest to the sporting goods industry for further development in recent years.

In this regard, the sport market has received a great boom through the development of smart sports equipment, such as the use of wearables in order to be able to collect personal performance data for training analysis and optimization.

These wearable systems are electrical mobile devices that are designed to be used without disturbing the wearers movement pattern. Therefore, the wearable devices have to be embedded in the original sport equipment to not irritate the athlete’s activity. The range of wearable systems extends from microsensors seamlessly integrated into textiles, consumer electronics embedded in smart clothing, to computer-controlled smart watches that are able to track heart frequencies and sleeping activities (Lukowicz et al., 2004). Example products are therefore fitness and activity tracker from Misfit, Garmin, Fitbit and Polar.

Although wearable devices are not only made to be used during sport activation. Many of these devices are designed to be used permanently. Therefore, wearable devices play a more and more important role in everyday life. Consequently, the systems are made in a way that the user is able to interact with their device as well as with their environment simultaneously and vice versa. That means that the devices are able to collect and present environmental and personal performance data of its user (Lukowicz et al., 2004). The hi-tech analytic company, Juniper Research, has revealed that by 2019 the global retail revenue of smart wearable devices will reach $53.2 billion (Smith, 2014).

1.1 Problem Statement

The potential and field of application is severely restricted to different kinds of sport, despite the strong interest of the sporting goods and health care industry in the development of the latest technologies.

As one of the oldest kinds of sport, the sport of boxing is one of the disciplines worldwide in which no noteworthy advanced performance analytic tools are used for training neither for competition purposes. Despite the fact that boxers participating in one of the most vigorous and complex disciplines of all sports to the athletes themselves as well as the equipment used. The complexity that the sport of boxing entails can be illustrated by the physical practice. The boxer, more than in any other sport, exposes himself to physical stresses due to the punches of their opponents. Although one of the main objectives of the sport is not to get hit, this is not possible in a normal competitive environment. Consequently, the athlete is exposed to frequent physical impacts to the head and body. The physical blows often result in tissue injuries ranging from minor cuts and abrasions up to more severe damages including head and neck injuries as well as broken bones in the hand and face area (Whiting et al., 1988).

For this matter, the sport of boxing became one of the most controversial considered disciplines of all sports in science and medicine. Organizations such as the British Medical Association (BMA) have passed resolutions for a general restriction of boxing and other full contact martial arts disciplines. The demand for a ban is motivated and expressed by the concern that the athlete’s health is taken under serious danger when heavy bouts acting to the athletes head and body (Anderson, 2007). Opposing parties argue against the call for a restriction of full contact sports by contending that all officially executed fights are under permanent supervision of coaches, referees and judges to interrupt the fight if the athletes health is put under serious risk and if necessary to stop the fight by expressing a technical knockout (AIBA, 2016).

To protect the competing athlete’s health, they require great psychologically and physically expertise in the field of endurance, strength, agility, coordination and speed to be competitive and to avoid serious injuries. Due to the gap of diagnostic devices, there is a need for performance and health monitoring by use of state-of-the-art technologies.

Existing research has focussed on boxing related injuries (Atha et al., 1985; Stojsih et al., 2010; Viano et al., 2005; Walilko et al., 2005). Whereas the pathology and mechanics that causes injuries as well as the appearing biomechanical values that occur during training as well as during a boxing or sparring fight, for a comprehensive performance monitoring are insignificantly observed outside laboratory conditions. Neither are smart instruments intended to be developed by the boxing associations and sporting goods industry that enable real time performance diagnostics and athlete monitoring, as it is appropriated in sports such as Formula1 or soccer.

1.2 Objective and research questions

The objective of the research is the development and instrumentation of an intelligent boxing glove. The research focusses on developing a unique sensor system and algorithms to quantify boxing related kinetic as well as kinematic parameters of the fist during a boxing punch. This study seeks to understand the biomechanical attributes that appear during a boxing bout and how the data can be used for performance diagnostics. The research aims to provide an innovative and highly accurate instrument for comprehensive performance monitoring in the sport of boxing, that to the authors knowledge, is not existing based on the literature review until the day the thesis was submitted. The research explores the advantages of sensor technologies, in the field of inertial and pressure sensing and provides possibilities to cope with the used sensor’s deficiencies for performance monitoring. The study prospects to understand how a sensor system has to be developed and designed to investigate boxing specific biomechanics outside laboratory conditions. Therefore, the research is focussing on providing both unique practical as well as unique theoretical perceptions in the field of wearable sensorics and boxing biomechanics. The perceptions gained offer unique information of kinetic and kinematic patterns in boxing to recognize performance differences and an innovative perspective into performance as well as risk measurement methods for the sport of martial arts.

The collected data can be of great value for the theoretical understanding of combat sports, provide ground breaking information for performance optimization, adjust rule standards, to reduce injury risks and enhance safety factors for competing athletes in the sport of boxing. Furthermore, great value can be provided for the sporting goods industry in the design and development of optimized combat sport equipment when on field data of the users and worn equipment is provided.

Therefore, the development of a boxing monitoring system would be a mile stone in the field of sport analytics. An instrumented boxing gear in the field of performance analytics is non-existing and would offer unique ways of athletic analytics and athlete monitoring during training sessions and competition.

The main research purpose is to develop an innovative instrumented boxing gear for the determination and analysis of novel biomechanical data in the field of boxing. Therefore, a highly accurate and comprehensive sensor system was developed to measure and analyse occurring biomechanics in boxing.

A detailed definition of the research questions is presented to specify the scope of research into the development of smart boxing gear for the measurement and analysis of boxing related biomechanical parameters as stated in the following:

1. What are the key performance parameters in the sport of boxing for performance monitoring?

2. How does a monitoring system has to be designed for measuring boxing related biomechanical performance parameters?

3. What sensors have to be used to develop a comprehensive boxing monitoring system?

4. How can the punch force be estimated by the use of smart boxing gear?

5. How can the monitoring system be used for orientation determination in three-dimensional space in a non-laboratory environment for the sport of boxing?

6. How can the system be used to estimate and evaluate injuries occurred in the sport of boxing?

7. How can boxing punches be evaluated to provide technical performance feedback?

8. How has a calibration function to be designed to calibrate the sensors used in the developed system for accurate data acquisition?

1.3 Significance of the research

With increasing professionalism and popularity of a sport, the equipment used also develops in terms of specialization (Ross Murray, 2010). Compared to other disciplines, the sport of boxing is exceptional in regard to the evolution of equipment used and the technical instruments applied for performance measurement and on-field monitoring. Many of the previous presented and applied methods did not work well in on-field situations in the sport of boxing or lack in the comprehensiveness of data collected as presented in the following.

The presented work was motivated by the lack of improved equipment and tools for state-of-the-art performance monitoring in boxing. There is a need for information about occurring on field biomechanical data in boxing.

The conducted research into the development of smart boxing equipment aids to detect appearing biomechanical attributes and allows the analysis of the punch thrown and its severity at impact by a novel boxing monitoring wearable device. The significance of the provided work can be expressed by the fact that no equipment is existing for real time performance monitoring that could improve ringside assistants such as medical staff, coaches, referees or judges with highly accurate data to observe the athlete’s performance and health. Based on the fact that boxing is among other sports a sport that causes injuries by intend rather than by incident is no tool available to detect biomechanics while injuries occur. The system developed offers the performance diagnostic in boxing in a non-laboratory environment and furthermore allows the better understanding into the performance biomechanics as well as to offer possibilities for the investigation of injuries occurred in the region of the hand. To develop such a sensor system would be a mile stone in the field of sport analytics. The novel method of an instrumented boxing glove in the field of performance analytics is non-existing and would offer new ways of athletic analytics and athlete monitoring during training sessions and competition for all coaches, athletes, scientists as well as medical staff.

1.4 Structure of the dissertation

The conducted research is presented in six chapters of the presented doctoral thesis. Chapter one is used to introduce the conducted research. Chapter two presents the state of research, following the introduction into the conducted research from chapter one, that has shown the relevance of this PhD as well as the objective and research questions in the first subchapters. Therefore, a critical assessment is conducted for the relevant literature in the field of boxing and wearable research. Additionally, the literature is used to provide fundamental expertise in the field of boxing biomechanics as well as sensor mechanics. These information are significant for the unique development of the boxing monitoring system.

Once the theoretical foundations are described and the state of research is discussed, chapter three presents the design and development of the novel sensor system. According to this, the sensor selection, calibration and validation as well as technical implementation is presented. In addition to this, observed types of errors and difficulties for the application of the boxing monitoring system are discussed. Furthermore, applied filter methods and developed algorithms are depicted.

Chapter four describes the experimental research in detail. Focussing on the applied analytical methods and obtained results of the conducted experimental studies. The main focus is set on this chapter as it presents the unique results obtained by the application of the developed sensor system. This chapter presents vital information in the field of smart technologies for performance diagnostics as well as extended significant information in the field of boxing biomechanics and punching technique.

The obtained results are discussed in depth in content and method, presented in chapter five. The conducted research work is set in reference to the presented literature from chapter two and put in context with the state of research.

The final chapter six represents conclusively limitations of the research and provides an outlook for further work. Conclusively the literature used is depicted at the end of the doctoral thesis. Figure 1 presents an overview of the structure of the presented thesis.

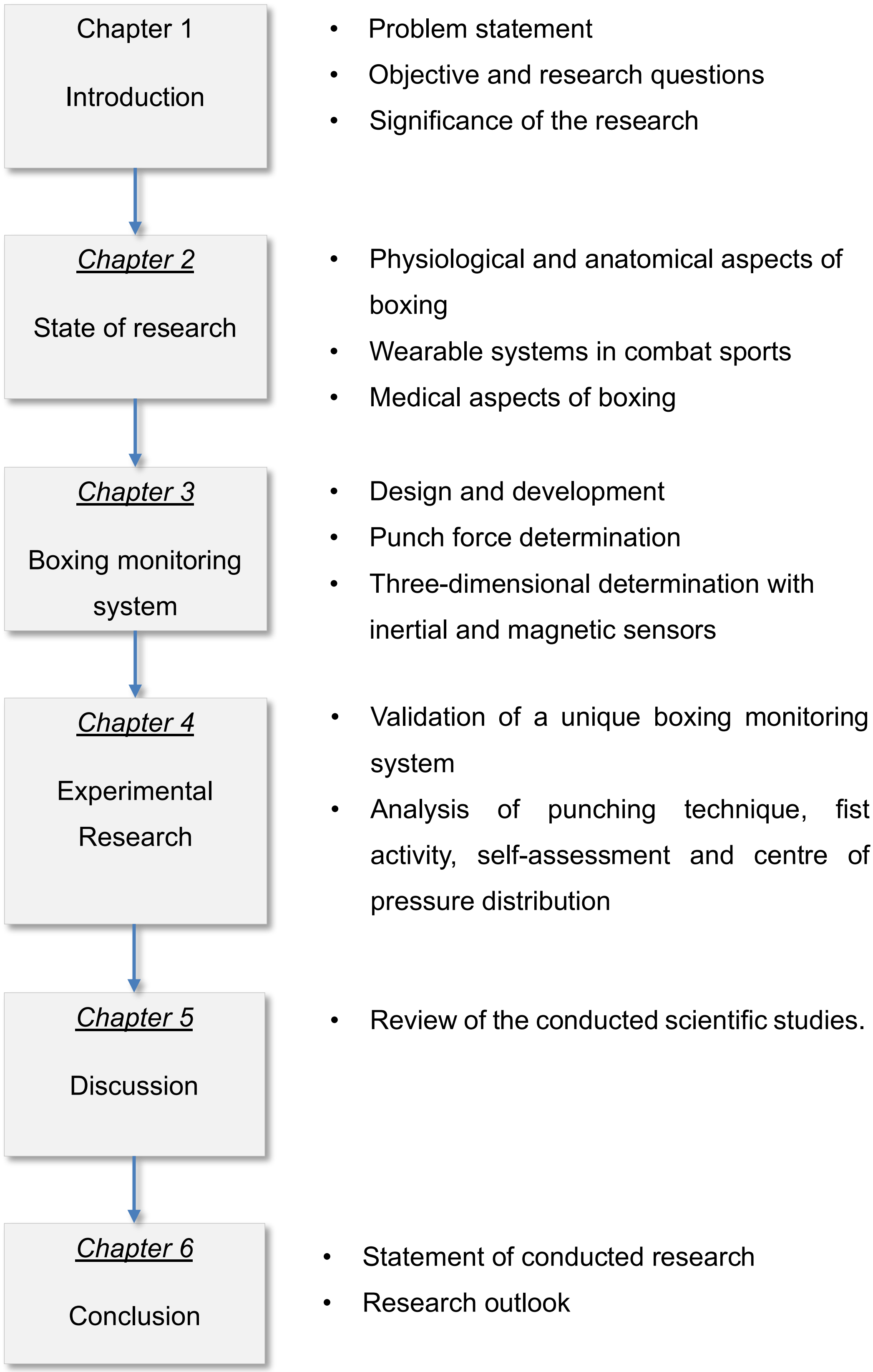


Figure 1: Thesis structure

2 State of boxing performance and wearable technology research

As the foundation of the presented scientific doctoral thesis, an extensive literature research was conducted throughout the course of the studies. For this purpose, a variety of scientific databases were searched for the systematic literature research, for the development of instrumentalized sports equipment for the measurement and analysis of boxing specific biomechanics. The primary databases investigated included Australian Standards, EBSCO Host, Elsevier, Emerald, Google Scholar, IBIS World, IEEE Xplore, Informit, Lynda.com, NCBI, ProQuest, PubMed, Research Gate, Sage Journals, Science Direct, Scopus, Sportdiscuss, Springer Link, Web of Science (WOS), Wiley online Library as well as local city and university libraries. As presented in table 1, the literature survey was conducted using a combination of identified keywords. The selection of the existing literature in English and German language was based on the flow diagram for study selection presented in Figure 2. The literature research resulted in a selection of 298 papers that are relevant for the presented work and were therefore employed for the execution of the research.

Table 1: Associated terms for literature research

BOXING **OR** COMBAT SPORTS **OR** MARTIAL ARTS	**AND / OR**	PUNCH **OR** BIOMECHANICS **OR** PERFORMANCE ANALYSES **OR** PUNCHING TECHNIQUE	**AND / OR**	FORCE **OR** MOTION **OR** MOVEMENT **OR** WEARABLE SENSORS **OR** PRESSURE SENSOR **OR** PIEZO RESISTIVE SENSOR **OR** FORCE SENSING RESISTOR **OR** INERTIAL SENSORS **OR** IMU **OR** ACCELEROMETER **OR** GYROSCOPE **OR** MAGNETOMETER **OR** EULER ANGLE **OR** QUATERNION	**AND / OR**	INJURIES **OR** HAND INJURIES **OR** HEAD INJURIES **OR** RISK **OR** MEDICAL ASPECTS **OR** INJURY EPI-DEMIOLOGY

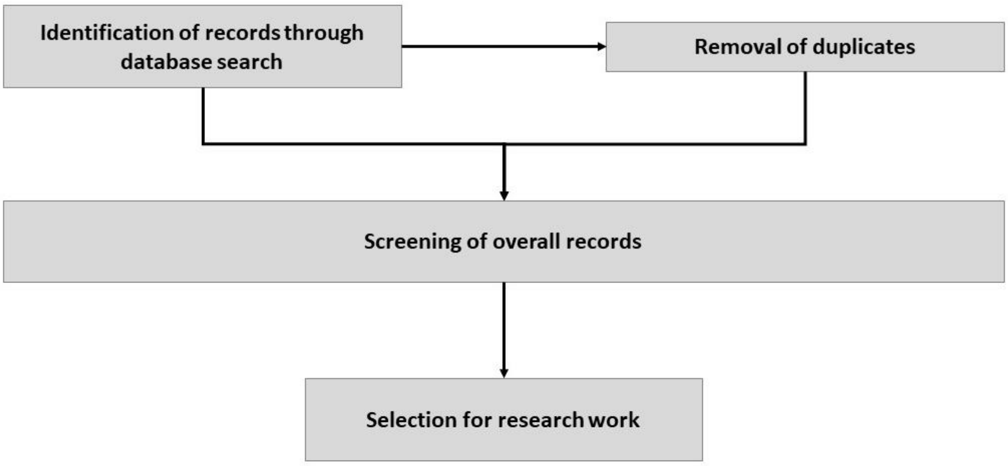


Figure 2: Flow diagram of scientific research selection

A fundamental component of the scientific propaedeutic of the research work involves the examination of sport-specific biomechanics and technical measurement methods, in order to develop a new type of performance analysis tool. In the following chapter, the existing and selected literature in the field of physiological and anatomical aspects of boxing, wearable systems in combat sports as well as medical aspects of boxing will be presented and reviewed. This step enables the identification of existing research gaps and the emphasis on the importance of the conducted scientific work.

2.1 Physiological and biomechanical aspects of boxing performance

For the development of boxing equipment, it is essential to understand the underlying fundamentals of the physiology and anatomy in the sport of boxing. The challenge to design and develop an innovative and unique boxing measuring system implies that the athlete’s biological system and the functional and biological reactions to forces arising from within and outside the body are holistically understood. Although boxing is known as the ‘sweet science’ there is ironically little research of the physiological requirements. Arsenau, Mekary and Léger (2011) describe the sparse research as a lack of tangible guidelines that lead to training methods that were developed through trial and error. Consequently, the demand for new methodologies and tools for performance analytics is obvious. Therefore, the development of the smart boxing glove should enable researchers to measure biomechanical parameters from which results can be derived to optimize training methods, the overall performance of assisted athletes as well as to reduce the risk of injuries.

The following chapter 2.1 outlines the fundamentals of physiology and anatomy related to the sport of boxing.
Boxing is a highly demanding sport which, due to its dynamic characteristics and constantly changing situations, requires a great number of punching and defensive actions, as well as a high mental capacity by the athlete to compete (Bruzas et al., 2014). In order to be successful, competing athletes need to consider different areas that contribute to their overall performance. Hence the performance of boxers is depending on various factors like age, sport specific experience, physical fitness, tactics, technique, functional capacity and many more (Guidetti et al., 2002).
Pfeiffer (2014) divides the aspects into four major components: a physical, a physiological, a psychological and a tactical component. The following chapter focuses on the physical and physiological perspective since these components have a mutual influence on the development of boxing equipment. On the one hand it is important to analyze the biomechanics of combat sports to better understand the effects of the forces acting on the musculoskeletal system. On the other hand, the modification of a boxing glove with integrated sensors can have a major impact on training

diagnostics and can therefore improve the physiological state of assisted athletes.

Physiological factors are a division of the field of biomechanics as shown in Figure 3. Arus (2018) differentiates a biological and a mechanical area in the field of biomechanics. Physiological factors are in conjunction with anatomical factors related to the biological area. Nonetheless the physiology of exercise is in a close relationship to biomechanics (Arus, 2018). An example is in combat sports therefore an athlete that can increase the impact on the physiological system of their opponent while taking account of a correct biomechanical execution of the punching technique.

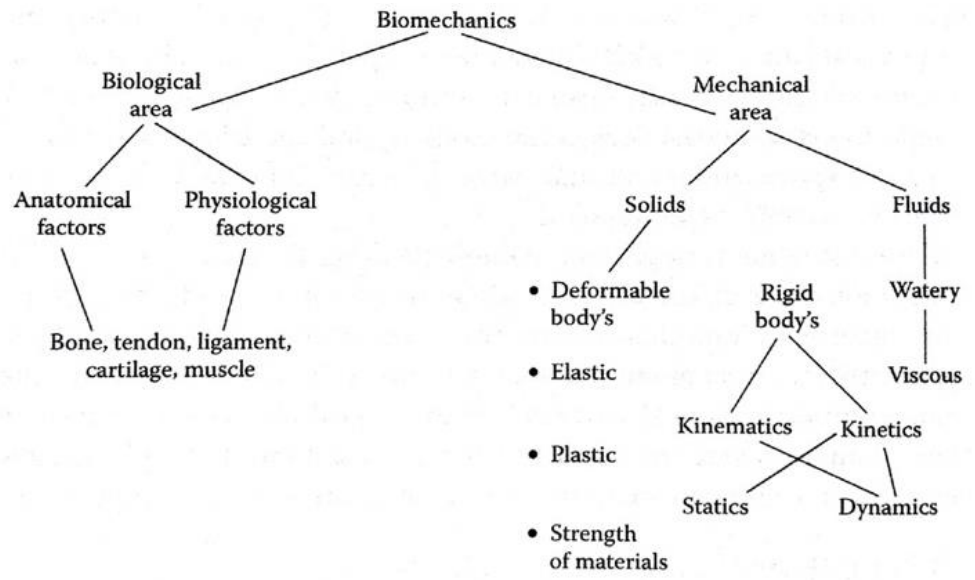


Figure 3: Biomechanics and its division (Arus, 2018, p. 6)

In the context of sport movement, the field of sport physiology is the discipline that deals with the question of how physical activity, exercise, or sport affects the human physical structure and functions (Birch et al., 2005). The fundamental principle of exercise physiology is describing the effect of movement on the human body and its cardiorespiratory system, the nervous system, the musculoskeletal system and the endocrine system (Birch et al., 2005). For the research in the development of boxing equipment it is important to understand the factors that directly contribute to the performance of an athlete like the cardiovascular fitness or the muscular strength of the upper and lower limbs. Furthermore, the aim is to build a smart boxing measurement system that can be used to support and enhance the athlete’s performance, e.g. in terms of the punch velocity and punch force analysis. These parameters are important impact factors to measure a boxer’s physiological profile (Chaabène et al., 2015).

Pfeiffer (2014) adds another perspective to the physiological component. Different target areas on the body of the opponent can have a varying influence on the physiological system. Pfeiffer (2014) describes that a liver punch can have a significantly stronger impact on the opponents physiological system than a punch to the upper arm, performed with the same intensity. It can therefore be stated that the physiological component of the athlete himself and his opponent are highly affected in a boxing match. The research in physiology examines short and long-term effects of physical activity on the system (Birch et al., 2005). Acute effects can be described as an increase of the heart rate resulting from high intensity punches throughout a round of boxing or a knockout caused by various heavy punches that have a direct impact on the central nervous system (CNS). The long-term or chronic (adaptive) effects of physical activity can be recognized by an improvement of the cardio vascular system after an intensive training program (Birch et al., 2005).

Only a few studies were conducted in the field of physiology and boxing, although the sport of boxing is gaining more popularity worldwide. The strict competition rules of international boxing associations like the AIBA are a limiting factor for data generation in a competitive setup like a boxing match. Amateur boxers and researchers have to follow the strict rules and regulations of the AIBA in terms of the equipment and uniform they can use in a competition (AIBA, 2019c, 2019b).

Chaabène et al. (2015) postulates that physical as well as physiological profiles of boxers are of great interest to athletes and coaches in order to reach high level performance in combat sports. Especially in live boxing matches there is little to no research analyzing physical and physiological impact factors of the athlete’s performance although these information are of great importance for the design and development of appropriate and effective training strategies (Chaabène et al., 2015). Furthermore, with statistical data about the physiological effects on the boxer himself, conclusions can be drawn for injury prevention methods. There is a strong global demand for new and innovative sports equipment, as stated before, that can be applied in a competition setup to generate physical and physiological data. With the publication of the latest version of the Amateur International Boxing Associations (AIBA) technical and competition rules it is stated that boxing sensors can be inserted in the competition gloves or on the bandages to measure statistical data during a boxing bout (AIBA, 2019b). This new rule change provides a great opportunity for future research in worldwide amateur boxing competitions. With the research and the development of the smart boxing monitoring system presented in this thesis and future adjustments to rules and guidelines of the boxing associations there is a huge opportunity to integrate the newly developed sensor system into boxing gear for performance analysis during boxing competitions. This would offer and allow new research in the field of physiology and biomechanics outside laboratory conditions.

In recent years few studies have been conducted in the field of physiology and boxing to examine important physiological factors of amateur and professional boxers. Despite the increasing popularity of boxing worldwide, research in the field of physiology and boxing is limited. Especially measurements recorded at live boxing matches are scarce even though they would be of great interest.

For the research into the development of a boxing monitoring system the physiological processes of the musculoskeletal system are of utmost interest. Although Birch et al. (2005) indicates four major areas in the field of exercise physiology, such as the nervous system, the endocrine system and the cardiorespiratory system, the development of the smart boxing glove focuses on the parameters that have a mutual effect on the musculoskeletal system. Therefore, the literature research of exercise physiology is focused on processes of the locomotor system that are triggered by physical movement in the sport of boxing and martial arts.

The boxing monitoring system should enable the athletes and coaches to measure performance parameters, inter alia, the speed, velocity and force of a punch as well as the orientation in three-dimensional space for technical

improvements. These parameters can be analyzed and the resulting data outcome can help to determine the overall fitness of the boxer.
Today's performance diagnostics in boxing are focusing on respiratory gas analysis and lactate as well as blood pressure measurements. The developed boxing monitoring system opens up new possibilities of technique and performance analysis that can be used as a support to the previous diagnostic methods that mainly focus on physiological aspects.

Halperin, Hughes and Chapman (2016) emphasize that the physiological measures are the foundation for periodized training. Furthermore, on the basis of these parameters coaches can optimally prepare an athlete to compete at the highest level and prevent injuries for example from overtraining (Ashker, 2011).

Chaabène and colleagues (2015) analyzed the physical and physiological characteristics in the sport of boxing. The authors concluded that major impact factors of the performance in the sport of boxing are, apart from muscular strength and power, the cardiorespiratory fitness, a low body fat index and high muscle mass percentages. In addition, the authors emphasize that it is essential to the competing athlete to have a well-developed aerobic capacity to sustain repetitive, high-intensity actions in an amateur boxing match (Chaabène et al., 2015). Boxers need to quickly recover between rounds and the body has to withstand the great physiological demands of boxing matches as boxing is a high intensity intermittent sport with three rounds of three minutes and one minute rest in between (for all Elite Men’s and Women’s competitions regulated by the AIBA) (AIBA, 2019b). In professional boxing athletes must cope with a duration of 12 rounds, with three minutes each for male competition and two minutes each for woman’s with a break of one minute in between (World Boxing Federation, 2019). In this regard, the aerobic and anaerobic metabolism is depending on the duration and activity of the athlete (Ghosh, 2010).

The cardiorespiratory fitness level of boxers were recorded by several authors. The research concluded that the aerobic and anaerobic fitness levels should be considered as a major factor contributing to the overall success of the athlete regardless of gender and ranking (Bruzas et al., 2014;

Chaabène et al., 2015; Guidetti et al., 2002; Halperin et al., 2016; Slimani et al., 2017; Smith, 2006). The maximal oxygen consumption (VO_2 max) was measured on a continuous graded exercise test (i.e. running on a treadmill or cycle ergometer). However, in some studies it is not clearly outlined what kind of testing procedure was applied. Furthermore, the various test methods led to different results in VO_2 max measurements as well as heart rate and lactate values (Arseneau et al., 2011). These performance analysis tests, that are generally used in the field of sport-science, are not directly related to the sport of boxing. Nonetheless tests procedures need to be specifically designed for boxing to meet the athlete's requirement profile and reliably measure the physiological parameters such as heart rate, blood pressure or VO_2 max. Chabene (2015) supports the assumption that performance tests need to be adapted with specific ergometers or boxing bulb tests for VO_2 max analysis. Arsenau and colleagues (2011) developed and validated a method to measure the oxygen uptake of sparring based on the VO_2 max values measured during pad work immediately after three to two minute rounds of sparring. However, these measurements are controversial because they cannot be guaranteed that the athletes training intensity was as hard as in a simulated competition situation as a sparring is supposed to be.

To better understand the endurance capacity in boxing matches specific boxing tests are recommended for future research due to physical movements and metabolic requirements that occur particular in boxing competitions.

Guidetti and colleagues (2002) revealed in their study testing "that the individual anaerobic threshold and the hand-grip strength measurements were highly related ($p < 0.01$) to boxing competition ranking" (Guidetti et al., 2002, p. 311) for eight elite amateur boxers tested of the same weight class. It can therefore be stated that both the anaerobic power as well as muscular power and isometric strength are important performance factors for boxing athletes. In reference to the analyzed literature Chaabène et al. (2015) underlines the importance of muscular power by stating "that punching force is paramount to a fighter's victory and one of the key indicators of amateur boxing performance" (Chaabène et al., 2015, p. 344). In recent years several tools have been used in scientific research to record punch forces.

As punch force is a key component of the conducted research and presented thesis, literature on methodologies for punch force determination will be outlined in detail in the following course of this chapter.

Overall studies investigating the physiological characteristics of boxers especially during a competition setup are scarce and new test methods must be developed and implemented in future research to obtain new and in-depth insights of the physiological profile of boxing athletes. Therefore, the concept of the presented research work goes beyond the actual state of research. The developed monitoring system has the aim to collect biomechanical parameters specific to the sport, that can be used to support the performance analysis and to draw conclusions about the physiology of the boxer based on experimental data collected.

Furthermore, with the goal to provide methods for performance analysis in the junior and amateur as well as the recreational sector, the research work presented can be of great interest. The system allows to collect sports-specific performance data during normal training and competition situations. This provides performance data to the coaches as well as to the athletes themselves. Hence the performance diagnostic can also be performed in the lower-class performance range and thus offer a larger number of athletes a helpful training tool to support and optimize the field of combat sports performance.

An important part for the development of sport equipment is the understanding of biomechanical processes of the accomplished performance, in this case of boxing related movements. For this understanding the consideration of the affected anatomical structure is of great importance to further incorporate the improvement of sport equipment and the possibility of injury risk reduction. In order to improve the understanding of biomechanical processes, the fundamental principles of anatomy, related to the sport of boxing will be explained briefly in the following paragraph.

In boxing, strength, speed and endurance determine the athlete's performance. More in detail, a distinction can be made between starting strength, explosive strength and muscular endurance (Weineck, 2008). In addition to the statement by Weineck (2008), Tittel and Seidel (2012) emphasize that the reaction time as well as the dynamics of movement execution are decisive factors in competitive performance. The authors postulating that boxing is a type of sport that is characterized by speed and strength since the vast amount of power comes from the speed of movement 70% whereas 30% comes from muscular strength (Tittel & Seidel, 2012). In addition, well developed coordinative skills are essential factors for the athlete in order to properly execute the offensive as well as defensive techniques while the fatigue increases during the rounds of a fight. The constantly changing situations in competition due to sudden, unexpected impacts of the opponent requires great concentration and good anticipation skills of the boxer as well as good inter- and intramuscular coordination. The better the coordination between agonist and antagonistically muscles are, the lower can be the energy consumption of the muscular system. The intramuscular coordination is defined by the activation of different motor units of the same muscle. In addition to the maximum strength training, the coordination of the muscles and the motor unit plays an important role to increase the performance in competition.

Tittel and Seidel (2012) point out that the whole body is involved in the motion sequence during a boxing punch. The authors specify that the boxing punch is not only caused by a contraction of the corresponding upper and lower arm muscles, it is rather a movement of the whole locomotor system starting from the flexors of the foot to the extensors and flexors of the fingers in an optimal kinematic chain (Dyson et al., 2007; Filimonov et al., 1985; Lenetsky et al., 2013a; Tong-Iam et al., 2017; Turner et al., 2011a).

The main muscle groups that are involved in boxing will be explained in the following paragraph for the straight punch as an example as presented in Figure 4. Based on this theoretical introduction, a kinematic and kinetic analysis of the punch is shown in the following subchapter.

Three major body part movements are stated for a conventional jab by the literature: 1) leg extension, 2) trunk rotation and 3) arm motion (Filimonov et al., 1985; Lockwood & Tant, 1997). The performance determining musculature for the punch are the leg muscles with the ankle flexors (musculus triceps surae) and the knee extensor (musculus quadriceps femoris). For the step towards the opponent as a primary movement of the punch the athlete can increase the power of his punch while making use of the biggest muscles in the human body, the musculus gluteus maximus (Weineck, 2008). The gluteus maximus adds power to the punch while extending the hip. Furthermore, the gluteus maximus, gluteus minimus and the gluteus medius are of great importance in stabilizing the body, raising the torso and enable the athlete to quickly move the lower extremities during offensive attacks and the execution of defensive techniques (Delavier & Gundill, 2013). In addition, the soleus and gastrocnemius help adding power to the punch by pointing the toes. Strong calf muscles can anchor the legs to the floor and help to effectively increase punching power in conjunction with the muscles of the lower body. The drive of the ground is described as a major contributor to the punch force by various authors (Filimonov et al., 1985; Lenetsky et al., 2013a) and plays a major role in the kinematic chain (2.1.1 kinetics and kinematics of the boxing punch).

The core muscles serve to transmit the kinetic energy that emanates from the ground to the upper limbs. The athlete needs strong back and abdominal muscles not only for throwing punches but also for absorbing blows. The rectus abdominis protects vital internal organs from hard hits by the opponent. Besides, a well-trained core musculature is required for the use of defensive techniques such as bobbing and weaving. Hereby the boxer constantly shifts the head and his upper body up and down as well as from side to side. Furthermore, the obliques rotate the torso and enhance the power of a strike particular in movements that involve a rotation around the longitudinal axis as it is presented by the two punching techniques of the hook and the cross (Delavier & Gundill, 2013).

The musculus latissimus dorsi supports in clinching an opponent, and more importantly the retroversion of the latissimus dorsi recoils the punching arm and therefore increases the efficiency of a strike. This is important for the conducted study 4.2. The musculus pectoralis major is involved in all striking movements. Especially during the execution of the hook punch, that incorporates a rotation around the longitudinal axis of the boxer, the pectoralis major muscle fibers contributing to a great extend the force generation in this movement. Furthermore, the chest musculature is working in conjunction with the musculus deltoideus for the anteversion of the punching arm. The deltoideus muscle plays a fundamental role not only for the straight punch but for all punches thrown by the athlete. The deltoideus muscle has an anterior, posterior and lateral part thus the flexion and extension of the deltoideus allows the arm to move in various directions. When the arm is lifted all parts of the deltoideus muscle contract simultaneously whereas the proportion of contracting muscle fibers of the anterior or posterior part determine whether the arm moves in an ante- or retroversion (Delavier & Gundill, 2013; Weineck, 2008).

When the boxer performs straight hits, the musculus triceps brachii is most effective by extending the arm explosively. For the uppercut and hook punching technique, the musculus biceps brachii, musculus brachialis and the musculus brachioradialis are adding power to the punch by flexion of the forearm.

Finally, the extensor carpi, extensor carpi radialis brevis, extensor digitorum and the radialis longus are main muscles to protect the boxer's wrist. These muscles are of great importance by pulling the hand inwards and clenching the fist in a rigid position while the fist hits the target (Delavier & Gundill, 2013).

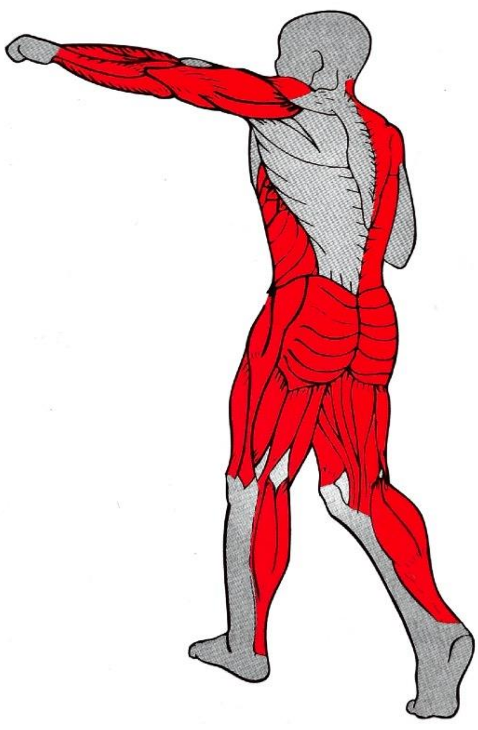


Figure 4: Muscle involvement for a straight left punch (Weineck, 2008, p. 342)

For the analysis of the anatomy of a boxer not only the muscles are of great importance as a performance determining factor but also the underlying biological structures such as bones, ligaments and tendons. Especially when it comes to injury prevention. The following paragraph will give a short overview of the bones of the hand which are directly involved during a boxing punch and are of special interest for the research of the Center of Pressure distribution on the boxers fist. This analysis is justified by the fact that the developed boxing measurement system can measure the impact forces which occur during a boxing punch. Hence conclusions can be drawn about the risk of injury to the biological structures of the hand. In order to develop a measurement system that visualizes forces and accelerations that appear in a regular boxing fight, the human hand is the most important factor that has to be understood as high forces are transferred from the hand to the target and vice versa.

Several scientific studies have shown that high forces are transferred to the opponent through short impacts where the fist collides with the opponent's body. These forces range from 1604 N for novice boxers to 4800 N for elite male boxers (Smith et al., 2000). In addition high velocities of the fist were reported by Whiting and colleagues (1988b) with an average velocity at contact ranged from 5.9 to 8.2 m/s and peak velocities of 6.6 to 12.5 m/s at maximally 21 milliseconds (ms.) before contact with the punching bag. These parameters show that the hand and its structures have to withstand not only high force but are also a key indicator for efficient force transmission from the athlete's fist to the target.

It must be noted that historically, various instruments were developed and used to determine the force and speed of different punching techniques, such as the 'cross', 'jab', 'hook' or 'uppercut', as the most popular punches thrown during a boxing match (Atha et al., 1985; Filimonov et al., 1985; Lenetsky et al., 2013; Pierce et al., 2006; Smith et al., 2000; Walilko, 2005; Whiting et al., 1988). Therefore, maximum velocities and punch forces varying due to the different measurement instruments used, as well as skill levels and punching techniques tested. This topic will be further investigated in the kinetic and kinematic subchapter 2.1.1.

In boxing it can be assumed that high forces arise at the knuckles of a boxer's fist based on several studies that investigated the punch force determination during various punches thrown with a clenched fist (Atha et al., 1985; Filimonov et al., 1985; Pierce et al., 2006a; Smith et al., 2000; Smith, 2006; Walilko et al., 2005). Nonetheless it is worth noting that there are currently no studies that show the magnitude of the impact forces that are explicitly acting on the joints and bones of the hand. Especially the metacarpophalangeal (MCP) joints are exposed to high levels of stress due to the protrude position when the boxer folds the phalanges of the second to fifth finger into the palm and presses the thumb on the middle phalange of the index and middle fingers as illustrated by Figure 5 (Arus, 2018a, p. 363). The 'normal fist' or horizontal position (a) presented in Figure 5 is commonly used in boxing. In this position the palm is facing downwards and the attempted punching contact zone is between the second, third and fourth head of the metacarpals (Arus, 2018).

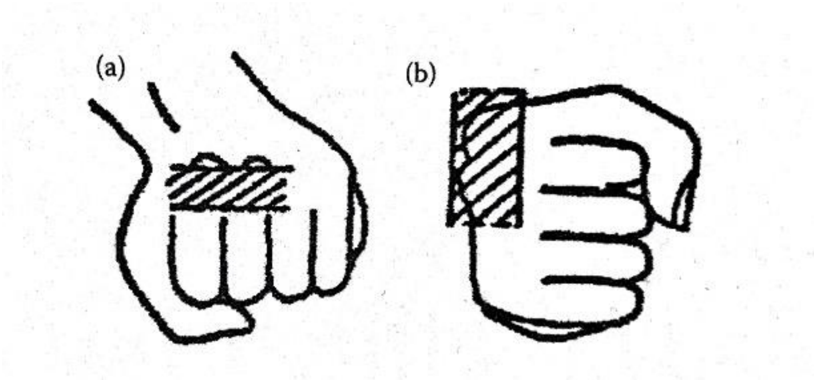


Figure 5: Punching contact zone for horizontal (a) and vertical (b) fist (Arus, 2018a, p. 363)

The impact force is transferred from the mentioned second to fourth heads of the metacarpals and the metacarpophalangeal (MCP) joints through the metacarpals themselves (Figure 6). As the second and third metacarpals are more stable, hard impacts on the fifth head of the metacarpal could cause a common injury in boxing, known as the boxer's knuckle (Van Der Zee et al., 2015). As the impact occurs some of the impact force is absorbed by the biological structure that surrounds the point of impact like the muscles, cartilage, tendons and the skin. For a better understanding of the anatomy of the hand, Figure 6 is illustrating the structure of the bones and joints of the left hand.

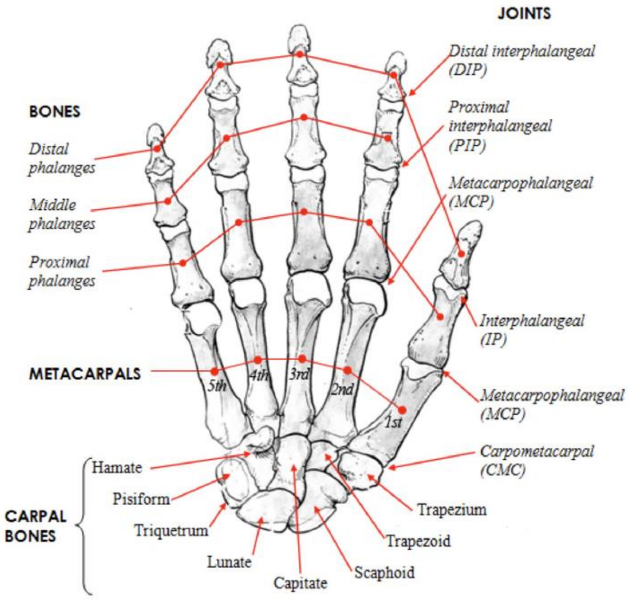


Figure 6: Anatomy of the human hand (Nanayakkara et al., 2017, p. 6)

The force is further transmitted from the metacarpals through the carpal bones to the ulna and radius. Due to the anatomical structure of the wrist 80% of the force is transmitted into the radius when pressure is applied on the fist (Shamus & Shamus, 2001). The fact that the force is not equally transmitted by the ulna and radius is a result of the radius being thicker and stronger at the distal forearm than the ulna. Therefore, the radius is the more stable bone and can absorb a greater amount of force than the ulna. Nevertheless, in boxing the horizontal punch as shown in Figure 5 (a) is most commonly executed due to the fact that with a twisted forearm more muscles are engaged and more power can be generated. Furthermore, the ulna is relatively longer by 0.84 mm in an extended and twisted position than in a supinated position where the palm is facing upwards (Palmer et al., 1982). The length of the ulna has a great influence on the strength of the wrist. Increasing the length of the ulna by only 1 mm means a major increase in the possible load-bearing capacity of the bone (Trumble et al., 1987). The relative length of the ulna is also decisive for the distribution of force between ulna and radius during the twisted punch. As illustrate by Figure 7 the ulna and radius wrap around each other in a entirely twisted punching position, that is creating a slack of the central interosseous membrane (Thomas, 2013). This results in an increased risk of injury as the bones bend away from each other when force is applied to the ulna and radius. In a vertical punching position, the interosseous membrane connects both bones and transfers the force diagonally between the bones.

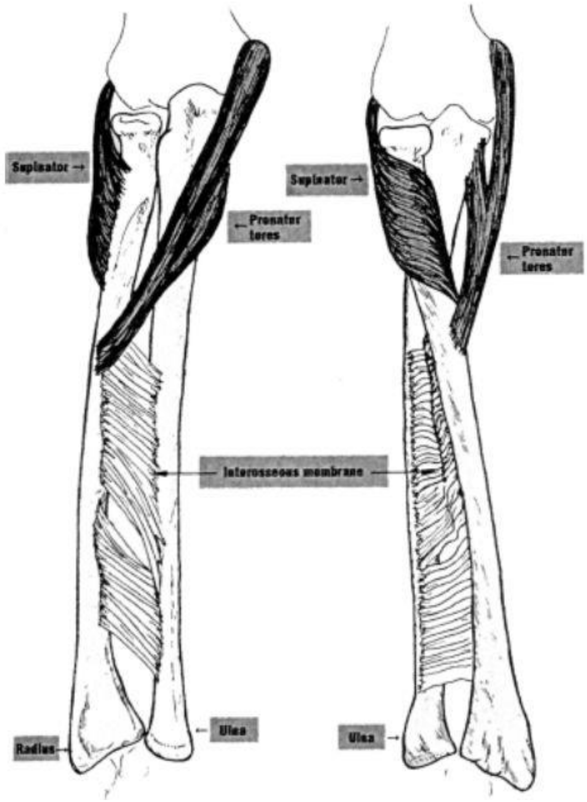


Figure 7: Forearm anatomy: The left view shows the supine position; the right view shows the prone position of the forearm (Thomas, 2013)

In order to better understand the cause of hand injuries in boxing, modern sensor technology is needed to determine the distribution of forces on the punching contact area of the boxer’s fist (i.e. the metacarpophalangeal joints and the proximal phalanges). The literature research outlines a lack of knowledge of the distribution of impact forces on the hand for various punching techniques and boxer profiles. In addition, it is essential to measure biomechanical parameters in order to gain important and necessary insights into the causes of hand injuries and to use the gained information for injury prevention interventions as well as possible improvements to the sport equipment itself. Hence a sensor system is developed in the conducted research work and presented in this thesis that not only allows to determine impact forces and accelerations of the hand but also that displays the accurate center of pressure movement on the boxer’s fist to offer new methodologies to gain novel insights in the cause of hand injuries (chapter 2.3).

2.1.1 Kinetics and kinematics of the boxing punch

Biomechanics forms a decisive scientific basis for the analysis of human movements. The biomechanical analysis of movement in boxing is an important part for the development of the boxing monitoring system. In order to highlight the crucial factors influencing performance in boxing, an overview of the existing literature will be given in the following chapter. Based on the existing research analysis, gaps in the scientific literature were identified and addressed in the further course of the work.

A definition of biomechanics is given by Nigg and Herzog (1999, p. 2):

> “*Biomechanics is the science that examines forces acting upon and within a biological structure and effects produced by such forces.” (Nigg & Herzog, 1999, p. 2)*

The research within the field of biomechanics addresses various areas for the study of human movement. This includes studies on the functioning of muscles, tendons, ligaments, cartilage and bones as well as the amount of stress and load of certain structures that affect the athlete's performance (Nigg & Herzog, 1999). In relation to the listed fields of investigation of Nigg and Herzog (1999), the biomechanical analysis of human movement according to Flanagan (2014) is targeting two goals. Firstly, the athlete's performance can be influenced by the analysis of biomechanical parameters and secondly, the risk of injury can be reduced by adapting and modernizing the equipment used (Figure 8).

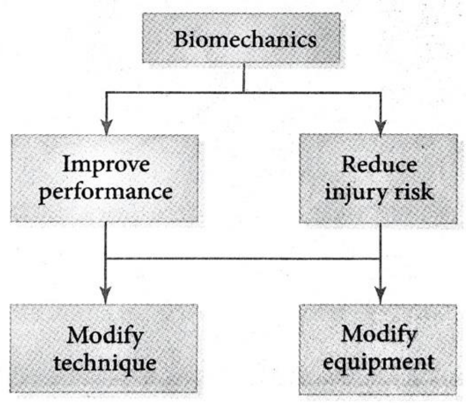


Figure 8: Two objectives of biomechanical analysis: improve performance & reduce injury risk (Flanagan, 2014)

In relation to the development of the boxing monitoring system, both objectives are considered. On the one hand, the developed boxing monitoring system serves athletes and trainers as a tool with which a precise performance analysis can be achieved. This includes important parameters such as punch force, acceleration and velocity of the punch. On the other hand, with the development of the instrumented boxing glove, forces that occur on the punching surface can be displayed and analyzed for the first time and presents therefore a unique inside into boxing punch biomechanics. On this basis, potential health risks during boxing matches and training can be made visible in order to help prevent severe injuries of athletes.

The research of kinematic and kinetics are part of the mechanical analysis of dynamics which is a subdivision of the classical mechanics (Flanagan, 2014). Both research areas of biomechanics are illustrated in Figure 9 (Grimshaw et al., 2006). The field of kinetics and kinematics has a particular significance for the following research since the human motion in the sport of boxing will be analyzed.

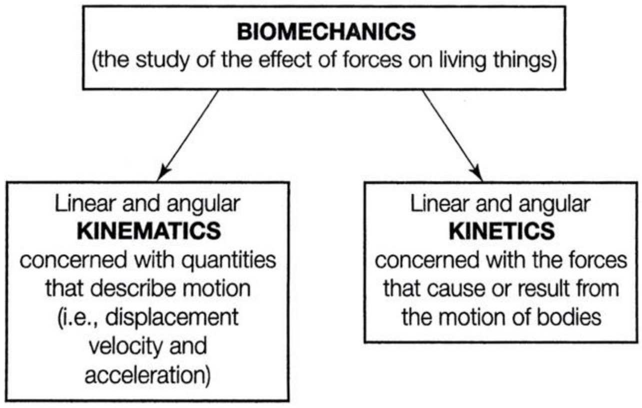


Figure 9: Biomechanics, kinematics and kinetics (Grimshaw et al., 2006, p. 12)

As highlighted by Figure 9, the kinematic analysis focuses on the study of linear and angular motion without regard of the forces that are causing the movement (Grimshaw et al., 2006; Robertson et al., 2014; Winter, 2009). In a kinematic analysis the displacement, velocity and acceleration of body segments is analyzed. Since there is an ambiguity in the literature concerning the influencing factors of an effective punch, the research presented in this thesis will examine on several biomechanical parameters like acceleration, velocity, displacement, orientation and punch force that includes not only kinematic but also the kinetic data which were obtained from experimental studies.

In general terms kinetics describes the forces that cause or result from the movement. This relates to internal forces from muscle activity, ligaments or the friction in the muscles and joints and external forces from the ground or active bodies (e.g. a punch hitting the target during a competition) (Neto, 2011). In boxing the muscles of the athlete are generating the force that accelerates the hand towards the target. When the boxer’s hand collides with an object, the object produces a force that acts on the hand and body of the boxer himself. This can be described according to Newtons 3rd law of motion, that states “when one body applies a force to another body, the second body applies an equal and opposite reaction force on the first body” (Robertson et al., 2014, p. 80). In terms of the research conducted in this thesis a kinematic and kinetic analysis is made analyzing acting forces and force distribution of the boxers fist, following Newtons law as well as the punch acceleration, orientation in space and the velocity which occurs during a boxing punch.

Since the 1980s, scientists in the field of martial arts have been trying to quantify the forces and speed that occur during boxing fights. However, due to missing or inadequate measuring instruments and the difficult setup of instruments in boxing fights it has been difficult to collect data and compare the findings published in the past. Furthermore, only few scientists have investigated how beginners and advanced fighters differ in key performance factors according to the expert-novice paradigm. Despite various efforts to measure forces and speeds on the boxer, there is still no uniform measuring instrument that allows the comprehensive measurement of relevant biomechanical data in a non-laboratory environment neither in a live boxing match. Due to the previously mentioned different measurement systems and methods, it is difficult to present existing studies in a meta-analysis. Therefore, the following chapter will provide a tabular overview of the studies on impact measurement that were conducted in recent years.

Although punching accuracy and speed are important performance-determining parameters in boxing matches, several studies have shown that punching force is the main performance indicator for success or failure in boxing matches (Loturco et al., 2016; Pierce et al., 2006a; Piorkowski et al., 2011; Smith, 2006). In professional boxing and heavyweight fights particularly, single hard hits can lead to a knock-out, and thus, to victory. Previous studies have used various instruments to measure impact forces in laboratory conditions. In this respect, the researchers used piezoelectric force sensors, among others, as these have a high validity and reliability. An overview of these different measuring techniques is presented in Table 2 including the measuring devices, the participants of the study, the chosen striking hand and punching technique as well as the measured force in Newtons. Most of the methods presented in table 2 are not applicable in the field and are therefore not suitable for obtaining realistic results that can be observed during a boxing training or competition.

Table 2: Dynamometry in punching force literature modified according to Lenetsky (2013a, p. 2) in chronological order

Dynamometry in punching force literature				
Study	**Subjects**	**Force Measuring Equipment**	**Punches Tested**	**Punching Forces, N**
Joch et al. (1981)	Elite (n=24), national-level (n=23), intermediate-level boxers (n=23)	Water filled punching bag equipped with pressure sensors	Straight punch	Elite 3453 (PF)
				National-level 3023 (PF)
				Intermediate 2932 (PF)
Atha et al. (1985)	Professional heavy weight boxer (n=1)	Padded pendulum equipped with piezoelectric force transducer	Cross Punch	4096 (PF)
Voigt (1989)	Karate students - well trained (n=10)	Developed punching dynamometer including accelerometry	Right punch similar to boxers straight right	3334 (MF) 2345 - 4866 (PF)
Fortin et al. (1994)	Unidentified	Water-filled bag with pressure transducer	Unidentified	Not included
Smith et al. (2000)	Elite (n=7), intermediate (n=8), and novice (n=8) boxers	Wall-mounted force plate (4 triaxial piezoelectric force transducers) with a boxing manikin cover	Elite rear hand mean force	4800 +/- 227
			Elite front hand mean force	2874 +/-225
			Intermediate rear hand mean force	3722 +/- 133
			Intermediate front hand mean force	2283 +/- 126
			Novice rear hand mean force	2381 +/- 116
			Novice front hand mean force	1604 +/- 97 (MF)

Birken et al. (2001)	Professional Boxer Vitali Klitschko (n=1)	Boxing glove and punching bag equipped with accelerometer	Cross punch	5315 (PF)
	Professional Boxer Wladimir Klitschko (n=1)			5545 (PF)
Dyson et al. (2005)	Male competitive amateur boxers (n=6)	Boxing dynamometer manikin which was matched to the shoulder height of each subject	Singular and combination straight punches in a prescribed sequence. Rear and lead hand.	Rear 4236 +/-100 (MF)
				Lead 2722 +/- 75 (MF)
Girodet et al. (2005)	Karateka (n=1)	Makiware equipped with 2 single-axis force sensors	Straight Punch	1745 (PF)
Walilko et al. (2005)	Olympic boxers weighing from 48 to 109 kg (n=7)	Hybrid III dummy equipped with a 6-axis load cell in the neck, a Tekscan's pressure sensor in the dummy's face, and Endevco accelerometers on the boxer's hands	Straight Punch	1990 - 4741 (PF)
				3427 +/- 811 (MF)
Pierce et al. (2006a)	Professional boxers (weighing 59.0–98.9 kg) - Junior Lightweight, - Light Welterweight, - Super Middleweight, - Cruiserweight, - Heavyweight (n=12)	Bestshot force sensor system imbedded in boxing gloves	Various punches – all of them were recorded during six professional boxing matches	866.6 - 1,149.2 (MF)
				5358 (PF)

Mack et al. (2010)	Amateur male boxers (n=39)	A HIII 50 th percentile male dummy (head, neck, and torso) with a frangible face. An upper neck load cell measured neck force and moments. Three gyroscopes and three accelerometers were fixed to the dummy head. Boxers were instrumented with FAB System (incl. 13 wireless sensors: accelerometers, gyroscopes, magnetometers)	2 x hook & 2 x straight punch each boxer	Straight 1100 – 4500 (PF) Cross 1800 – 8000 (PF)
Chadli et al. (2014)	Amateur college athletes (n=11)	Torsion bar fixed on a frame consisting of strain gauge sensors and two accelerometers. One attached to the target and one worn inside the glove	Strike with maximum power	761 - 1162 (PF)
Loturco et al. (2016)	Amateur boxers from Brazilian National Team (n=15)	Force platform covered by a body shield was mounted on a wall at height of 1m perpendicular to the floor	Jab and cross punch	Jab 1212.22 +/- 269.62 (MF) Cross 1368.33 +/- 266.27 (MF)
MF = mean force; PF = peak force.				

As stated above, punch force is a critical factor in evaluating the efficacy of training programs. Athletes and coaches currently lack any measuring instruments to analyze the force of impact, punch speed and other important biomechanical parameters in training or competition with a high degree of accuracy. In this respect, there is also no possibility to classify the athletes in a scouting system based on their performance parameters. Nevertheless, the importance of tracking performance metrics is particularly evident in other sports such as football. For years now, various statistics have been recorded for the athletes, including ball contacts, shots at the goal, ball possession in the various zones on the pitch, meters run, but also physiological parameters such as heart rate. With these parameters' athletes can be assessed all over the world by analyzing and comparing performance measurements. One of the most important parameters in martial arts is the analysis of the punch force and number of punches thrown. Even though there is no general valid system that is used in a boxing gym or competitive environment, several studies with martial arts athletes were carried out in the past that will be explained in the following paragraph following Table 2.

One of the first authors to analyze the punch force in combat sports were Fritsche, Joch and Krause (1981). The research group used a punching bag filled with water to measure the change of fluid pressure with a pressure sensor applied to the boxing bag. However, it should be noted that kinesthetic perception differs greatly when hitting a human body part or a punching bag filled with water. In addition, this method requires a laboratory and the punching bag must be instrumentalized beforehand. Therefore, this method is not portable and cannot be used in a normal boxing environment. In addition, the punching bag must be stabilized after each punch in order to be able to record reliable data. This is very time consuming and does not allow combination punches to be recorded validly.
Atha et al. (1985) and Villani and Preli (2003) used ballistic pendulums in their studies to record the punch force. The study investigated professional heavyweight boxers while they were striking with maximum punch forces against a suspended ballistic pendulum. Atha et al. (1985) reported a peak force on impact of 4096 N accomplished within 14 ms of contact and the transmitted impulse caused an acceleration of the target head of 520 m/s^2 that is equal to an acceleration of 53g. Birken, Morlock, Gross and Weltin (2001) advise that in automotive accident research these severity of hits are considered critical for the human head even if the contact time is only 20 ms.

In a study by Birken und colleagues (2001), the highest impact force was measured by former heavyweight world champion Wladimir Klitschko at 5545 N. Wladimir and Vitali Klitschko performed in the conducted study single maximum power strikes on a punching bag (21kg) equipped with acceleration sensors. The boxing gloves were also equipped with acceleration sensors so that the acceleration of the hand was measured until impact. For Vitali Klitschko a maximum acceleration of 1420 m/s^2 was measured with a contact time of 20ms. The second boxer tested, Wladimir Klitschko, had a much lower acceleration of 853 m/s^2 of the glove but transferred a higher impulse to the punching bag (196 Ns Vitali and 203 Ns Wladimir). Therefore, it can be assumed that Wladimir put a higher effective mass into the punch that produces a higher punch force.

Smith et al. (2000) have developed a boxing dynamometer which included four triaxial piezoelectric force transducers. A boxing manikin, that was designed to represent the head and upper body of the boxer, was attached to a support plate that was connected to the force transducer and could be adjusted to the desired height of the boxer. The boxers reported that the kinesthetic perception was similar to punching in a boxing match. However, even this system has limitations as the construction cannot be used flexibly in the field. On the other hand, it could be guaranteed that the piezoelectric transducers have a good temperature stability and are therefore well suited for long-term use. The transducers were calibrated prior to the measurement to ensure the validity of the measured data. The validation showed a percentage error of less than 3% between the calculated force and the mean force measured by the dynamometer at impacts above 500 N. Overall, the study showed that the maximum punch forces in the elite group were significantly larger than in the intermediate group and the novice group. For the group of elite boxers an average of 4800 N was measured for the rear hand and 2847 N for the lead hand (Table 2). In comparison, for the intermediate participating group the researchers measured punch forces of 3722 N for the rear hand and 2283 N for the lead hand. The novice group achieved punch forces of 2381 N (rear hand) and 1604 (lead hand). There are clear differences in the amount of punch force between the two punch executions of the rear and lead hand. Smith and colleagues (2000) agreed with the statement of Joch et al. (1981) and Filimonov et al. (1985). The authors describe the effect based on the ground reaction force, that has a significant influence on the total force produced when athletes are striking with the rear hand and use their leg drive to release more power to the punch. Furthermore, Hickey et al. (1980) are reporting that the body rotation and the distance over which the punch is thrown has a major impact on the total force achieved by the athlete.

Dyson et al. (2007) and Loturco et al. (2016) carried out investigations with a boxing dynamometer as well. The boxing dynamometer had a similar design to the one used in the work of Smith and colleagues (2000). To determine the punch force, a Kistler Force Plate was covered with a body shield and was attached to a wall at shoulder height of the participating athletes. In the study of Dyson et al. (2007) six competitive amateur boxers performed different punches (straight, lead and rear hand) on the dynamometer for 30 seconds. On average 19-20 punches were counted for each hand in one round. In the further analysis six punches were selected from the middle phase of the punch sequence to report the force and speed for the punches thrown. For the rear hand, with the targeting head, a mean force of 4236 N and for the Lead hand a mean force of 2722 N was determined (Table 2).

In another study conducted by Loturco and colleagues (2016), the researchers examined the punch force of 15 athletes from the Brazilian National Team (9 men and 6 women). The athletes were instructed to deliver a total of 12 punches (three jabs standardized position, three crosses standardized position, three jabs self-selected position and three crosses self-selected position) on the body shield and force plate attached to the wall. The measured values were all significantly below the reported results of Smith et al. (2000) and Dyson et al. (2007).

For the tested male participants, the highest mean force value of 1368.33 N was achieved with the execution of the self-selected cross. The group of female subjects reached a maximal mean force of 987.50 N in the same test for the self-selected cross. Since the maximum values recorded are significantly lower than in the study of Smith et al. (2000) and Dyson et al. (2007), it can be assumed that the athletes of the Brazilian National Team did not hit the boxing dynamometer with maximum effort. One reason could be the athletes' risk of severe injury, since the blow against the rigid force plate was only cushioned with a soft cover padding. However, a punch against a hard target like a wall significantly increases the risk of hand and wrist injuries such as a fracture of the 4th and 5th metacarpals (Patil et al., 2020). Loturco et al. (2016) also mentioned that the total number of punches had been reduced to 12 in order not to risk any injury of the elite athletes.

In the studies by Walilko, Viano and Bir (2005), Viano et al. (2005) and Mack, Stojish, Sherman, Dau and Bir (2010), the authors used another system for impact force measurement. A Hybrid III dummy was equipped to determine the impact force by use of accelerometers and a load cell implemented in the dummy's neck. This set-up enabled the research teams to determine the translational and rotational head accelerations and to measure the forces arising at the neck of the dummy in order to draw conclusions about the risk of head injuries.

Walilko et al. (2005) reported a mean translational acceleration of the head of 58g (SD = 13g) with an average duration of 11.4 ms. The authors recorded a mean rotational acceleration for all punches of 6343 rad/s^2. The resulting mean HIC (head injury criterion) from all punches was at 71 (SD = 49). They also identified that the HIC has a linear relationship with the punch force (r = 0.88, p = 0.00) and that the HIC differs with the weight class of the athletes. The calculated punch force ranged from 1990 to 4741 N with a mean force of all punches of 3427 N (SD = 811 N). In addition, Walilko et al. (2005) found a significant difference for the punch force in the different weight classes (p = 0.02). It was shown that the punch force increases linearly with the weight class (r = 0.54, p = 0.02).

Viano and colleagues (2005) reported the highest punch force for the hook with a force of 4405 +/- 2318 N and a maximum hand velocity of 11.0 +/- 3.4 m/s. These measures resulted in a translational acceleration of 71.2 +/- 32.2 g and a rotational acceleration of 9306 +/- 4485 rad/s^2. Compared to the study of Walilko et al. (2005) the findings of Viano and colleagues (2005) presented a higher translational and rotational acceleration of the head whereas the subjects in the study of Walilko et al. (2005) showed a higher punch force at impact. Both studies presented a similar peak force range of 1666 to 6860 N as already described in the existing literature (Atha et al., 1985; Dyson et al., 2007; Joch et al., 1981; Lenetsky et al., 2013a; Pierce et al., 2006a; Smith et al., 2000).

Overall, the authors emphasize that high punch forces and accelerations acting on the head of the athlete while being hit are increasing the risk of severe brain injuries (Mack et al., 2010; Viano et al., 2005; Walilko et al., 2005). It can be stated that boxers hit the target with a higher speed however a lower HIC value was measured compared to American football. A reason for this result can be, that the impact occurs with a lower effective mass in boxing compared to American football. Furthermore, the duration of impact was found to be minor in boxing punches with a relative preponderance of rotational accelerations in boxing compared to American Football (Viano et al., 2005). Despite this, the authors emphasize that head injuries are more severe and dangerous in boxing than in football.

Nevertheless Stojish and colleagues (2010) point out that although important findings were made, the studies are “limited due to the lack of bio fidelity of the jaw and Hybrid III head form for such an application” (Stojsih et al., 2010, p. 725). Furthermore, the total number of punches per boxer in the studies mentioned is low, which has an influence on the significance of the study.

A new approach was taken by Pierce and colleagues (2006a). For the punch force measurement, the boxing gloves of twelve professional boxers were equipped with the bestshot System™ (Figure 10). The system incorporates a lightweight flexible capacitive force sensor embedded in the hitting area of the glove. Furthermore, a microcontroller and a battery were embedded in the wrist area of the glove. The implemented measurement system weighs 36g and the athletes reported that they could not notice any difference between the modified glove and a normal glove during the boxing match. The measured force is further transmitted to a receiver via radio frequency, evaluated by a computer program and can be utilized for broadcasting or scientific research (Figure 10).

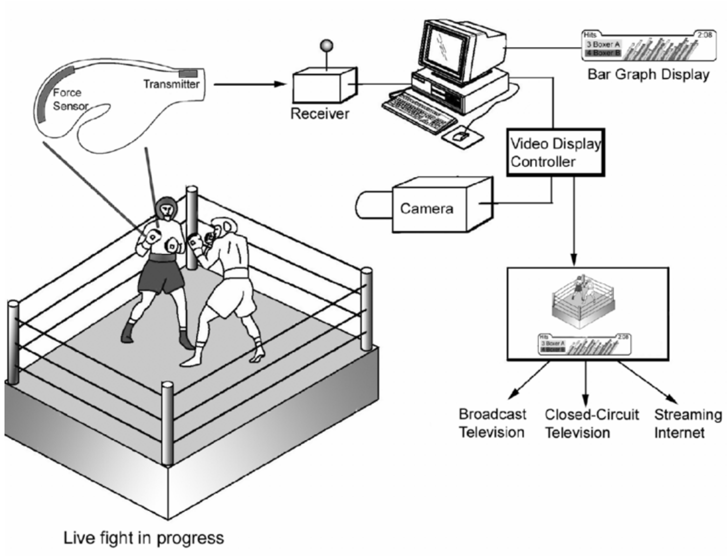


Figure 10: Bestshot System for measuring punch force (Pierce et al., 2006a, p. 4)

The calibration of the glove was performed by applying drop tests with a drop test platform from ARCCA Incorporated of Penns Park, PA. Everlast gloves in sizes 8-10 ounce were instrumentalized and tested with the force sensor. During the testing, the glove was vertically attached to a piece of wood and connected to a load cell. A wooden platform was then dropped onto the glove several times from different heights. The occurring force was measured simultaneously by the capacitive force sensor and the load cell. For a 3rd order calibration curve the average error of the differences between the measured and the calculated forces of the bestshot System using 8-ounce boxing gloves was 4.0%. For the 8- and 10-ounce boxing gloves an almost identical value could be measured as the foam in the gloves did not differ (Pierce et al., 2006a).

This system enabled the scientists to measure punch force on moving targets. This approach differs greatly from the static measurements on shielded force plates and test dummies in laboratories described previously. Until this date, less is known about the forces and accelerations that occur in live boxing matches. By using gloves equipped with force sensors it was possible to measure and evaluate the forces in six fights of different weight classes from light to heavy weight.

The average punch force ranged from 866.6 N (Super Middleweight) to 1149.2 N (Light Middleweight) and did not correlate significantly with the weight of the boxers. The greatest mean punch force was found in the Light Middleweight (1149.2 N) and in Light Welterweight (1124.3 N). Nonetheless a multiple regression analysis showed no significant relationship between the mean punch force and the weight of the boxer (Pierce et al., 2006a). Likewise, the cumulative punch force showed no significant correlation with the weight of the boxers. Contrary the cumulative punch force was found to be related to the outcome of the competition. In the three fights where judges objectively judged the fight, the boxers with the higher cumulative force have won the fight unanimously (Pierce et al., 2006a). It is particularly noteworthy that the majority of the 1675 punches were made with a force of less than 1000 N (59.2%). In total, 89 punches were above 2000 N and only 18 punches were above 3000 N. This is contrary to the high forces measured for punches in laboratory studies mentioned previously (Atha et al., 1985; Dyson et al., 2007; Loturco et al., 2016; Mack et al., 2010; Smith et al., 2000; Walilko et al., 2005). This is an indication that the punch force is dependent on the target on which the blow is executed. With moving targets, significantly lower punch forces were measured in comparison to solid bodies that were reported in studies by Atha et al. (1985), Birken et al. (2001) and Smith et al. (2000). This suggests that further studies need to be carried out in conjunction with the work published by Pierce et al. (2006a) to understand the relationship between head injury risk and the forces acting on the bodies in live boxing fights.

Halperin, Hughes and Chapman (2016) give further reasons for the deviating measurements of the punch force in the literature. Factors that may have an influence on the measurement of the punch force are among others, differences in the classification of the athletes into different performance categories, deviations due to the respective weight class, non-standardized boxing equipment and, above all, the accuracy of the measurement system used (Halperin et al., 2016).

Since the boxing monitoring system to be developed is not only intended to measure forces that occur but also to display kinematic parameters such as speed, acceleration and movement in space, the following paragraph will review the literature on kinematics related to punches in martial arts and boxing.

For the development of a modern wearable, it is important to consider the body as a holistic system in order to understand the movement in its full dimensions. In this regard the examination of the kinematic chain is of special importance, as the resulting force of the fist is the sum of the cumulated forces of the individual body segments (Arus, 2018a). Arus (2018a) further explains that in modern biomechanics the term kinematic chain is described as kinetic chain since it is a transfer of forces between segments. Therefore, the system does not analyze the individual components of the kinematic chain, but rather the resulting end product as an effective impact force.

The study of the kinetics and kinematics of punches is primarily aimed at visualizing the movement of the arm, the impact and the resulting forces (Turner et al., 2011a). Although successful boxers use a distal to proximal movement sequence to generate the greatest power for the punch as those found in sports like baseball pitching, shot put or javelin, there are very few studies that investigate how the forces are generated and transmitted through the kinematic chain to produce an effective blow (Turner et al., 2011a).

One of the first authors who have studied the influence of individual body segments on the power of punches was the research team of Filimonov , Koptsev , Husyanov and Nazarov (1985). The authors agree that boxing has a distinct synchronization between the arms, legs, and trunk movements, with a significant impact in terms of the kinetic chain to increase the punching power (Filimonov et al., 1985). They pointed out that a punching movement consists of leg extension, trunk rotation and arm action. The study examined the punches of 120 boxers from different performance levels. The boxers were divided into the categories Master of Sport, Candidates for Master of Sport, Class I, Class II & III. The study design included a questionnaire, observations and a force tensiometric dynamometer. The researchers' brief was that the punches, performed by all athletes, should be at maximum speed and power. From the results it is clear that the Master of Sport group & Candidates for Master of Sport showed the largest leg engagement with 38.46% whereas the Class II & III athletes had only 16.51% contribution of the back leg (Filimonov et al., 1985). The authors conclude that athletes in the higher power classes have a better coordination of the arm, leg and trunk movements. In addition, the athletes from the Master of Sport group were able to gain more strength for the punch by extending their legs and transferring the power through the kinetic chain from the legs to the fist.

Another study that deals with the segmental analysis of body units was conducted by Dyson, Smith, Martin and Fenn (2007). The study examined six male amateur boxers using electromyography while performing boxing strikes on a dynamometer. The authors were able to demonstrate muscle recruitment during a rear hand punch for eight muscle groups involved. The following Table 3 shows which muscles were examined and their function during a punch.

Table 3: Muscles investigated using electromyography and their actions (Dyson et al., 2007, p. 591)

Muscle	Code	Muscle action in punch delivery.
Gastrocnemius	G	Plantar flexion of foot and knee flexion.
Biceps Femoris	BF	Hip extension and knee flexion.
Rectus Femoris	RF	Hip flexion and knee extension.
Upper Trapezius	T	Elevation of the scapula
Anterior Deltoid	AD	Arm flexion and horizontal adduction.
Biceps Brachii	BB	Elbow flexion and supination of the forearm.
Flexor Carpi Radialis	FCR	Wrist flexion and wrist abduction.
Triceps Brachii	TB	Elbow extension.

The test persons were instructed to hit the target either with maximum speed or with maximum force. The recruitment sequence of the muscles varied slightly when hitting the body or head at maximum speed or maximum force. The following Figure 11 shows the muscular recruitment sequence for a punch with maximum force to the head (Dyson et al., 2007).

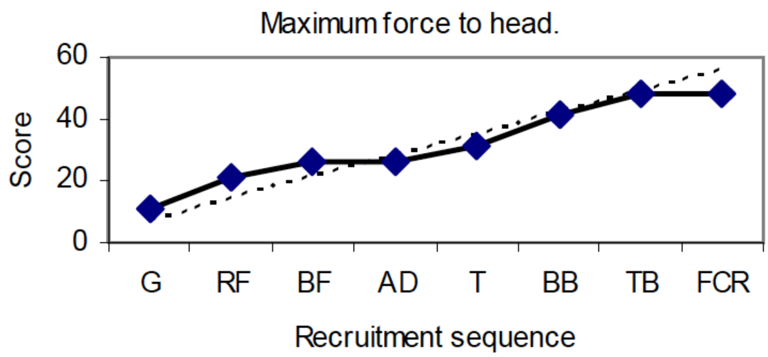


Figure 11: Muscular recruitment during deliveries with maximum force to the head (Dyson et al., 2007, p. 593)

For blows to the head with maximum force, it can be seen that the musculus gastrocnemius was first activated by plantar flexion of the foot. This was followed by knee extension through the rectus femoris muscle (RF) and hip extension through the biceps femoris (BF). Following this, the anterior deltoideus (AD) was innervated for the flexion of the arm at the glenohumeral joint. The musculus trapezius (T) lifts the shoulder blade and the biceps brachii (BB) initially held the arm in a flexed position. By activating the musculus triceps brachii (TB), the arm is extended and guided to the targeting object. Finally, the flexor carpi radialis (FCR) provides for the flexion and abduction of the wrist at the target (Dyson et al., 2007). However, it should be noted that the muscle activation during a punch at maximum speed differs from a punch with maximum force. Consequently, the kinetic chain is also applied differently. The authors found that the anteversion of the upper arm by the anterior deltoideus started immediately after the initiation of the movement by the gastrocnemius. In contrast, for a blow with maximum force, after the start of the movement through plantar flexion in the ankle and flexion of the knee, the activation of the rectus femoris begins in order to effectively use the force from the legs. The peak activation of the flexor carpi radialis and the triceps brachii took place almost simultaneously in the final phase of the stroke (Dyson et al., 2007). In total, both the muscle activation and the impact force were higher in those strokes that were performed with maximum force. The authors describe an increased impact force of 38% (1587 N) compared to the maximum speed punches. In addition, a 27% greater muscle activity of the rectus femoris was measured. The rectus femoris is responsible for the extension of the rear leg and is therefore a decisive element for increasing the power of the punch. Dyson and colleagues also support the theory that a blow at maximum force or maximum velocity begins with the muscle recruitment in the legs with a force progression all the way up to the executing fist and point of impact (Dyson et al., 2007).

The following illustration (Figure 12) from Tittel and Seidel (2012) acts as an representation of the kinetic chain during a straight right punch. The authors analyze athletic movements based on the muscles involved. The black muscle loop represents the agonists and the red muscle loop the antagonists. The illustration serves as an overview of the active musculature described previously, in chapter 2.1 about the physiological and anatomical aspects of boxing, for a blow with the right hand. The depicted muscle loops provide a schematic understanding and represent only a part of the 42 muscle groups which, according to Tittel and Seidel (2012), are involved in a hit with the rear hand. Besides the co-contraction of the agonists and antagonists, the synergists support the motor movement by stabilizing the joints. The graphic of Tittel and Seidel (2012) summarizes the interaction of agonists and antagonists during the transmission of force through the kinetic chain from the legs to the fist.

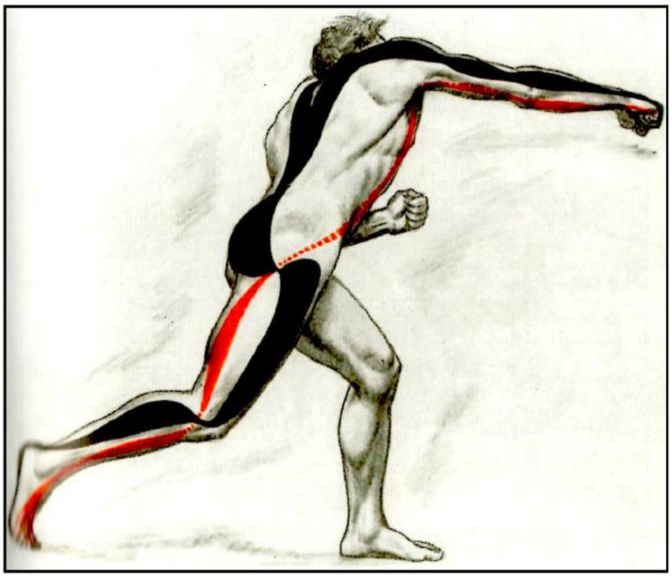


Figure 12: Visualization of the kinetic chain during a straight right punch (Tittel & Seidel, 2012, p. 283).

In contrast to kinetic, kinematic describes and analyses movements in linear and angular motion. This includes displacement, velocity and acceleration. In a work by Cheraghi and colleagues (2014) the kinematic data of eight male right handed elite amateur boxers was measured for a knock-out blow with the right straight. The authors used high-speed cameras and body markers to measure the angular variation at elbow, shoulder, hip, knee and ankle joints. The measurement of a complete impact cycle was carried out from the first joint movement at the ankle to the impact of the fist on the targeting object. The authors reported that ankle, knee and elbow extensions started at 45, 60 and 80% of the punch cycle (Cheraghi et al., 2014). This supports the findings of Dyson et al. (2007) and reflects the sequential activation of the muscles groups from distal to proximal. In addition, the authors describe that the ankle and knee extension led to a shift in weight from the rear foot to the front foot. The forward shift of the body mass led to an increase in punch momentum and speed. Cheraghi et al. (2014) reported a mean fist maximum velocity of 7.8 m/s which is similar to the results of Atha et al. (1985), Unterharnscheidt and Taylor-Unterharnscheidt (2003), Walilko (2005) and Whiting et al. (1988b). Although the recorded kinematic data showed similar patterns between the athletes, large standard deviations were recorded for some variables.

According to Cheraghi et al. (2014) a possible explanation could be the execution of different movement techniques of the boxers tested. Therefore, the authors recommend to not follow a uniform technique pattern but to promote the individually successful techniques of an athlete.

A study carried out in (2011) by Piorkowski, Lees and Barton examined the influence of the different types of punches (Jab, Cross, Lead Hook and Reverse Hook) and their execution (single maximum, in synch and out of synch combination) on the speed and time obtained. For the study, 10 boxers were equipped with anatomical markers to be examined using a 3D motion capture system. The speed and contact time were recorded for the different punch variations. The authors could detect a significant difference in speed for the punch execution. Single maximal strokes had a significantly higher speed (mean 9.26 $\pm$ 2.09 m/s) compared to combination strokes 'out of synch' (7.49 $\pm$ 2.32 m/s), 'in synch' left (mean 8.01 $\pm$ 2.35 m/s) and right lead punches (mean 7.97 $\pm$ 2.53 m/s) (Piorkowski et al., 2011).

It was found that reverse hook punches had a significantly higher contact speed compared to straight line jabs or cross punches. This is consistent with the results of Whiting, Gregor and Finerman (1988b) but could only be proven for the single maximum reverse hooks. The higher contact speed can be attributed to the greater range of motion and a larger acceleration path which can be achieved with a semicircular hook punch. The fist is guided to the target object by shoulder flexion and adduction resulting in torque which is generated at the shoulder joint (Piorkowski et al., 2011).

In addition, Atha et al. (1985) and Walilko (2005) analyzed the speed of the fist for punches which were executed with maximum effort. Atha et al. (1985) found a maximum speed at impact of 8.9 m/s when examining a professional boxer. Walilko et al. (2005) measured the punch velocity of seven Olympic boxers and could determine a hand velocity of 9.14 (SD 2.06) m/s which is consistent with the results of Atha et al. (1985). Both studies were carried out with the help of high-speed camera systems and accelerometers integrated into the gloves.

Whiting, Gregor and Finerman (1988b) reported similar results for the analysis of fist velocity of four experienced boxers. They used a 3D optical motion capture system to study the linear and angular kinematics of the athletes' shoulders, elbows, wrists and boxing gloves. They observed that the average velocity during contact was between 5.9 and 8.2 m/s. The highest velocity of max. 6.6 to 12.5 m/s was recorded at 8 to 21 ms before contact of the hand with the punching bag. In the study by Whiting et al. (1988) the focus of the kinematic analysis was on combination punches, as the authors point out that in preliminary studies “the throwing of isolated, singles punches was not a realistic representation of competition-level punches” (William C. Whiting et al., 1988b, p. 131). Based on the recorded combination punches a greater variance in the average speed can be seen (5.9 to 8.2 m/s) compared to the single maximal punches of Atha et al. (1985) and Walilko et al. (2005).

All in all, it can be assumed that the variance of the punching speed is also greater in competitions, since factors such as fatigue, body weight, skill level and the fighting styles specifically developed by the boxer have an influence on the speed and the impact of the punch. Furthermore, it can be stated that the consideration of the kinematic chain has a significant influence on the effectiveness of the punch and its impact. Therefore, coaches and athletes should, apart from training the upper extremities, put a special focus on the leg work in order to transfer more power from the legs to the fist. Nevertheless, the literature research in kinetics and kinematics shows that there is no valid boxing measurement system that records both impact force and kinematic data such as acceleration, velocity and the fists three-dimensional orientation in space. As the following chapter illustrates, the focus of previous research approaches and developed analysis systems is predominantly based on the measurement of the acceleration occurring during the boxing punch.

2.2 Wearable systems in combat sports

A review of the existing literature in the field of competition and movement analysis in sports shows that the measurement and analysis of performance data derived from sensors have become an important aspect in coaching in a wide variety of sports. To support the work of the coaches, modern micro-electro-mechanical systems (MEMS) such as inertial sensors offer a cost effective, accurate, non-invasive and portable method to analyze and highlight performance aspects (Filippeschi et al., 2017). If the kinematics of the movement is to be described, then the 3D orientation of the inertial measurement unit (IMU) must be represented in dependence of a reference coordinate system (usually a Cartesian coordinate system), since the angular and linear velocity and acceleration of the body segments and joints are to be measured in relation to each other as well as to the reference system (Camomilla et al., 2018).

Boxing is particularly attractive for inertial measurement unit motion tracking as the widely used optical motion capturing system can only be applied under laboratory conditions. The literature reviewed indicates that results in competition or sparring may vary significantly from those data obtained in test setups in laboratories (Pierce et al., 2006a). Besides, boxing is a physically demanding sport and requires a high skill level as well as explosive strength and a quick reaction time. Consequently, there is a great demand to implement new technologies such as inertial sensors into the field of boxing to meliorate the performance analysis in terms of the technique executed in training and competition and the force produced while punching. The developed performance monitoring system can help coaches and athletes to review their punch output and analyze bouts over a time of several years to improve even at an elite level. Furthermore, the developed smart boxing glove can assist judges during a fight with objective and reliable data. In addition, researchers are enabled to generate real time data with a high accuracy to analyze the kinematics of boxers independently from the laboratory environment in a more realistic and competitive experimental setting.

Currently the 35-year-old system of CompuBox is used in boxing competitions to evaluate fights (Lelinwalla, 2015). The punch output of both athletes is entered into a computer program by two observers, that are sitting next to the ring. The input data is then evaluated by the software of CompuBox to rate the event. During the observation, hits and missed punches are distinguished as well as jabs and power punches and the total number of punches is added up. Further statistics are calculated and collected for the different competition classes so that coaches and athletes can for example review the average number of punches in various weight classes over several years. However, it should be noted that the developer Bob Cannobio himself stated that CompuBox was not designed to rate boxing matches (Hauser, 2018). The reason for this is that punches considered as power punches are not necessarily damaging blows. In boxing one knock-out hit alone is enough to win the fight, this means that the CompuBox system can only be a support but not a substitute for the judges and coaches. In addition, the system cannot be used to make a statement about the impact or the speed of the punch. Whereas the development of the boxing monitoring system could generate valuable information in competitions in the coming years, which could be accessed by judges for competition evaluation, by ring doctors to protect the athlete from severe injuries as well as coaches and athletes for performance monitoring.

The literature research has shown that the primarily used systems for the measurement of performance data in boxing are based on inertial sensors. Originally, the inertial measurement units were developed for attitude estimation in aerial navigation. At the end of 1990 the technological progress made enabled the use of IMU's in the field of human motion capturing analysis. Today the inertial measurement units used for human motion tracking mostly include accelerometers, gyroscopes and partly also magnetometers (Worsey et al., 2019) .

The sensors measure the angular velocity, linear acceleration and the vectors of the local magnetic field along the sensing axes. If the 3D orientation is to be measured, a magnetometer must be included in the IMU (Camomilla et al., 2018). The three sensors are available with up to three axes each and can respectively display the spatial orientation along nine axes. For human motion capturing the data of the three sensors and their nine sensing axes are merged and evaluated by algorithms to provide information about the orientation of a body. In addition, the data must be corrected for noise and drift by calibration processes and sensor fusion algorithms.

In a systematic review by Camomilla and colleagues (2018), who evaluated the use of wearable inertial sensors for sport performance analysis, a selection of 286 studies and 23 reviews were presented from 2040 papers. The report shows that since 2009 there has been a strong increase in the number of articles published in the field of performance analysis using wearables. Most of the authors (38%) deal with the analysis of elite and professional athletes. Furthermore, the most frequent technique analysis was carried out using inertial sensors (163 papers), 62% of which were carried out in training. In contrast, only 7% of the analyses took place during competition. This is an indication of the lack of sports-specific wearables in various disciplines that can measure accurate and reliable data in competition and are approved by the sports organizations as official sports equipment. This gap can also be seen in the field of combat sports, as only eight (2.8%) of the 286 records found in the review of Camomilla and colleagues (2018) studied the performance features of combat sports athletes. The authors agree that the integration of wearables in combat sports is under-researched although the technologies are available at low cost and produce accurate results (Filippeschi et al., 2017; Worsey et al., 2019). In this respect the thesis can make an excellent contribution to the research of wearables in combat sports and specifically in boxing.

In another systematic review published one year later by Worsey, Espinosa, Shepherd and Thiel (2019), who examined the use of wearables as a performance analysis tool in combat sport, it is stated that more studies were found compared to the results of Camomilla and colleagues (2018). Of the 36 records included in the systematic review the majority of studies using inertial sensors were found in the sport of boxing (38.89 %, 14 out of 36 records). In addition, the review outlined the performance features that were measured with the help of inertial measurement units. This includes the strike quality, strike classification, strike frequency, head impacts, automatic scoring, movement speed (footwork), power output, endurance and grappling technique (Worsey et al., 2019).

As already mentioned in chapter 2.1 about the physiological aspects and anatomical aspects in boxing, the performance of athletes depends on various parameters. The depending parameters include in particular the speed of the upper limbs and the strength of the legs as a supporting element for the generation of power through the kinematic chain, the inter and intra muscular coordination as well as the ability to deliver precise hits at maximum speed and minimum impact time. Since performance features are most important to the success of a combat sport athlete, the strike quality is most often measured by wearables (44%, 16 out of 36 records) (Worsey et al., 2019). 100% of the 16 studies analyzed the strike quality using parameters like punch acceleration, velocity and force as described in chapter 2.1.1about the kinetics and kinematics of a boxing punch (Atha et al., 1985; Birken et al., 2001; Chadli et al., 2018; Mack et al., 2010; Voigt, 1989; Walilko et al., 2005; Worsey et al., 2019).

In addition to the kinetic and kinematic parameters, impact accuracy is also a decisive factor for success in boxing. Since in a study by Davis et al. (2013) victorious amateur boxers were the ones who performed the better ratio of punches thrown to punches landed, in contrast to the boxers with the highest number of blows. In a study by Shepherd, Thiel and Espinosa (2017), the fatigue and associated deterioration in precision was measured in six elite male boxers with two high intensity inertial measurement units. The authors used two inertial sensors per athlete, each sensor attached to a glove superior to the distal radioulnar articulation. The boxers were instructed to hit as hard and as fast as possible for a duration of 11 sets of 2 minutes, with 5 seconds break between sets. With the IMU's, the pitch angle, punch force (calculated from the acceleration) and the hand speed were recorded. With these data and the inverse time between the strokes, an automatic classification of the fatigue of each athlete was made. For the hand speed and the punch force (acceleration) a significant decrease during the intensive training session could be measured with a Pearson correlation coefficient of $r = -0.97$ for acceleration and $r = 0.89$ for the time in between punches (Shepherd et al., 2017). The pitch angle remained relatively constant during the boxing session but the standard deviation was found to be high with an $r = -0.67$. This is justified by Shepherd and Colleagues (2017) with the different skill levels and the physiological differences of the boxers. Nevertheless, it should be noted that the elite boxers manage to hit the target (punching bag) precisely, despite increasing fatigue over the rounds. Overall, this study shows that IMU's can be used successfully in boxing to record performance metrics. In this case the performance metrics were recorded to predict fatigue but there are many other applications and research questions that can be assessed by applying inertial measurement units in the field of combat sports.

Due to the outlined research limitations, the research work in this thesis is intended to provide athletes and coaches in the field of martial arts with a performance analysis tool that allows valid data to be recorded and evaluated in real-time in training and competition settings. Kinematic parameters are investigated and evaluated with the use of inertial sensors. Furthermore, kinetic data on the impact force of punches will be measured with the newly developed sensor. The only wearable system described in literature that was used to measure impact force outside of laboratories was the bestshot system used by Pierce et al. (2006a). However, this system lacks the ability to record and analyze kinematic parameters. As a result, the sensor system developed in this thesis offers a unique opportunity for comprehensive performance diagnostics for kinetic as well as kinematic data that has not been available to scientific research to date. Therefore, this innovative development aims to overcome the existing technology deficit in the sport of boxing for direct performance analysis. Furthermore, this research work contributes to provide new insights into the analysis of biomechanical parameters in the field of martial arts.

2.3 Medical aspects of boxing

In order to fully illustrate the research possibilities of the comprehensive sensor system, the following section reflects the sport of boxing from a medical perspective. In addition to the analysis of performance relevant parameters, the data obtained by the sensor system can be used to study the causes of sport-related injuries. This is of crucial importance for the progress of research on acute and sub-acute injuries in boxing and combat sports in general.

Due to the high physical stress on the anatomical structures (especially in the upper body and head region) during training or competition, boxing has an increased risk of injury compared to other sports. The art of pugilism were criticized for several years because of the high risk of injury and the recurrent deaths. However, it has to be considered that the purpose of boxing is to knock out the opponent and therefore it is accepted that the boxers take the risk to be harmed inevitably. Walilko (2004) summarizes the paradigm as follows:

> "*Boxing is different from all other athletic competitions in the fact that the nature of the sport causes injury by intent rather than by accident. Injuries are coincidental in other sports, but in boxing, the aim and objective of the sport is to incapacitate your opponent*" (Walilko, 2004, p. 17).

Particularly in boxing competitions and sparring, there is a lack of diagnostic tools that can generate valid data to estimate the extent of severe injuries and the probability of the occurrence of long-term consequences.

This is closely related to the underlying risk factors in the sport of boxing which have not yet been sufficiently clarified as stated by Zazyrn, Cameron and McCroy (2006). The authors primarily highlight that there is no scientifically substantiated evidence in the research literature regarding the risk factors that are associated with the development of injuries in professional or amateur boxing. In particular the authors claim, that this is a result of the retrospective nature of the majority of the studies available about boxing, as well as the circumstance that the prevailing studies have investigated retired boxers instead of performing athletes (Zazryn et al., 2006). Furthermore, the authors emphasize the difficulty that in boxing (especially in sparring or competition) there are currently only very limited possibilities to investigate the cause of the injury. In recent years, the use of modern inertial sensor technology has enabled studies to be carried out in the field of head injuries and sport-related concussions in contact sports, which have led to important findings, particularly in the area of the central nervous system (Stojsih et al., 2010). Stojisih and colleagues (2010) used the Impact Boxing Headgear (IBH) system, a modification of the existing head impact monitoring telemetry system (HITS), to investigate in the translational and rotational acceleration of the human head which can lead to severe brain damage. With the IBH system, a real-time analysis of head impacts in boxing was performed. The headgear system was equipped with 12 single axis linear accelerometers and recorded data in real time at 1000 Hz for a period of four 2 min sparring sessions on 30 male and 30 female amateur boxers. The authors found out that the majority of impacts were under the threshold for mild head injury with no significant difference between genders (Stojsih et al., 2010). Nevertheless, this investigation is only an initial observation that does not consider the athlete's medical condition over time. According to McCrory and colleagues (2009), there are several risk factors that can have an influence and must be taken into account for the evaluation of the injury risk. This includes, most notably, the number of knock outs the athlete has already experienced in his career (McCrory et al., 2009). Therefore, it is recommended that boxers are monitored by a health monitoring system which among other things lists previous and ongoing injuries and incorporates fight statistics including data from sensor measurements, like the developed Smart Boxing Glove.

Current safety practice in boxing includes pre-competition examinations by a medical doctor to determine fitness for competition and observation of athletes during a fight, as well as providing first aid when a boxer is knocked out. However, it has to be noted that medical regulations for the protection of boxers vary widely between the boxing federations. The AIBA manifests in its medical handbook much stricter regulations for the protection of boxers than the professional boxing associations (AIBA, 2016). Nevertheless, in the past years there have been repeated cases of boxing deaths which have led to criticism of the regulations and ringside medicine. Although the total number of deaths worldwide is decreasing, there are several cases of boxing related deaths from head injuries sustained in a boxing fight each year. Manuel Velazquez is listing a total number of 1,465 boxer between 1890 and 2007 in his collection (Svinth, 2007). Of these, the majority (923 deaths) are assigned to professional boxing matches, whereas 293 deaths were registered in amateur boxing. One reason for the higher mortality rate in professional boxing may be the moderate regulations regarding medical care before and during boxing matches.

It becomes very clear that action must be taken, above all to protect the athlete's health in competition. This can be conducted, for example, by tightening medical controls. In addition, modern technology can also improve the safety of athletes by using sensor technology in competition to support the ring doctors and referees in their decision and to indicate the danger of serious injuries at an early stage with the help of data science. Worsey et al. (2019) further state that the establishment of an automatic scoring system in martial arts can significantly reduce the risk of injuries to the athlete. The use of such an automatic scoring system in combination with a technology that is able to identify the severity of head impacts would revolutionize the sport of boxing and significantly reduce the incidence of serious injuries to have a major safety factor to the nature of the sport (Worsey et al., 2019).

Head injuries have been frequently investigated in both professional and amateur boxing in recent years, especially in regards to the neurodegenerative damage caused by the repeated impacts of the boxers fists (Michael Loosemore et al., 2017). Whereas the hand and wrist of an athlete has received little attention in scientific studies to date, although hand injuries are a common injury that force participants to take long training and competition breaks. In a study published by Pappas (2007) injury rates of hospital treatments in emergency departments for combat sports (including boxing, wrestling and martial arts) were compared and classified for their anatomical region. The results show that between 2002 and 2005, most injuries in boxing, martial arts and wrestling were found in the upper extremities (Pappas, 2007). In a systematic review by Loosemore and colleagues (2015), the authors analyzed the proportion of boxing injuries which occur during boxing competition or training for different anatomical locations of the human body. The results of Loosemore and colleagues (2015) have shown that the second most common region where injuries appear are the upper extremities including the hand and wrist, following the amount of head injuries (Michael Loosemore et al., 2015). Therefore, research into the causes of hand and wrist injuries should be further investigated.

When the hand is accelerated rapidly and hits the target at a high speed during a punching stroke, an enormous force acts on the structures of the hand, which can cause injuries to the hand and wrist (Hayton & Dickson, 2019). In boxing, two injuries of the hand and wrist are most common, the ‘boxers knuckle’ and the carpometacarpal instability.

The ‘boxers knuckle’, can mark the end of a boxer's career. The injury often occurs on the metacarpophalangeal joint of the middle finger, as it is in an exposed position when the fist is clenched. In a ‘boxers knuckle’, repeated blunt trauma with powerful flexion of the metacarpophalangeal joint, injures the capsule of the metacarpophalangeal joint and cause a longitudinal tear in the digitorum communis tendons, which can lead to swelling, pain and limited extension of the joint (Jako, 2009; van der Zee et al., 2015).

The carpometacarpal instability was considered as the second most frequent boxing injury in the literature (Hayton & Dickson, 2019; M Loosemore et al., 2015; Michael Loosemore et al., 2017; Noble, 1987) . The carpometacarpal instability occurs more often when athletes perform a hook punch (radiograms: row 1, a - e) since the wrist is already in a flexed position compared to the uppercut (radiograms: row 2, a – e) and straight punch (radiograms: row 3, a – e) as illustrated in Figure 13.

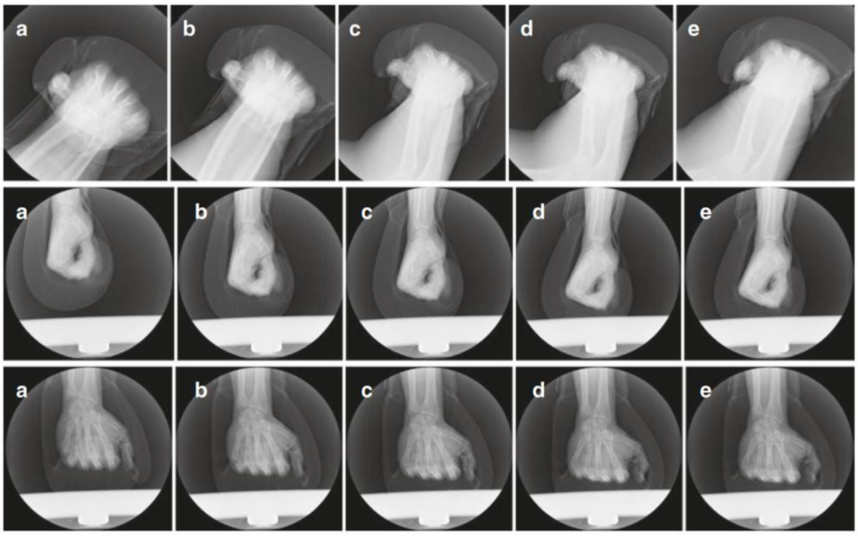


Figure 13: Radiograms for hook, upercut and straight punch (Luchetti et al., 2018, p. 4)

In addition the muscular structures of the hand and forearm fatigue during the fight and the wrist collapses under the influence of excessive impact force into flexion, which leads to a high strain on the dorsum of the carpometacarpal joint (Michael Loosemore et al., 2017)

The carpometacarpal instability as shown in Figure 14 is a result of the flexion force transmission to the metacarpal head, creating a secondary dorsal leverage effect on the proximal end of the metacarpal in the carpometacarpal joint (CMC) (Hayton & Dickson, 2019). The carpometacarpal instability causes a synovitis and mild capsular tearing that can lead to periarticular hypertrophic bone formation (Michael Loosemore et al., 2017; Luchetti et al., 2018; Noble, 1987).

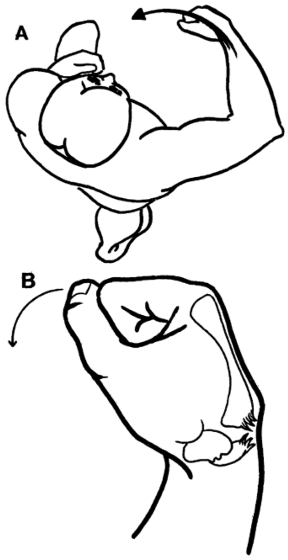


Figure 14: Carpometacarpal instability in flexed wrist position during hook punch (Noble, 1987, p. 345)

Hence it is important that the impact force that is transmitted to the hands is reduced by a shock absorbing padding in the glove and that the use of hand bandages to secure the wrist is enforced as well as proper punching technique is executed.

As mentioned before, there is little research in the field of hand injury investigation that attempts to identify the causes of injuries in boxing. One reason is the lack of precise measuring instruments with which the force distribution on the punching area of the hand can be measured directly in the field, both in competition and in training.

The only study investigating the distribution of force on the knuckles while punching was conducted in (2015) by Loosemore, Lightfoot, Meswania and Beardsley. The research team used pressure films to calculate the distribution and magnitude of the force acting on the punching area of the hand. In addition, it was examined whether there are significant differences in the distribution of force among different athletes, since in the field it can be observed that some boxers are more prone to hand and wrist injuries than others. For the study, the pressure film was fixed on top of the MCP joint from the 2nd to the 5th digit for three male boxers. The result of the study showed a significant difference in the distribution of force between the metacarpal heads and also between the athletes ($p < 0.05$). In addition, it was found that the second knuckle had the largest proportion of force whereas the third knuckle the smallest proportion. However, the authors state that the reliability and validity of the measurement technique has to be verified in future studies. This is especially important when the punching technique of different athletes is to be analyzed to determine which punching technique is associated with an increased risk of injury for the hand and wrist area.

Due to the special requirements for the production of boxing gloves it is the aim of this work to implement a measuring system into the glove that does not significantly change the glove in an optical and haptic manner and which is able to measure important data on forces, accelerations and the three-dimensional movement in space independently from laboratories in order to draw conclusions about for the prevention of injuries and technical analysis of the boxing punch.

3 Boxing monitoring system – Design and Development

The design and development process are based on the literature research executed in the field of instrumented sport equipment and the biomechanical information of boxing techniques, as well as stress and strains exerted on the performing athletes.

The objective of the presented research conducted is the development of a boxing monitoring system that allows the comprehensive performance analysis of a boxing punch. The data generated by means of the developed sensor system is used to gain profound novel conclusion on emerging biomechanics in the sport of boxing.

To gain a profound inside it is necessary to gather actual emerging data of the movements executed, to assess the gathered information and to draw conclusion about the recorded data. For this purpose, the used monitoring system and its design and development are presented in this chapter.

Sensors are used for the quantitative as well as qualitative determination of physical parameters. The developed system consists of the sensor itself as well as the acquired evaluation process. The occurring physical values are converted from non-electrical input parameters into electrical output variables by use of scientific methods for postprocessing purposes, developed throughout the research process. This chapter serves to present the design and development of the hard- and software based on the designed development flow chart Figure 16.

Composition and design of a boxing glove

Many sports use sport-specific clothing and equipment to reduce the risk of injury from external forces and to increase the safety of athletes (Watkins, 2007). For the development of a unique boxing performance monitoring system, it is important to consider the composition and design of the equipment in which the developed sensor system is implemented and used at. This is important for different reasons. On the one hand it is important to determine the position the sensors can be implemented at for accurate data acquisition and on the other hand, it is essential to keep the equipment's specific characteristics without changing the material properties or equipment dynamics.

With increasing professionalism and popularity of a sport, the equipment used also develops in terms of specialization (Murray, 2010). The composition and design of the boxing gloves have a long history that can be backdated to the ancient world, 3650 BC. Unlike in modern days, boxing gloves were used for different purposes than they are used nowadays. The first civilization that seemed to use a kind of boxing equipment was the Aegean population called Minoans. The Minoan population used to live on Crete, a Greek island, from 3650 to 1400 BC. In the time of the Minoan athletes, a single piece of leather lined with non-woven fleece was used to protect the athletes forearm, wrist and hand including the knuckles during training and competition (Miller, 2006). The four-meter-long leather straps are called a "himantes" (Miller, 2006). Like modern day boxing gloves, the purpose of the "himantes" was to support the anatomical structure of the hand and to prevent the athlete´s knuckle against rolling over when hitting a target. Over time, the purpose of the "himantes" was changed and modified with a contradicting purpose. By use of artificially hardened leather straps, the "himantes" was used to cause extensive damages to the opponent. The punching severity was increased because the hardened leather straps carved into the opponents skin causing deep blood dripping wounds (Murray, 2010).

Other than for competition purposes a more protective glove was used for training purposes. The Greek athletes have already used a cushioned glove consisting of a pillow wrapped around the punching area of the knuckles for sparring training. The so called “spharai” protected both the athlete himself as well as his sparring partner against severe injuries (Sweet, 1987).

The first modern boxing gloves were invented in England in the 18th century by Jack Broughton. The so called “mufflers” resemble the modern days boxing gloves and were made out of horsehair (Britannica, 2019c). Even though the “mufflers” are used primarily for training purposes.

The first rules for boxing glove were mentioned in the Marquees of Queensberry rules by John Graham Chambers back in 1867. Paragraph eight of the regulations stated that, “the gloves [have] to be fair-sized of the best quality, and furthermore have to be new [for competition purposes]” (Britannica, n.d.).

Since then, boxing gloves are a primarily component of modern-day boxing rules. This is officially regulated for professional as well as amateur boxing, as boxing gloves are the only protective equipment to be worn by boxers. The gloves are used to absorb and dissipate the energy of the blows delivered between the boxers. The function of the boxing gloves is therefore to reduce the intensity of the blows in order to protect both the boxer's hands as well as their opponents contact area (Chadli et al., 2018). To ensure that some of the punches´ energy is absorbed and dissipated, the primary boxing glove design consideration is based on the boxing glove cushioning material used. The most common material used for boxing glove damping is high-density polyurethane, cotton, latex, or polyvinyl chloride (PVC) foam. These materials have the benefit of good elasticity and a memory effect, that the foam returns back to its original shape right after it was compressed. The material memory characteristic to return back to the original shape is the most important characteristic to avoid severe impact injuries. A study conducted by (Unterharnscheidt, 1995) found out that the last blows of a series of punches can be measured with higher accelerations at impact. This result has indicated to the researcher that the materials return to its original form varies as well as that the materials memory ability faded during a series of punches. This drawback can lead to severe injuries and is highlighting the importance of the selected padding material. Other manufacturers are still using horsehair, although this damping material is being used with decreasing frequency. The cushioning material should not be able to move inside the glove or be directly damaged. Damaged cushioning material should be replaced immediately in order to absorb the maximum energy of the blows to ensure the athletes safety (Chadli et al., 2018).

If foam is used as padding material, the gloves form is moulded in one piece. This enables that the energy is absorbed over an augmented surface area without interruption. The body is subjected to more damage by a force concentrated on a small area and the associated high pressure than by a force distribution on a larger contact area (Grimshaw et al., 2006). For competition boxing gloves the sleeve is made out of high-quality leather, whereas low quality boxing glove sleeves are mainly made out of vinyl. Both high quality as well as low quality boxing gloves require a minimum of seams and uneven surfaces to avoid scratching or cutting injuries. The weight of the leather sleeve should not exceed half of the boxing gloves weight, so that the ratio between leather and padding is almost similar in high quality boxing gloves that are certified by the boxing associations. The weight of boxing gloves is indicated in ounces and can range from 6 to 16 ounces (1 ounce = 28.35 grams). The weight of the glove that has to be used depends on the weight class of the competing athletes. Lower weight divisions are using a minimum of 8-ounce gloves whereas heavy and medium weight classes are using 10-ounce gloves or heavier. The individual regulations in glove weight and therefore padding material used is justified by the athlete's mass and the resulting severity the punch can cause. A heavy weight boxer would be able to overharvest the damping material properties of a feather weight athletes' glove and could cause severe injuries during a fight. Whereas a feather weight athlete would not be able to cause enough repercussion at their opponent to decide the fight for themselves when using heavy weight boxing gloves with more damping material. The effect of boxing glove weight and peak impact was also studied by (Girodet et al., 2009) by use of a punch apparatus. The research finding is supporting the regulations on weight divisions in boxing, the boxing glove weight and therefore the amount of damping material that has to be used to reduce impact related injuries.

Another design characteristic is focusing on the thumbs, besides the glove composition in terms of damping material used. Due to injuries that were caused in the past by sticking thumbs into the opponents’ eyes, the regulations for boxing glove equipment are stating that the thumb has to be fixed to the main part of the glove´s body, to avoid these kind of injuries (Chadli et al., 2018). The German Institute for Standardization has created a guideline for testing and demands of martial arts protective equipment including the damping material (DIN EN 13277-7:2009) (German Institute for Standardization, 2009).

The attachment of the boxing glove varies between amateur and professional boxing. In amateur boxing the glove has to be fixed by a Velcro type closure whereas in professional boxing the closure is most likely made of laces and then covered by tape to protect against sharp laces that can cause cutting injuries (Chadli et al., 2018).

The design and composition of the boxing gloves damping material, sleeve as well as kind of attachment are important characteristics that have to be considered for the development and research process presented by this thesis. The analysis of the sporting equipment, in this case of the boxing glove, in terms of composition and design is therefore an important step to determine the systems key characteristics to be fair sized, flexible and applicable for maintaining the regulations for boxing gloves when instrumenting the developed sensor system into the sport equipment.

3.1 Design and development of the sensor system

The design and development concept of the sensor system is based on Tränkler and Obermeiers (1998, p. 17) concept for sensor systems as presented in Figure 15. Therefore, initially the main priority is taken on the setup requirements and the environment the system is deployed in. The electronic systems in martial arts must meet a variety of requirement criteria to cope with the high accelerations at impact, environmental influences such as high temperature and humidity, difficulties with the wireless connection as the sport equipment will be rotated around all axis, a high sensing rate to avoid insufficient sensing due to the short impact times, and a very limited space for embedding the instruments in the sports equipment (Worsey et al., 2019). A system to be developed must therefore be designed in a way that a direct impact on the sensor does not injure the athlete neither affect the functionality and sensor properties. For this reason, a requirement analysis was performed in a first place based on the following key factors under consideration of the approach by Günthner (2008, pp. 25–27):

Physical properties

The sport of boxing has strict rules when it comes to the physical properties of boxing gloves in amateur as well as in professional type boxing. The sport equipment itself is defined by its size and weight as well as the materials used and is an integral part of the official competition regulations (AIBA, 2019b, 2019c). Therefore, it is important to design the sensor systems physical form without changing the boxing gloves properties significantly against the existing rules.

Sensor components

The most important achievement is to develop a comprehensive performance analysis tool under consideration of the physical properties of the sport equipment. Therefore, an extensive development process was performed to design the most suitable sensor system for data acquisition. An important part is the selection of the most suitable sensors, considering feasibility as well as cost and size. For this purpose, a variety of different sensor systems were exposed:

- Accelerometer, gyroscope and magnetic sensors
- Piezoresistive sensors
- Capacitive sensors
- Piezoelectric sensors
- Flexible goniometer
- Electromagnetic Tracking system (ETS)
- Sensing Fabric
- Force sensors
- Electromyography

Consequently, a force sensing resistor solution based on a piezoresistive principle was selected in a first stage due to its good feasibility, low cost, small size, high spatial resolution and high possible sampling rate. Piezoresistive sensors ranging from a diameter of 0.20 mm to 1.25 mm depending on the material used, for the implementation in to the sport equipment. In a following development step, accelerometer, gyroscope and magnetic sensors are used to detect kinematic movements of the boxing glove in three-dimensional space.

Measurement range, resolution and performance

A crucial item in the development process of innovative sensor systems is the systems deployment of a sufficient measurement range. The study aims to conduct research in a field in which less studies were executed in and therefore minor information is supplied. To gain novel information about the biomechanical conditions of in field boxing punches, it is important not to lose information due to a minor measurement resolution. Therefore, the systems capability is tested during the research process to adapt and improve the systems feasibility for a comprehensive performance monitoring.

Electronic requirements

The developed measurement system must be suitable for non-laboratory environments. This means the system must be cohere in terms of power supply and calibration process as the aim is to not use external equipment for the boxing punch performance monitoring.

Software requirements

The systems feasibility depends on the algorithms developed and filter methods applied, to achieve a high-precision for real-time data processing. A variation of systemic structures, sensor elements, models and system processing methods are taken into consideration. The system is consecutively simulated, tested and applied during the research process to test the boxing monitoring systems applicability and validity.

Incorporation of the sensor system to the equipment used

Following the systems requirement analysis. Another important step is the interface of the electronic design with the sport equipment itself. The “design for wearability focuses on a specific and important issue within the design space for developing wearable computing systems; wear-*ability*, the physical shape of wearables and their active relationship with the human form” (Gemperle et al., 1998, p. 1) plays a major role in the development process. Therefore, the placement, size, shape, weight, long term use, accessibility and attachment of the sensor system was designed with high attention to splice the system into the equipment without changing the equipment properties and interfering the normal use of the sport equipment.

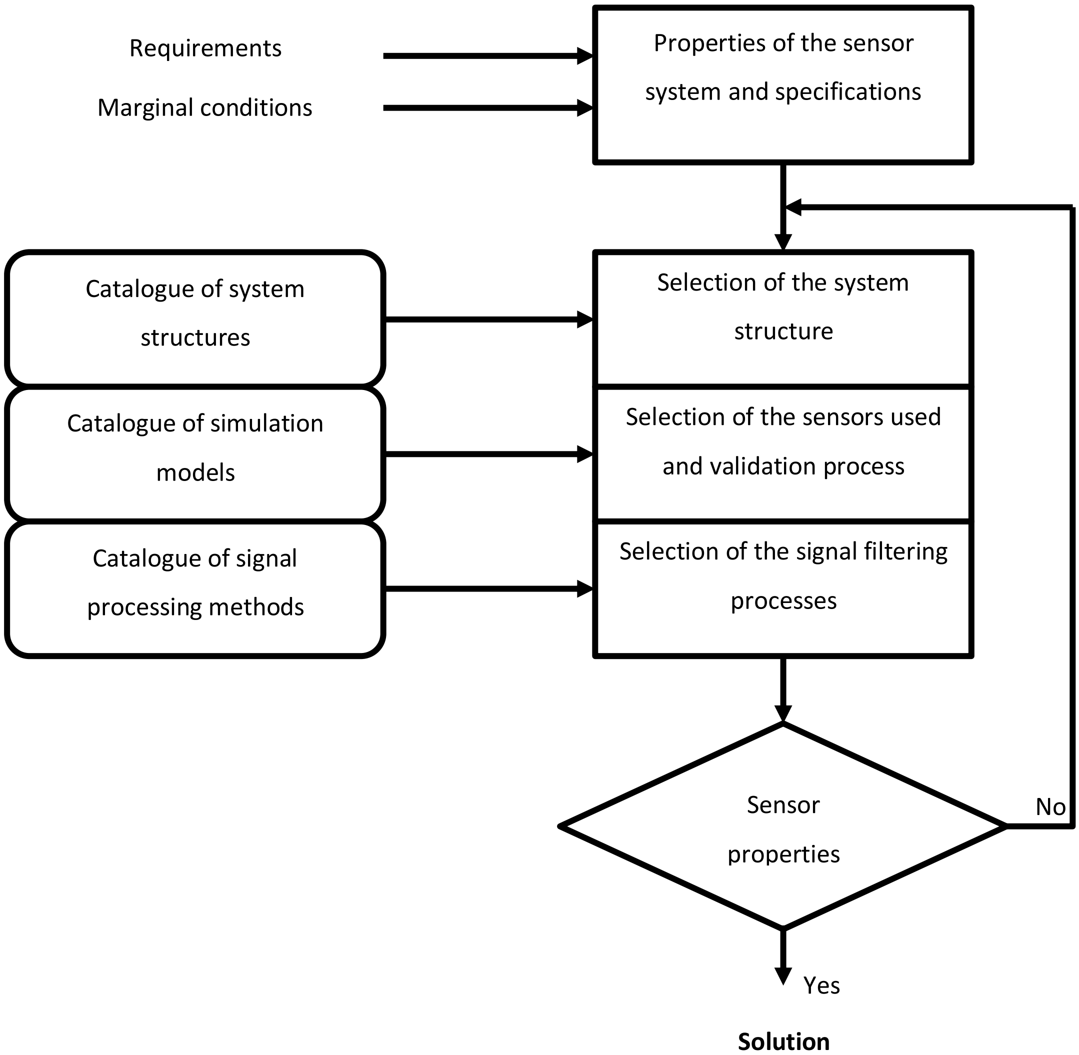


Figure 15: Design concept for sensors and sensor systems (Tränkler & Obermeier, 1998, p. 17)

A specific development flowchart for the development of the boxing monitoring system was elaborated on the basis of the design concept for sensor systems according to Tränkler and Obermeier (1998), as well as the highlighted key factors according to Günthner (2008). The development process of the sensor system was therefore executed as shown in the flow chart Figure 16. The described development steps are based on each other in a systematically order and thus made it possible to ensure that no development step is omitted during the research work, as well as that the system conforms to the specified requirements for experimental research.

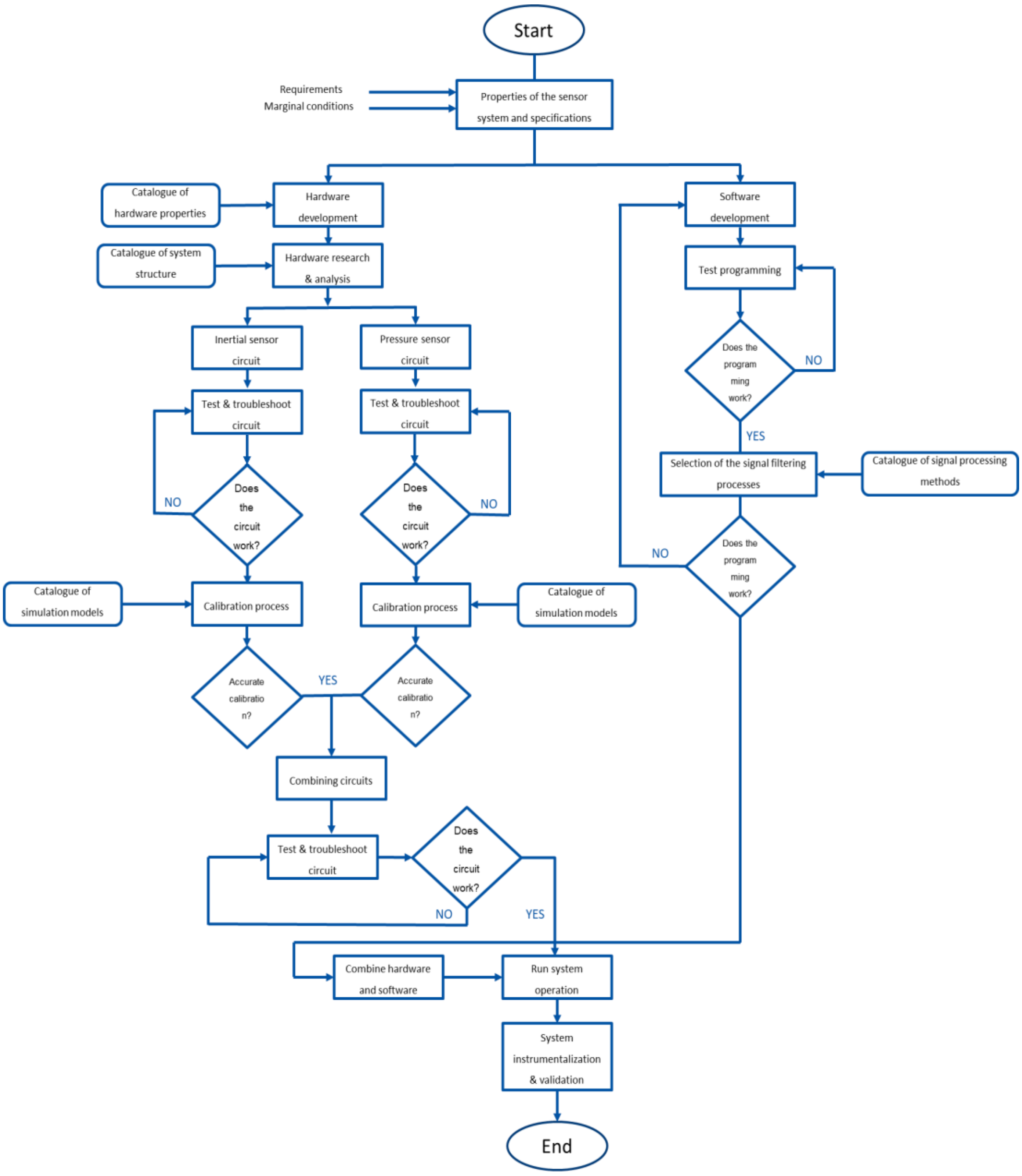


Figure 16: Development flow chart of boxing monitoring system

3.1.1 Hardware design and development

The initial focus of the research work is based on the development of a new sensor system and thus in a first step on the development of a new sensor hardware. As presented in the development flowchart Figure 16, a great number of different sensors were evaluated for the potential applicability of the developed sensor system. As shown in chapter 3.1 about the design and development of the sensor system, a piezo-resistive pressure sensor was selected in a first step to execute the development process before the system was extended in subsequent development steps. The measuring principle of the sensor technology applied, for the measurement of acting forces, is based on the measurement of a change in electrical resistance. Therefore, the integrated microelectronic is creating a 3.3 voltage output into the sensor system. This enables the sensors to measure the relative change in electrical resistance, by an applied pressure to the sensors through the reference resistor. The technical principle of the piezoresistive pressure sensors used is described in detail in the following chapter 3.2.2 as well as the calibration methods applied. From this point, the change in electrical resistance is processed further in order to analyse the force as a calibrated sensor output. For this purpose, as shown in the flow chart Figure 16, a large number of different sensors were evaluated for their applicability, accuracy and repeatability in the field of boxing and in particular for the biomechanical testing of punch forces.

Since a large number of different prototypes were designed and developed with varying degrees of modification to the respective predecessor models, only decisive development steps will be described in the further course of this chapter.

In a first step different piezo-resistive sensors were tested and evaluated regarding their sensor properties. This initial testing of different sensors enabled further sensor tests to be carried out. With the help of the sensors selected in the pre-selection phase, a first rudimentary prototype was developed based on standard off-the-shelf sensors. This prototype was used to gain fundamental knowledge for the further work with piezo-resistive pressure sensors. The main focus was on the gain of information about the sensor behaviour of dynamically executed impact forces, the instrumentalization in sports equipment and the changed signal output as well as the identification of possible sources of interference. The first prototype opened up a wealth of information for the further development process. The first generation of instrumentalized gloves showed an elaborate instrumentation into the sports equipment as well as a minor displacement of the sensors within the glove. The first prototype also revealed a reduced number of loading cycles with a high measuring accuracy as a result of the sensor displacement. Furthermore, the first prototype did not allow the investigation of the centre of pressures on the surface of the fist, as well as the investigation of fist activity regarding fist opening and fist clinch. An advantage of the first generation of the development process was the use of off-the-shelf sensors and therefore low acquisition costs, since no customized design had to be developed and manufactured.

A subsequent decisive development step was the production of a first customized sensor design. For this purpose, a four times five sensor matrix was designed and manufactured. With the help of the first customized sensor, insights could be gained into the manufacturing process. However, the manufactured sensors demonstrated poor manufacturing in the processing of the sensors as well as the processed materials in the first tests. Conducted sensor tests revealed that a maximum of four impacts per sensor were possible before a complete loss of the sensor signal had occurred. Further investigations of the manufactured sensors have revealed that an adhesive applied during production to laminate the sensor polymer, continuously damaged the conductor paths of the individual sensor cells and ultimately tore them off completely when forces are applied. This problem led to the failure of the affected sensor cells and all subsequent sensor cells in the column of the sensor matrix. Due to the limited number of possible measurement repetitions, further investigation of the sensor output, calibration and validation of these sensors was not possible. Additional investigations revealed that the manufactured sensor showed significant deficiencies due to a too high sensor thickness and an inflexible polymer that served as base layer. Due to the inflexible base material, the sensor cells in the peripheral sensor area as well as the centre sensor cell were kinked. This resulted in a persistent and non-calibratable sensor signal due to permanent sensor deformation. In addition, the polymer used showed strong limitations in the integration and use within flexible sports equipment. When a force was exerted on the sensor in the installed state against a three-dimensional head model as shown in Figure 17, the polymer used showed plastic deformation resulting in buckling folds. This showed that even with a good sensor manufacturing process the used sensor polymer was unsuitable for boxing due to the plastic deformation and the resulting permanent pressure exerted on the sensing material. These investigations outlined the importance in the selection of the base material of the sensors, for the further development process.

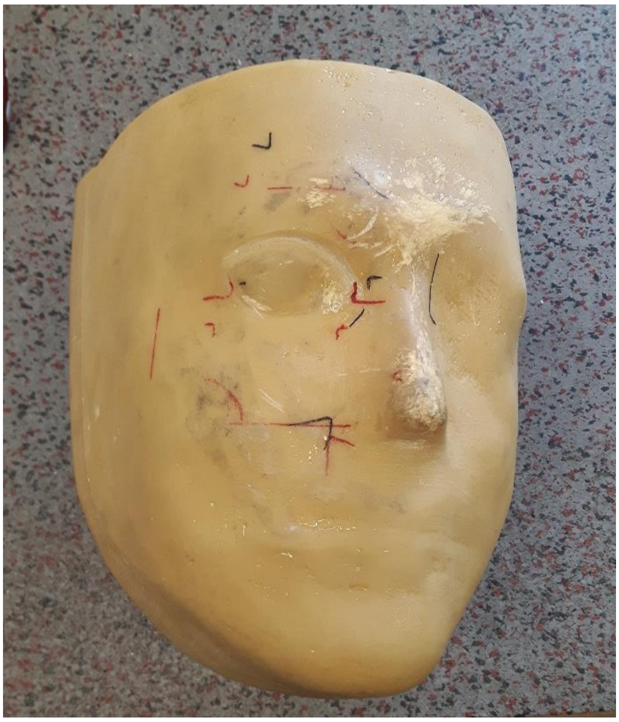


Figure 17: 3D head model for impact tests

Since the sensors used have demonstrated a poor capability for a customized production, the evaluation process of the sensors had to be repeated to find new sensors for the further development process. For this purpose, new tests with sensors from different manufacturers were carried out to validate important sensor properties under laboratory conditions and dynamic impact tests. At this stage, different sensor designs were designed, developed and tested for their applicability in different prototypes. This step was according to the results of the first limited manufactured sensor.

In addition to the design and testing of different sensor designs, various carrier materials were evaluated for their applicability. For this purpose, different polymers and silicones were tested to be used as carrier material. An important development step was therefore the testing of different silicones, that are suitable due to their flexibility, high durability and reversible deformation. In addition to the material properties, different thicknesses were tested. The development of a silicone carrier material demonstrated good capabilities to customize a sensor matrix into a sports equipment. Furthermore, the sensors used were additionally protected by the silicone cover. The developed sensor design moreover showed a high degree of flexibility and a correlation of measurement accuracy of >95% in comparison with a Kistler force plate. A negative effect of the silicone mould was the mathematical consideration in the calibration function. Although this design showed a great design to integrate the sensors into the sports equipment with the aid of a silicone mould. For the integration into the sport equipment, the sensors had to be applied precisely to the silicone carrier in order to cover the entire impact surface with sensors for an accurate punch force determination.

The use of a manufactured polymer as a carrier material was a further significant development step after the use of the silicone mould. The new carrier material enabled the sensor thickness to be reduced by 60% compared to the silicone mould. In addition, the reduced dimensions in the arrangement of the individual sensor cells of the new sensor design enabled the anatomical structures of the hand to be better taken into account in order to achieve the best possible results for punch force measurements. Furthermore, the new sensor design illustrated in Figure 18 enabled a faster sensor fabrication and an increased sensor flexibility. The new design also facilitates the implementation of the sensor in the required sports equipment.

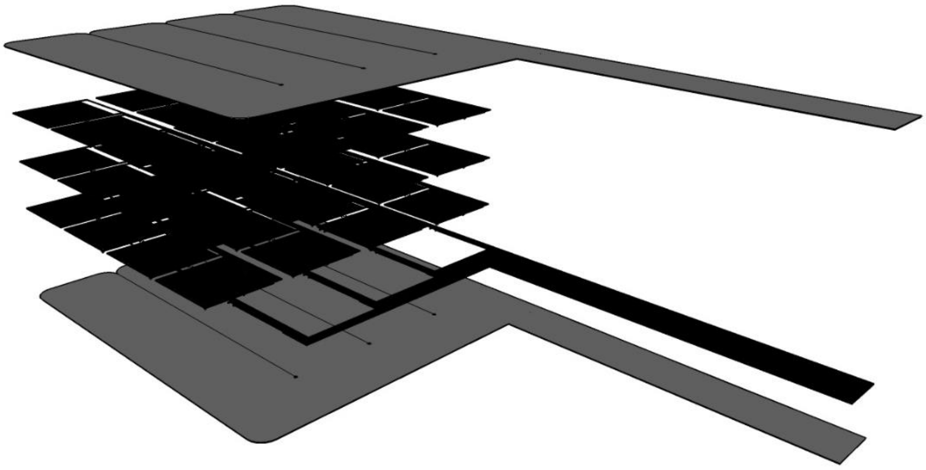


Figure 18: Piezoresistive pressure sensor design

As will be shown in the further course of the presented thesis, the system has been continuously improved due to new insights in the biomechanical performance analysis of boxing. One of these extensions was the integration of new sensors for the analysis of fist opening and closure. After extensive tests on the optimal sensor positioning for the measurement of fist activity, additional sensors were integrated in the metacarpal and interphalangeal joint area of the boxing glove.

A further decisive development step was the expansion of the existing sensor system for the measurement of punch biomechanics with inertial sensors. In order to develop a complementary sensor system unlike existing systems, the incorporation of inertial sensors was an essential part. In a first step, the existing system was extended with a six degrees of freedom inertial sensor, based on a +/- 16g acceleration sensor and a +/- 2000 deg/s gyroscope. Tests of the programmed sensor system proved a successful orientation determination up to a rotation of 90° in the rotation around the transverse and sagittal axis of the fist. In a simulated punching motion of the sensor, the problem of singularity effects emerged and the limitation of an angular measurement based on Euler angles became obvious. The first extension of the sensor system with inertial sensors provided important insights into the rotational representation as well as potential sources of measurement interference during the punching movement. To overcome the limitations of six degrees of freedom-based motion analysis, the system was extended with a magnetometer in a further important development step. This development step led to the extension to a nine degrees of freedom inertial based measurement for the rotation in three-dimensional space. In addition, the determination of the spatial orientation of Euler angles was changed to a Quaternion based rotation measurement method in order to avoid singularity effects and thus to eliminate a primary source of interference, experienced during the initial movement analysis. Further important findings on the extension of the existing sensor system with inertial sensors were obtained in impact simulations against a boxing apparatus. The simulations proved the limitation of the measuring range of the acceleration sensor, limited to +/- 16g, to measure the total impact acceleration, including the acceleration at the point of impact. The sensor system for inertial measurement of kinematic impact parameters was subsequently extended with an additional +/- 200g acceleration sensor to further measure the impact acceleration at the point of impact. This extension of the inertial measurement sensor system showed an excellent possibility to measure and analyse the entire acceleration spectrum. The high range acceleration sensor is therefore used to measure high accelerations that occur during the impact. This sensor has a low resolution for measuring small accelerations such as the movement in three-dimensional space. Therefore, the low range acceleration sensor is used, as it provides a good resolution for measuring low accelerations, but is incapable for measuring higher accelerations. Figure 19 presents a block diagram of the incorporated hardware components within the boxing monitoring system.

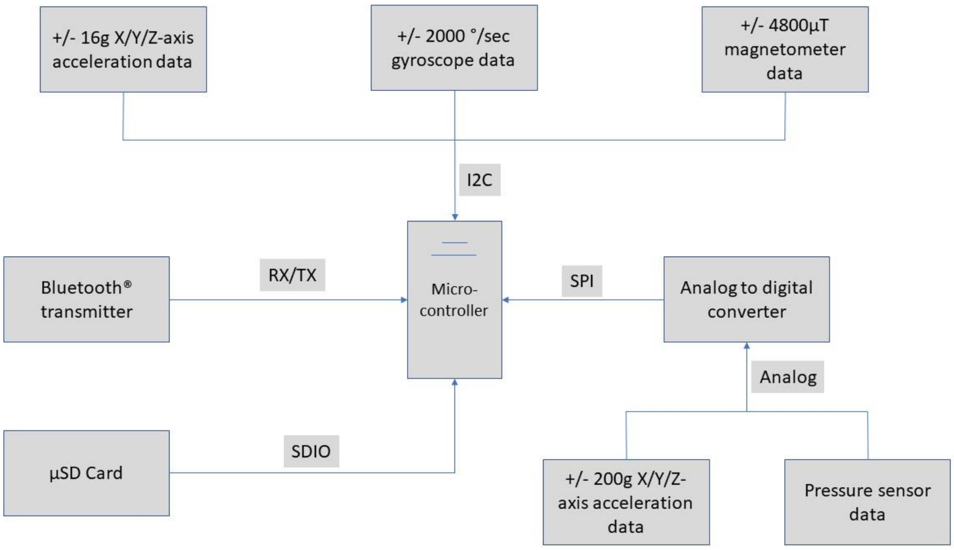


Figure 19: Node block diagram

3.1.2 Software design and development

The structure of the software of the developed boxing monitoring system is divided into two sections: the analysis of the rotation in three-dimensional space and the analysis of the impact force measurement. For this purpose, the sensor data is obtained as 8-bit integers by means of the microcontroller. After the raw data was collected, the data is calibrated on the microcontroller and converted into meter per second squared for the acceleration sensor, degrees per second for the gyroscope data and milli gauss for the magnetometer data. The further calibration is conducted with the help of predicted calibration data to calibrate the system automatically. The calibration data of the inertial sensors for the determination of the rotation in three-dimensional space is carried out according to the location of application of the sensor for the experimental data collection of the studies presented in the following chapters. This step facilitates the straightforward use of the sensor system for data acquisition with experimental subjects. To measure the orientation of the sensor system in three-dimensional space, an open-source Madgwick Quaternion filter is used following the calibration to analyse the orientation without singularity effects from the inertial sensor data. Following the calibration process, the rotation calculated in the form of Quaternions is converted into Euler angles for better visual purposes. This enables the visual understanding of the measured data in the form of pure angles instead of abstract numbers. Furthermore, the measured acceleration data of the accelerometers are filtered by a Zero-Velocity-Update developed, to measure and analyse the velocity of the fist during the punching movement.

The pressure sensors used for impact force measurement are calibrated in the same way as the inertial sensors, using individual calibration functions for accurate impact force measurement.

Subsequently, the data is sent to a computer for further statistical analysis, using MATLAB (2018b) (The MathWorks, Natick, MA, USA), by means of a Bluetooth module (Figure 20).

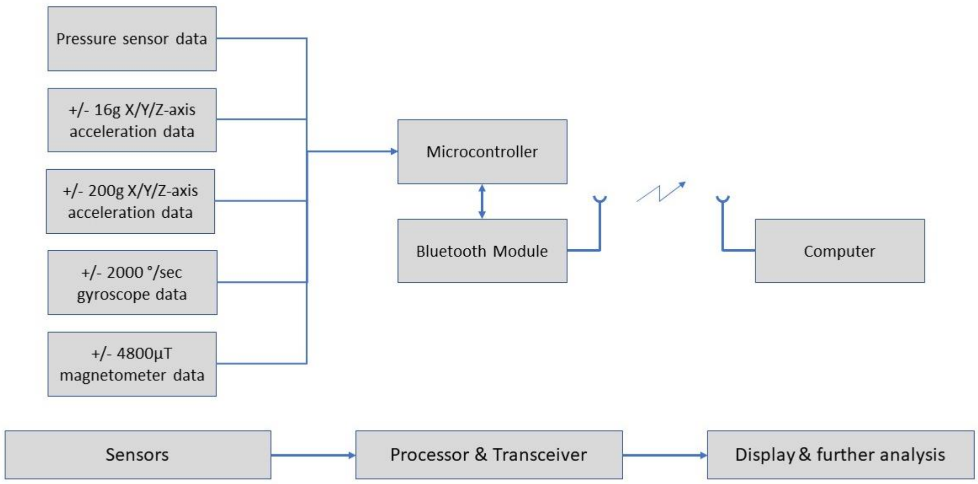


Figure 20: Node block diagram of sensor processing

3.1.3 Assembly

An important part for the development of the boxing monitoring sensor system is, besides the development of the hardware and software, the integration of the sensor into the sports equipment to be used. In this case into the boxing glove. Therefore, it is important to design the systems properties in a way that the boxing gloves properties are not changed significantly against the existing rules for the sport equipment as well as to follow the AIBA technical competition rules, effective as of February 9, 2019 number 47.1 and 47.2 regarding the application of boxing sensors into the sport equipment (AIBA, 2019c).

The design guidelines for the interaction of the wearable sensor and the human body defined by Gemperle et al. (1998) as well as the guidelines for magnetic and inertial measurement unit use by Camomilla et al. (2018) are taken into account for the integration and positioning of the sensor technology. The developed sensors must be securely attached and fixed to the human body or the sports equipment itself to prevent relative movements between the sensors and the human body. A loose attachment or an unsecured fit of the sensor attachment can lead to undesired vibrations and displacement of the sensor system. This can result in undesirable signal artifacts and impairment of the sensor accuracy. Therefore, it was important to investigate the location where movement occurs to determine the best position to place the rigid and semirigid electronic components of the sensor system for performance measurement.

The AIBA technical rules 47.1 and 47.2, about the application of sensors in boxing, are stating the application in the boxing glove itself or in the sport bandages on the hand and wrist. For this purpose, an evaluation was carried out to determine the best possible areas for sensor positioning. The investigation evaluated different areas in the glove and on the hand where the sensors and electronics can be applied to, in order to provide sufficient attachment. Particular attention was paid to the athletes' health safety as well as the most inconspicuous possible manipulation of the glove by installing the sensors and the protection of the electronic components against major impacts while maintaining the accurate measurement performance.

In the course of the scientific work, the instrumentation of the sensor system into the sports equipment was adapted to the state of development of the sensor system and was performed in three successive development stages.

The first prototypes were successfully tested in a non-installed state before the first instrumentation of the boxing glove was conducted. The developed sensor system for punch force measurement was integrated into the frontal contact surface of the glove. The microelectronics used for data processing were attached in a separate box at the wrist area with the aid of a regularly used boxing bandage.

In a further development step, in which the overall dimensions of the microelectronics were scaled down, the sensor system enabled the first complete instrumentation to be placed within the boxing glove. The microelectronics were then integrated and sewed into the medio palmar wrist area of the boxing glove (Figure 21).

In the course of the continued development process, the addition of further sensors and further miniaturization, the positioning of the sensor system was adjusted. For this purpose, various tests were carried out, to evaluate the best areas for integration in terms of both the protection of the athletes and the protection of the electronic components from impact, moisture and heat accumulation. The AIBA specifications had to be taken into account in order not to influence the physical properties of the glove. A special focus was placed on the miniaturization of the electronic components in order to change the characteristics of the sports equipment to a minimum and to prevent the manipulation of the glove from being noticeable and obvious to the athletes. The system was subsequently integrated in different strategic areas of the glove. To measure the three-dimensional spatial orientation of the fist, inertial sensors were integrated into the dorsal central area of the hand in the boxing glove. The positioning of the sensors for impact force measurement in the frontal contact area of the glove has not been changed since the first stage of development as it has demonstrated excellent measurement results. The microelectronics used for data processing and transverse was integrated in the medio palmar wrist area of the boxing glove with the help of a silicone coating. A schematic breakdown of the individual system components within the boxing glove is shown in Figure 21.

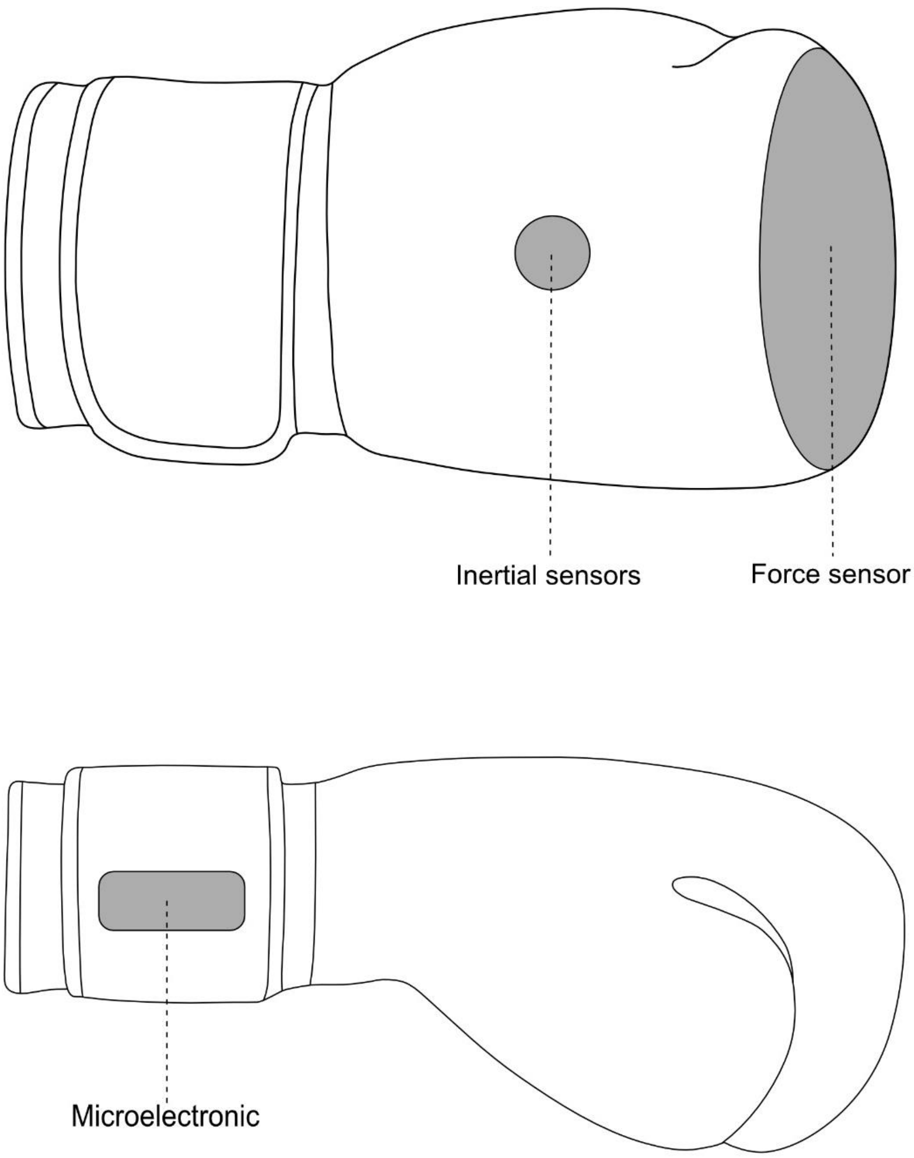


Figure 21: Schematic of the developed sensor system instrumented to the sport equipment

3.2 Punch force determination with piezoresistive pressure sensors

The literature review has revealed a major gap of research in the field of performance diagnostics and wearable technologies in the sport of martial arts and combat sports, especially in the Olympic discipline of boxing. Therefore, chapter 3.2 presents the research conducted into punch force determination with piezoresistive pressure sensors for the development of a comprehensive and high-precision performance monitoring system in combat sports. Considering this, the chapter outlines the technical principle of the custom developed pressure sensor including the sensor calibration method.

3.2.1 Technical principle

The detection of punch force, in units of force with the SI unit Newtons (N), as well as the force distribution of the punch within the contact surface of the boxing glove is executed by the development of pressure sensor arrays. Pressure sensors or Force Sensing Resistors (FSR) are used in a great variety in wearable applications for medical as well as performance analytic purposes. Different pressure sensors were tested during the research process based on piezo resistivity. This type of pressure sensor is operating by harnessing the piezoresistive effect that some materials experience when elastic deformation occurs (Fiorillo et al., 2018; Tränkler & Obermeier, 1998).

The etymological background of the word “piezoresistive” arouses from the Greek word “piezein” and the Latin word “resistere”. The first part, “piezein”, means to apply pressure or to compress. The same usage of “piezein” can be found in the name-giving description of the piezoelectric effect and illustrates the operating principle of the sensors. The second part of the word piezoresistive comes from the Latin word “resistere” and means to stop (Dirjish, 2015; Fiorillo et al., 2018).

The piezoresistive effect was first discovered by Lord Kelvin (William Thomson, 1st baron Kelvin, 1824-1907) back in 1856, when the physicist discerned the change of resistance in mechanically loaded wires made out of copper and iron (Winter et al., 2012). The first sensor based on the piezoresistive effect was developed by the American physicist Percy W. Bridgman in 1911 who investigated the piezoresistive behaviour in polycrystalline metals. In 1911, Bridgman developed a piezoresistive pressure gauge made out of manganin, an alloy of copper, manganese and nickel (Krehl, 2009). In further work Bridgman described the characteristics and essence of the piezoresistive effect (Krehl, 2009).

With the discovery of the piezoresistive effect in silicon (Si) and germanium (Ge) in 1954, a further step in the development of piezoresistive devices was achieved by the pioneering scientist C.S. Smith (Fiorillo et al., 2018), almost one century after the discovery of the piezoresistive effect in copper and iron by Lord Kelvin in 1856. Since then, the scientific interest, involving the piezoresistive effect in sensors is greatly increasing. This can be seen in the number of publications that were published from 1963 until 2020 as presented in Figure 22. In the time between 1970 and 1980, two main applications for piezoresistive sensors led to the foundation of many new companies focussing on the development and manufacturing of piezoresistive based pressure sensors. The two main areas were the medical and the automotive industry (Büttgenbach, 2016).

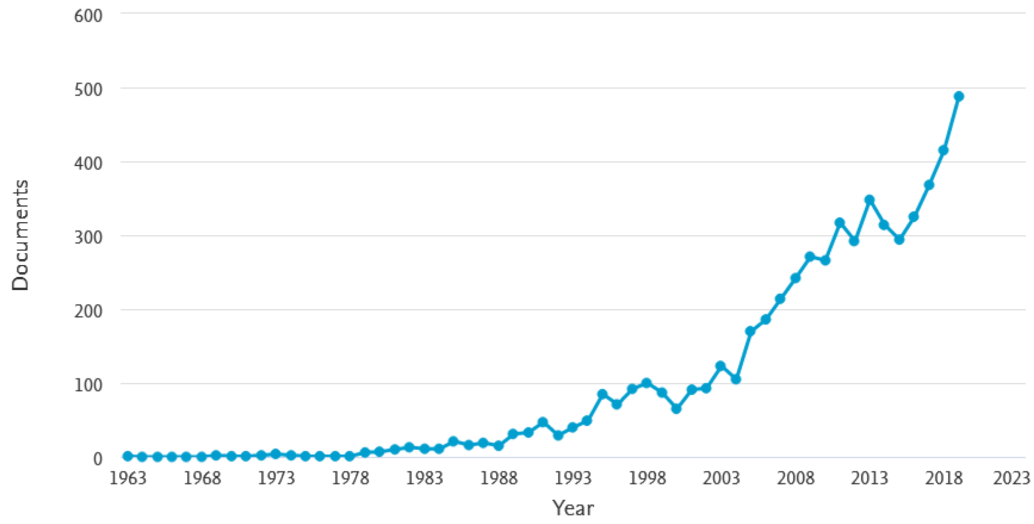


Figure 22: Literature per year involving the use of piezoresistive sensors (Scopus, 2020)

Piezoresistive pressure sensors are manufactured by the distribution of conductive particles on an insulating polymer matrix in an irregular manner that forms the sensitive area of the sensor. This distribution of particles is obtained by using low frequency ultrasonic waves to achieve the irregular dispersion of the particles, that forms the sensitive area of the sensor (Paredes-Madrid, Palacio, et al., 2017 and Fiorillo et al., 2018). The sensitive area is supplied as a polymer film or applied in a screen-printing process during the manufacturing procedure. The polymer composite made out of conductive and non-conductive particles causes a change in electrical resistance when a force is applied to the sensors sensitive area. The characterization of materials that potentially can be used as conductive and non-conductive materials for the fabrication of these sensing elements continues to be an active and much considered area of research (Paredes-Madrid, Palacio, et al., 2017). Materials used for the conductive part are ranging nowadays from micronized metals such as nickel, copper, silver, aluminium and iron. In addition to micronized metals, carbon particles such as carbon nanotubes, carbon fibre, graphite, pyrolytic carbons and carbon blacks are used as conductive materials in the same way (Adam Bilodeau et al., 2015; Meti et al., 2016; Wang & Cheng, 2014; Wang & Han, 2013). The conductive materials are dispersed along an insulating polymer matrix during the manufacturing process of the conductive polymer composite. As an insulating material, rubber, elastomers, epoxy resin, Polydimethylsiloxane (PDMS), polyvinyl chloride and polyvinylidene fluoride are the most common materials used for the insulating polymer matrix (Canavese et al., 2011; Mei et al., 2015; Paredes-Madrid, Palacio, et al., 2017; Stassi et al., 2014).

The operation principle of force-sensing resistors within the polymer composite of conductive and non-conductive materials are either operating on the basis of quantum tunnelling, percolation or a combination of both phenomena. Which principle dominates can be controlled by the type and shape as well as the particle concentration of the conductive materials used during the design concept and manufacturing process of the sensor (Bloor et al., 2005; Stassi et al., 2014). The particle concentration is also referred as the volume fraction of the filler material by Bloor et al. (2005).

If stress is applied to the sensors sensitive area, the applied force is acting against the interatomic structure of the polymer composite. Furthermore, the applied force causes a reversible change in contact of the sensors contact area as well as the composites form. The resistive element of the sensor is deformed against the substrate and the conductive material comes into contact with the sensors active layer. Plastic deformation as a material property of the polymer composite is not preferred as it would change the sensor properties permanently (Schaumburg, 1992). An increase or decrease of the sensor's conductivity and electrical resistance is then initiated.

An increase of the resistivity leads to the positive pressure coefficient of resistance (PPCR) for high aspect ratio particles, such as carbon nanotubes (CNTs), graphite nanosheets, and carbon black agglomerates with high complexity (Stassi et al., 2014). The increase behaviour of the electrical resistance is described by the percolation theory. This phenomenon can be observed in conductive polymers when the particle concentration within the polymer matrix is above the percolation threshold (φ_c) (Basta et al., 1994; Hou et al., 2013; Knite et al., 2004; Zhou et al., 2008). In this case, the conductive particles are in contact when the sensor is at rest, i.e. when the applied stress, σ, is equivalent to zero. When the sensing element is exposed to stress, the particles begin to migrate apart sequentially and, as a result, the resistance of the polymer composite increases again (Paredes-Madrid, Palacio, et al., 2017).

The electrical resistivity (ρ) of such a conductive polymer composite can be calculated by equation one where ρ_0 is a prefactor depending on details of the transport process, the volume fraction (φ) and the percolation threshold (φ_c). The variable x represents a critical conductivity exponent that is independent from the chemical nature and geometry of the elements (Zhou et al., 2008).

$$\rho = \rho_0(\varphi - \varphi_c)^{-x}$$

Equation 1: Electrical resistivity (ρ) of conductive polymer composite

The quantum tunnelling operation occurs in contrast to the percolation phenomenon mode when the particle concentration of the conductive material is below the percolation threshold (φ_c). In general, a decrease in electrical resistivity is observed in low-aspect-ratio particles, like metallic powders and carbon black. As a result, this effect is called the negative pressure coefficient of resistance (NPCR) (Stassi et al., 2014) and can be observed in the physical principle of quantum tunnelling. The quantum tunnelling effect is, as mentioned previously, the most common physical principle that appears in force sensing resistors. The sensor design concept for the punch force determination with piezoresistive pressure sensors was realized by sensors based on the quantum tunnelling effect. Therefore, this effect is explained more in detail.

The quantum tunnelling effect appears when the distance s of conductive particles is reduced to $s - \Delta s$ once pressure is applied to the sensors sensitive area. Based on the rectangular potential barrier theory, the reduction of the particles distance causes an increase of the transmission between the surrounding particles (Figure 23).

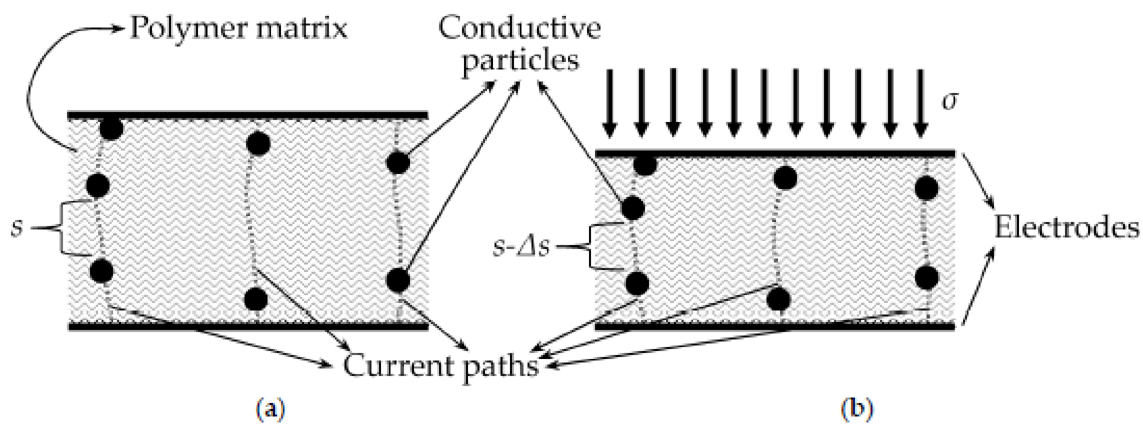


Figure 23: Representation of the quantum tunnelling theory in compressed and non-compressed polymer composites after Paredes-Madrid et al. (2017, p. 5)

As Figure 23 presents, the figure indicates a theoretical model of a polymer composite with randomly distributed conductive particles within the composite and their current paths as dotted lines between the particles.

Figure 23 (a) presents the unloaded composite with a distance (s) of the conductive particles. Figure 23 (b) shows an applied force (σ) to the composite with a reduced interparticle distance and tunnelling paths ($s - \Delta s$) between the particles within the polymer matrix of the sensors sensitive area (Paredes-Madrid et al., 2017).

The literature research has revealed several theoretical models with the attempt to provide comprehensive explanation of the phenomenon of quantum tunnelling published by e.g. Zhang, Pan, Zheng, and Yi (2000), Luheng, Tianhuai, and Peng (2009), Kalantari, Dargahi, Kövecses, Mardasi, and Nouri (2012) and the most recent model by Paredes-Madrid, Palacio, Matute, and Parra Vargas (2017).

The foundation of the stated principles is based on the fundamental research conducted by Simmons (1963) in the field of quantum tunnelling. Simmons theoretical model was developed based on the Wentzel-Kramer-Brillouin (WKB) approximation. The equations developed by the authors (equations 2-4) are sectionally functions of the magnitude (U) in regard with the height of the rectangular potential barrier (Va) divided by the electron charge (e). The electron charge (e), electron mass (m) and Planck constant (h) are considered to be constants when using Simmons model of quantum tunnelling (Paredes-Madrid et al., 2017). Paredes-Madrid et al. (2017) have presented Simmons equations as following:

If $U \approx 0$

$$I(U,s) = \frac{3\sqrt{2mV_a}}{2s}\left(\frac{e}{h}\right)^2 Uexp\left(-\frac{4\pi s}{h}\sqrt{2mV_a}\right)$$

Equation 2: Simmons equation $U \approx 0$

If $U < V_a/e$

$$I(U,s) = \left(\frac{e}{2\pi h s^2}\right)\left\{\left(V_a - \frac{eU}{s}\right) exp\left[-\frac{4\pi s}{h}\sqrt{2m\left(V_a - \frac{eU}{2}\right)}\right]\right.$$
$$\left. - \left(V_a + \frac{eU}{2}\right) exp\left[-\frac{4\pi s}{h}\sqrt{2m\left(V_a + \frac{eU}{2}\right)}\right]\right\}$$

Equation 3: Simmons equation $U < V_a/e$

If $U > V_a/e$

$$I(U,s) = \left(\frac{2.2e^3U^2}{8\pi h V_a s^2}\right)\left\{exp\left[-\frac{8\pi s}{2.96heU}\sqrt{2m{V_a}^3}\right]\right.$$
$$\left. - \left(1 + \frac{2eU}{V_a}\right) exp\left[-\frac{8\pi s}{2.96heU}\sqrt{2m{V_a}^3\left(1 + \frac{2eU}{V_a}\right)}\right]\right\}$$

Equation 4: Simmons equation $U > V_a/e$

The most prevalent accepted model was developed by Zhang et al. (2000). The developed model assumes, according to Ohm´s law, that by rearanging Simmons low Voltage equation, the conductive polymer electrical resistance (R_{pol}) can be calculated as a voltage independent quantitiy (equation 5).

$$R_{pol} = \frac{2s}{3A\sqrt{2mV_a}}\left(\frac{h}{e}\right)^2 exp\left(-\frac{4\pi s}{h}\sqrt{2mV_a}\right)$$

Equation 5: Resistance of a polymer composite

Zhang et al. (2000) states that the interparticle separation (s_0) can be calculated, when the conducting particles are spherical, of equal size and are arranged in a cubic lattice (Zhang et al., 2000). Furthermore, the equation uses the particle diameter (D) and the filler volume fraction (θ) that is descibed as the ratio between the conductive and non-conductive particles within the polymer composite (equation 6).

$$s_0 = D\left[\left(\frac{\pi}{6}\right)^{1/3}\theta^{-1/3} - 1\right]$$

Equation 6: Calculating inter-particle separation (Zhang et al., 2000, p. 2741)

The change of interparticle-separation in relation to stress is calculated by "the strain [(ε)] of the polymer matrix, σ the applied stress, and M the compressive modulus [(Young´s modulus)] of the polymer matrix" (Zhang et al., 2000, p. 2741).

$$s = s_0(1-\varepsilon) = s_0\left(1-\frac{\sigma}{M}\right)$$

Equation 7: Calculating change of inter-particle separation (Zhang et al., 2000, p. 2741)

In contrast to Zhang et al., the most recent model is developed by Paredes-Madrid et al. (2017). The developed model is similar to the model created by Zhang et al. based on the fundamental research model in quantum tunnelling by Simmons (1963) but in addition, uses the contact resistance concept by Kalantari et al. (2012). Furthermore, the model takes the phenomenon of sensitivity degradation into account that some force sensing resistors exhibit. The experimental study by Paredes-Madrid, Matute, Bareno, Vargas and Gutierrez Velasquez (2017) determined that the degradation of sensitivity is a voltage-dependent phenomenon that can be prevented by setting a suitable supply voltage in the driving circuit. Consequently, this factor was taken into account in the subsequent investigations (Paredes-Madrid, Matute, et al., 2017). Paredes-Madrid et al. (2017) developed their own model based on the equation eight from Kalantari (2012) to calculate the total resistance of force-sensors. The groundwork was therefore conducted by Kalantaris concept. Paredes-Madrid´s principle is derivated as follows.

The equation for calculating the force-sensors resistance takes the contact resistance between two different surfaces into consideration. It is ascertained that the contact area varies between the two stages of a force-sensor at rest compared to the stage when stress is applied. A reduced electrical percolation and resistance is a result of the variation of the touched contact area. A descriptive schematic view of contact resistance is presented by Kalantari et al. (2012, p. 574) in Figure 24. Figure 24 (a) illustrates the contact area when no pressure is applied. Whereas Figure 24 (b) presents the increased contact area when force is applied to the sensor.

$$R_{total} = 2R_{Con} + R_{Pol}$$

Equation 8: Total resistance of force sensors by Kalantari et al. (2012, p. 2741)

Based on the equation of contact resistance, the resistance is calculated by equation nine. Equation 9 includes the electrical resistivity of the two materials $\rho 1$ and $\rho 2$, the applied force F and the Meyer hardness of the softer member H (Kalantari et al., 2012).

$$R_{Con} = \frac{p_1 + p_2}{4}\sqrt{\frac{\pi H}{F}}$$

Equation 9: Contact resistance (Kalantari et al., 2012, p. 575)

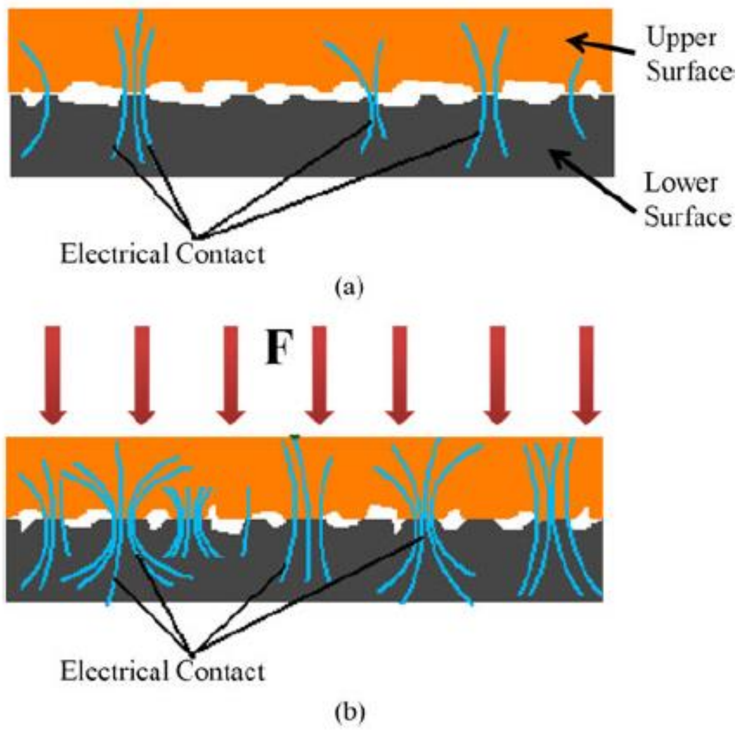


Figure 24: Descriptive schematic of current path through contact (Kalantari et al., 2012, p. 574)

Paredes-Madrid uses equation 8-9 from Kalantaris et al. (2012) by redefining the variables of R_{Pol} to R_{bulk} and R_{Con} to R_C as presented in equation 10.

$$R_{FSR} = 2R_C + R_{bulk}$$

Equation 10: Total resistance of FSR with renamed variables (Paredes-Madrid et al., 2017, p. 14)

The external applied voltage to the force-sensing resistor V_{FSR} is predicted by splitting “the voltage across the polymer composite (V_{bulk}), and the voltage across the contact resistance (V_{Rc})” (Paredes-Madrid et al., 2017, p. 14). The contact resistance is proposed by equation 11 where R_{par} is the resistance of the conductive particles and R_C^0 the value of the contact resistance at rest.

$$R_C = R_{par} + \frac{R_C^0}{\sigma^k}$$

Equation 11: Resistance of conductive particles by (Paredes-Madrid et al., 2017, p. 15)

Paredes-Madrids et al. (2017) final equations for calculating the resistance of polymer composites based on quantum tunnelling, contact area and external applied voltage is presented as following for the three different stages.

If $V_{bulk} \approx 0$

$$R_{bulk} = \frac{2s_0(1-\sigma/M)}{3[A_0 + A_1\sigma^{A_2}]\sqrt{2mV_a}}\left(\frac{h}{e}\right)^2 \exp\left(\frac{4\pi}{h}s_0(1-\sigma/M)\sqrt{2mV_a}\right)$$

If $V_{bulk} < V_a/e$

$$I = \frac{[A_0+A_1\sigma^{A_2}]e}{2\pi h s_0^2(1-\sigma/M)^2}\left\{\left(V_a - \frac{eV_{bulk}}{2}\right)\exp\left[-\frac{4\pi}{h}s_0(1-\sigma/M)\sqrt{2m\left(V_a - \frac{eV_{bulk}}{2}\right)}\right] - \left(V_a + \frac{eV_{bulk}}{2}\right)\exp\left[-\frac{4\pi}{h}s_0(1-\sigma/M)\sqrt{2m\left(V_a + \frac{eV_{bulk}}{2}\right)}\right]\right\}$$

If $V_{bulk} > V_a/e$

$$I = \frac{2.2e^3V_{bulk}^2[A_0+A_1\sigma^{A_2}]}{8\pi h V_a s_0^2(1-\sigma/M)^2}\left\{\exp\left[-\frac{8\pi s_0(1-\sigma/M)}{2.96heV_{bulk}^2}\sqrt{2mV_a^3}\right] - \left(1+\frac{2eV_{bulk}}{V_a}\right)\exp\left[-\frac{8\pi s_0(1-\sigma/M)}{2.96heV_{bulk}}\sqrt{2mV_a^3\left(1+\frac{2eV_{bulk}}{V_a}\right)}\right]\right\}$$

The authors stated in their results that the described model was unfortunately not able to accurately predict some experimental observations. The fundamental basis for the degradation of sensitivity was not found, and the proposed model was not able to predict it either. The authors state that to improve the accuracy and repeatability of the measurements, there has to be an optimal supply voltage that minimizes creep while preventing sensitivity degradation in force sensing resistors (Paredes-Madrid, Matute, et al., 2017).

The statement from Paredes-Madrid et al. shows that there is no comprehensive model existing that predicts the quantum tunneling prediction in FSR sensors comprehensively and that the field of understanding and predicting the quantum tunneling effect in force-sensing resistors is an open and complex research area. Nevertheless, high accuracy and high resolution measurements are possible using piezoresistive sensors by performing an accurate calibration method.

Piezo resistive pressure sensors are setup in different layers. Two main configurations can be distinguished in terms of the sensor design layout. The two configurations are called the ThruMode and ShuntMode design. The ThruMode design consists of several sandwiched layers in which two layers are used as a carrier foil (i.e. upper and lower layer). These two carrier foil layers are made out of a synthetic material on which a silver ink is applied that act as the sensor electrode and extends to the connectors. The next layer is the actual piezoresistive area of the sensor and consists of the conductive particles that are dispersed in a non-conductive polymer to create the polymer composite sheet. An additional synthetic layer is sandwiched between the polymer composite and an electrode sheet that acts as a spacer. This layout results in a separation of the two electrodes when no pressure is applied to the sensor and therefore to an infinite resistance.

The second main existing design configuration is called the ShuntMode design. This design distinguishes its configuration by an interdigitated electrode design feature. These two electrodes are located on one layer instead of two separated electrodes as it is presented in the ThruMode design layout. The ShuntMode configuration is made up of different layers as in the fashion of the ThruMode design. The main feature are the two interdigitated silver electrodes that are printed on the first layer (circuit layer). The circuit layer is separated by a spacer similar to the ThruMode design to the following layer. The polymer composite consisting of the conductive and non-conductive particles is applied to an additional layer carrier substrate. The ShuntMode design configuration has the advantage that the electrodes can be designed easily on one single layer because of the two interdigitated electrodes. An advantage of the ShuntMode design is that all electrical connectors are on one layer and that by the reduced number of printing layers, the amount of silver ink is less than compared to the ThruMode design concept. The ShuntMode design has economic advantages, especially in a great volume of production.

The ShuntMode design configuration was therefore used for the development of the boxing monitoring sensor system and the measurement of punch forces by use of piezoresistive sensors as presented in Figure 18.

3.2.2 Calibration

Chapter 3.2.2 is outlining the piezoresistive pressure sensor testing and calibration process for the punch force determination in combat sports.

Punch forces in boxing and other martial arts disciplines can range from light contacts, so called pit pats of 250 N, up to 6.000 N tested in laboratory conditions (Mack et al., 2010; Pierce et al., 2006b) according to the literature review presented in chapter 2. For the development of a comprehensive monitoring system for combat sports it is essential to detect the entire feasible force range with an additional offset above and below possible punch forces with a great accuracy. For the development of the boxing monitoring system a tolerance buffer of 10% for boxing punches above and below possible punch magnitudes outside laboratory conditions was taken into account.

3.3.3.1 Experimental setup

The experimental setup can be subdivided into two parts. The first part executed was an initial sensor testing conducted for a preliminary selection process. The second part was a detailed investigation of the tested sensor properties. This chronological order is based on the fact that a large effective range of pressure can appear and be investigated in martial arts striking. The aim of the initial testing is to narrow down the quantity of qualified pressure sensors and manufacturers by means of the sensors measurable effective force range. The selection rests upon the feasible pressure range of the different sensors tested in a standardized experimental setup. A total of nine different sensors were tested during the selection process. The preliminary testing was executed by the use of a Zwick / Roell material testing device and the testXpert® III Version 1.4 (ZwickRoell GmbH & Co. KG, Ulm Germany). In this setup, the sensors were verified on their accessible measuring range, as mentioned before and additionally verified on the sensor signals repeatability. Increasing pressure level tests were executed for the entire expectable pressure range. The pressure exerted by the Zwick / Roell material testing device was calculated in advance of the experiment. The calculation is based on the sensor size of the samples provided by the different manufacturer in allowance of the analysed effective punching area that was tested in a prior experiment. A uniform pressure distribution was achieved by the application of customized spacer that were mounted to the sensors sensitive area (Figure 25).

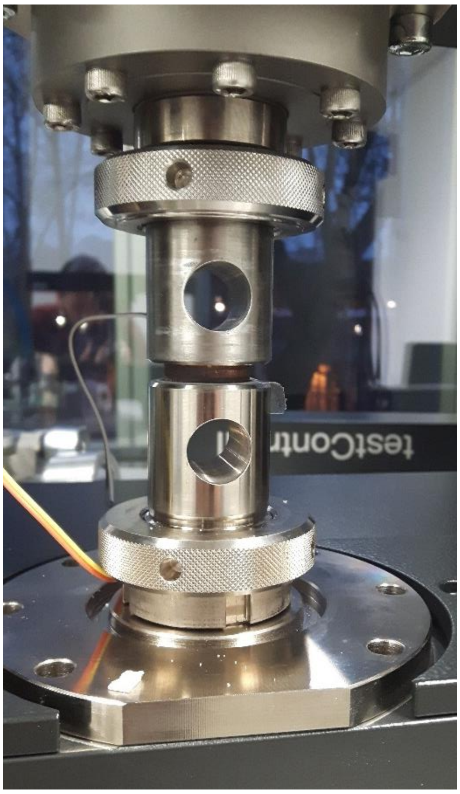


Figure 25: Zwick / Roell sensor property testing setup

The pressure exerted was increased in a systematic manner until the maximum expectable pressure was reached or the sensor response has saturated before the maximum expectable pressure was achieved. The second case led to a manual abortion of the testing protocol and an exclusion of the sensor for the following research steps of the development. This testing is the first part in identifying the most suitable sensor for the application and development of a unique boxing monitoring system.

Potential sensors that have passed the initial sensor testing, were taken to be further tested on its sensor characteristics and dynamic behaviour.

The subsequent experiment was performed in an application-oriented setup with appearing pressure behaviour as it can be investigated during a strike impact condition. A customized foam model was designed and made for each of the different sensors that passed the preliminary testing. The design allows the incorporation of the sensor into a foam padding, similar to the condition the sensor will be used within the conclusive development process. In this customized experimental setup, pressure was applied by use of a padded batting hammer. The impact intensities were measured by use of a Kistler force plate for evaluation purposes. This measuring instrument uses piezoelectric quartz sensors. It is considered to be one of the most reliable methods for measuring dynamic forces. The total error is considered to be less than 1%. Furthermore, this technology provides low hysteresis and deformation, with a high measurement range, linearity and sensitivity for scientific applications (Barnett et al., 2001). The device of a Kistler force plate is used as gold standard for the measurement of impact biomechanics in gait analysis and other motion analysis research experiments (Barnett et al., 2001). The data generated by the Kistler force plate was recorded using Vicon Nexus software for motion capture in life sciences. The dynamic testing is an important part for the validation of the sensor properties. The second test is aiming, other than the first initial sensor testing, to test the sensors behaviour in a representative manner to strike impacts with short contact times of 15 to 25 ms, including both the loading and unloading period of the sensor signal as it was assessed among other by Atha (1985). The pressure exerted was acclivitous to test the sensors until the maximum expectable pressure was reached.

The novel padded batting hammer setup was selected as the most appropriate experimental setup to the sensors in a representative application-orientated condition. The selected sensors were connected to individually calculated reference resistors ranging from 2.2 kΩ up to 10 kΩ. The sensor signal was then analysed in respect to the sensor output voltage as an indicator for the resolution of the sensor. The output voltage allows an additional classification of the sensors for the development selection. A greater output voltage allows a more detailed accumulation of the applied pressure to the sensor response and therefore the applicable resolution. In contradistinction to a large output voltage, smaller output voltages enable a minor resolution and therefore a restricted depiction for further analyses. The output voltage was transmitted via an analogue to digital converter (ADC) to the computer for raw data processing and further analysis using MATLAB (2018b) (The MathWorks, Natick, MA, USA).

Another important variable for data analysis is the coefficient of sensor conductance. Sensor conductance is similarly as the output voltage, transmitted via an analogue to digital converter to a computer for data processing. The conductance is used to test the sensor response on repeatability and accuracy compared to the Zwick / Roell and Kistler force plate determined force. In order to predict sensor repeatability, the presented experimental procedure was tested for a minimum of five times for all sensors in terms of statistical valuation of the sensor output and response. Furthermore, the experimental procedure was repeated on different days to analyse sensor accuracy and repeatability not only within a limited series of tests conducted during one day but furthermore, to test the sensor performance on different consecutive days for inter experimental validity. Long term sensor validation was executed in a third phase after the most suitable sensor with the greatest measurement performance of the tested sensors was selected. To keep high scientific standards, all tests conducted using the same experimental test protocol and setup.

3.3.3.2 Experimental method

The initial sensor testing was conducted using a Zwick / Roell material testing device as stated above. A systematic gradient step test was designed in order to detect the sensors entire effective measurement range. Figure 26 is illustrating the applied loading sequence of eleven cycles in total. The determined effective range was defined from 0 up to 550 N, equivalent to an exerted pressure of up to 1.17 MPa with an increase of 50 N (0.11 MPa) for each cycle. The force range is based on the effective sensitive sensor area determined prior to the testing of 4.7 cm^2 for the sensors tested. The gradient step test for sensor selection was started with no pressure applied to the sensor surface. Therefore, the material testing device pressure stamp was placed with a minor gap of approximately two millimetres to the sensor spacer that was mounted on top of the sensors sensitive area. The spacer was used to assure an equal pressure distribution across the sensors sensitive surface area and to avoid involuntary force shunt to ensure consistent test conditions for all sensors. The pressure was applied with a forward speed of one millimetre per minute in both directions loading and unloading to the initial starting position when no pressure was applied. A delay of two seconds was set before the subsequent pressure cycle was initiated. The initial sensor testing was conducted five times in a row for all possible sensors and all force level to be tested to compare and determine inter test results (Figure 26). A measurement frequency of 1.000 Hz was set for the sensor data acquisition and 500 Hz for the Zwick / Roell material testing device due to the machines limited maximum measuring frequency.

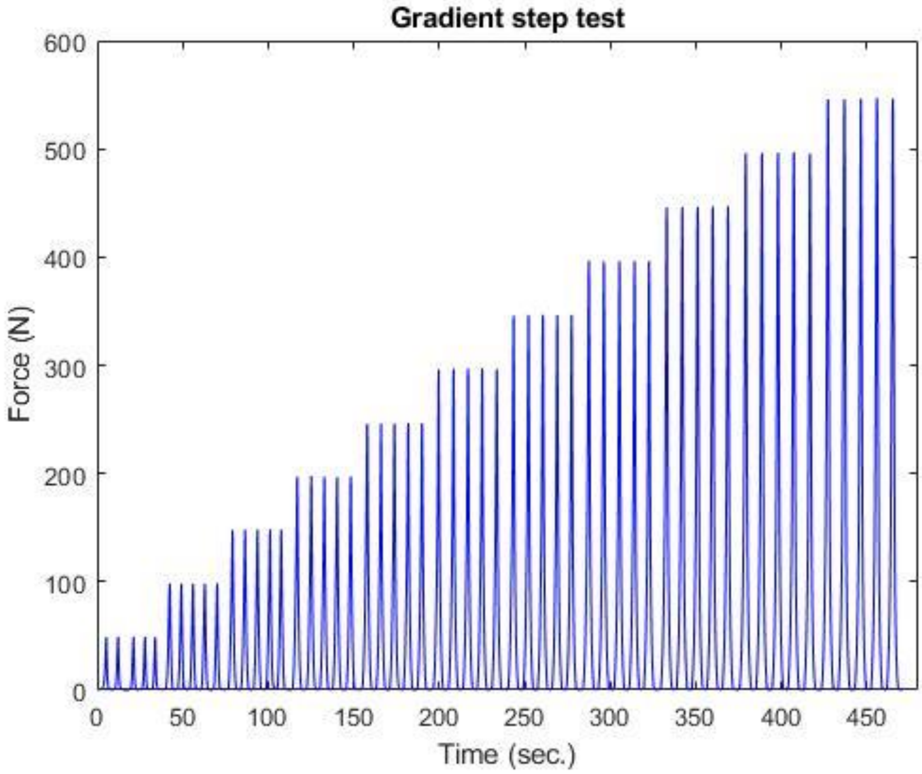


Figure 26: Gradient step test loading sequence for sensor selection

The preliminary dynamic sensor analyses in terms of repeatability and accuracy determination for the sensor selection assessment was conducted by statistically comparing sensor-derived conductance and Zwick / Roell derived force using a polynomial fit function. Furthermore, the sensors were tested on hysteresis. The analyses will be described in detail in the following chapter 3.3.3.3 about the experimental results obtained.

All sensors that have passed the initial dynamic experimental series and offer the ability to detect the entire effective measurement range are tested and analysed on sensor characteristics in detail in the second phase. Therefore, in a subsequent experiment, the most appropriate experimental setup to the sensors in a representative application-orientated condition was defined by using a Kistler force plate. The testing method was similar to the first one presented.

A step test was executed to test the sensor responds on impact. Therefore, a gradient impact series of 20 hits was executed to test the sensor resolution. The novel padded batting hammer setup allowed the simulation of impact durations similar to minimum impact length achieved in expert boxing. Figure 27 is illustrating the loading sequence for the presented experiment with impact forces from 0 up to approximately 890 N. The last test cycle was tested to analyse possible saturation at much greater impact magnitudes. Again, a delay of one second was set to clearly separate the impacts as well as to analyse creep behaviour.

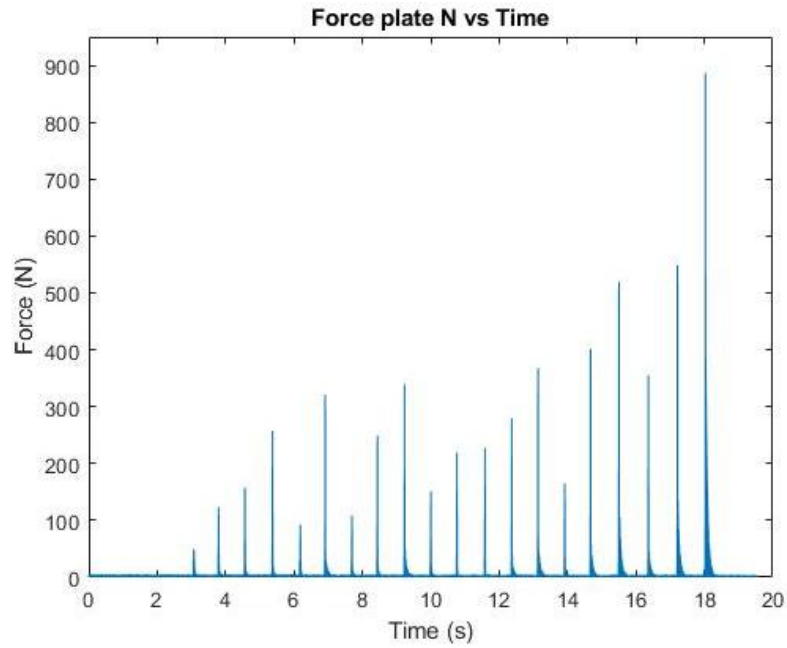


Figure 27: Kistler force plate impact tests

Creep behaviour could be observed in some of the sensors tested. This behaviour can be defined as the delay in sensor signal output following an applied pressure condition. This behaviour is influenced by the material characteristics of the conductive particles along the insulating polymer matrix. A low hysteresis is relevant for the development of a highly accurate and repeatable sensor system.

Sensor creep was determined in percentage and compared between the different loading cycles as well as test runs. The creep percentage is calculated on sensor conductance. Therefore, the first sensor output value after pressure is released of the sensor (G_F) and the last sensor value before the new loading cycle begins (G_L) within a two second time frame was taken for the calculation of creep reduction percentage (equation 12). The method and adapted equation is based on Parmar, Khodasevych and Troynikov (2017) although the authors have misused the term of sensor drift for the depiction of sensor creep.

$$C_P = 100 * (G_L - G_F)/G_F$$

Equation 12: Adapted creep percentage

The entire testing was repeated five times in a row with an additional experimental series on the subsequent day. Similar to the initial sensor testing, a measurement frequency of 1.000 Hz was set for the pressure sensors to collect a minimum of 20 data points in total for the entire impact phase duration of approximately 20 ms as expected in expert boxing. The Kistler force plate data collection was set to 1.000 Hz to match the sensor measuring frequency. This avoided the interpolation of data points as it had to be performed for the initial sensor testing due to a limitation of measuring frequency of the Zwick / Roell material testing device at 500 Hz.

In addition, sensor accuracy and repeatability were evaluated in the two experimental designs. Investigating the accuracy is the first step in compiling individual calibration functions for the sensors tested.

The examination of the sensor output allows the analyses of specific output pattern by comparing the Kistler force plate and pressure sensor output against each other (Figure 28).

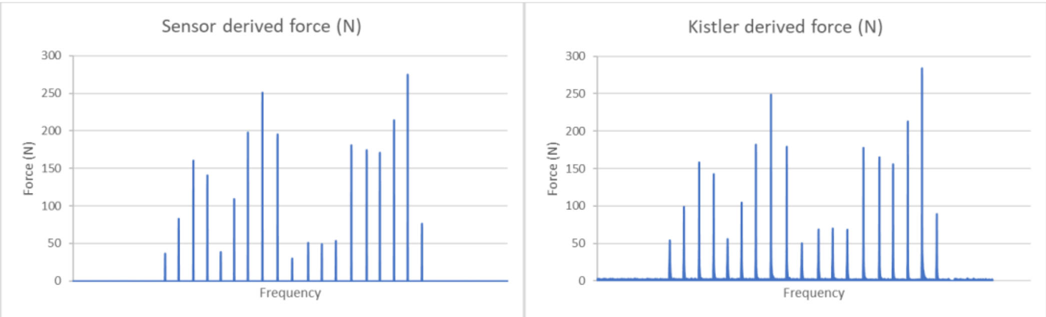


Figure 28: Signal output of Sensor (a) and Kistler (b) derived measurement

In a first step, the sensor output data was analysed on saturation. If no saturation has occurred, the data output of both, the Kistler force plate as well as the sensor were analysed in detail. Therefore, the force time curve progression, constituting a leptokurtic curve shape, of the Kistler force plate was compared against the sensor conductance time progression.

For the accuracy testing, all sensors that have past the saturation testing phase were analysed. The sensor-derived conductance (G) was compared against the Kistler force plate derived force, measured in Newtons (N). The peak values of both the sensor and the force plate were compared against each other. A polynomial fit function was used for statistical analyses. The accuracy calculation is the first step for compiling calibration functions for the tested sensors and to further validate the most accurate sensor for the projected application.

Sensor repeatability was tested by analysing the results obtained of the polynomial fit calculated for all cycles tested in a single run as well as inter experimental comparisons of cycles repeated in different runs and different days. The comparison of accuracy for repeatability testing is analysed in form of the coefficient of determination (R^2) and denoted in percentage.

After the experimental tests were carried out with all sensors during the selection process, the sensors were ranked according their experimental results in terms of effective measuring rate, drift, hysteresis, accuracy and repeatability.

The top-rated sensor with the best sensing characteristics of all tested sensors was selected for the further development process. Therefore, additional tests were conducted to find the most accurate and reliable calibration method for the selected sensor.

An important quality in the development and accomplishment of the calibration method is the execution of the calibration process in an application-orientated condition as close to the final sensing condition as possible, by keeping high scientific quality criteria in terms of objectivity, validity and reliability.

The research was interested in detecting peak forces in boxing. Therefore, the first calibration method tested has focussed on peak data comparison. Systematic gradient step tests were executed using the Kistler force plate. For this approach, a gradient impact series of 20 hits was executed by use of the testing setup described. Gradient step tests enable the consideration of a great impact range. The test was repeated five times to generate a dataset of 100 cycles with forces ranging in average from 50 up to 550 N. For the comparison of peak data output, peak conductance values measured by the pressure sensors were analysed against peak force values determined by the Kistler force plate. This method has obtained great accuracy. Even thought, the calibration method is based on a low number of 100 data points.

To increase the effectiveness of the calibration function, a new calibration function was applied. The new method implies the entire set of data obtained. In a first attempt the impact was subdivided into the loading and unloading phase using MATLAB R2018b. Both phases were analysed separately. Again, a gradient impact test of 20 hits was executed considering the same force range from 50 up to 550 N. Kistler force plate derived force and sensor-derived conductance output was separated in to loading and unloading phases. The different phases of all 100 runs were used to create the calibration functions using polynomial fit function for statistical analyses

To separate the two phases takes a greater period of time, especially in a later step of the development process, when performing the entire data processing within the discrete microcontroller. Therefore, in a third step, the loading and unloading phase was not separated anymore to create two individual calibration functions. At this phase, the entire impact progression was analysed together to establish one overall calibration function for the impact event. Polynomial fit functions were used again for statistical analyses and the development of calibration functions.

3.3.3.3 Experimental results

The first testing conducted had the objective to test the sensors possible effective measuring range, that that can be covered. Figure 26 presents the experimental results of the gradient step tests conducted with the Zwick / Roell material testing device up to a force range of 550 N. The testing has revealed no saturation for four of the tested sensors (PR1_IHG_FS / PR2_IHK_FS / PR3_IRG_FS and PR4_NR_FS). None of these sensors has reached the pre-defined limit of the sensors effective measuring range at less than 550 N. Saturation of the sensor's effective measuring range was evaluated for the two sensors PR5_IRK_FS and PR7_SS_FS at 550 N. A lower saturation level was detected at 500 N for two of the sensors (Sensor PR6_R_FS and PR8_SSI_FS). This saturation level does not allow the use of the sensors for the further development with the purpose to cover the entire force range that experienced athletes can reach in laboratory conditions based on existing literature. The lowest saturation level was detected for the PR9_DV_FS sensor <500 N.

The second characteristic is observed with the gradient step test by testing the sensor signal output in regards of the sensor creep behaviour. The tested sensors can be distinguished in two groups. One group has shown a reduction in sensor creep by greater than 90% whereas the second group of the tested sensors on signal creep has reduced creep by >54% <64%. The best sensors tested have reduced sensor creep by >99.99% (SD= 0.003) within the measurement cycles conducted during the entire tested runs (PR1_IHG_FS and PR4_NR_FS). Sensors PR2_IHK_FS, PR5_IRK_FS, PR7_SS_FS and PR8_SSI_FS have reduced sensor creep by >95% <99% (SD= 1.45). A creep reduction of 65 to 66% was detected by the sensors PR6_R_FS and PR3_IRG_FS (SD= 0.46). The lowest reduction of sensor signal creep was observed within sensor PR9_DV_FS by 54%. The fastest reduction of signal creep to its signal steady state at 0 Siemens (S) was attained by PR1_IHG_FS after 0.28 seconds, followed by PR2_IHK_FS with 0.6 seconds, PR4_NR_FS (1.5 seconds) and PR5_IRK_FS (2.0 seconds).

The following analyses of the sensor characteristics for the sensor selection is the determination of the sensing accuracy between sensor determined conductance (G) and Zwick / Roell determined force (N) denoted in percentage. The best overall accuracy was achieved by the PR7_SS_FS sensor with 99.74% followed by the PR1_IHG_FS sensor with 99.6%. A minor accuracy was achieved by sensors PR2_IHK_FS, PR3_IRG_FS, PR4_NR_FS, PR5_IRK_FS, PR6_R_FS, PR7_SS_FS and PR8_SSI_FS. The tests have shown a greater accuracy of ~90% (SD= 2.67) that was still in the defined acceptable accuracy range for the further development. The least accuracy was achieved by sensor PR9_DV_FS with an accuracy of 64% between sensor determined conductance and Zwick / Roell determined force.

Even though seven sensors have shown a great and acceptable overall accuracy between sensor output and Zwick / Roell data. A detailed analysis reveals that the tested sensors show significant differences among the individually executed force levels tested. The best overall accuracy was achieved by Sensor PR7_SS_FS with 99.74% as stated above. A detailed analysis reveals, that once the level of 450 N was reached, the sensor clearly shows that the previously presented accuracy is significantly reduced. In the following two measuring stages the sensor accuracy was reduced by 6.73% down to 93.01%. Sensor PR2_IHK_FS, PR4_NR_FS and PR5_IRK_FS exhibit an identical signal behaviour as sensor PR7_SS_FS. Great accuracy can be achieved up to 450 N by sensor PR2_IHK_FS with an accuracy of 98%. Once the pressure level is achieved and loaded further, the sensor signal output results in a reduction of the sensing accuracy by 12%, to a measuring accuracy of 86%. The same limit of accuracy at 450N, with a high measuring accuracy of 98%, is analysed at sensor PR5_IRK_FS. Exceeding this limit results in a decrease by 7% for loads up to 500 N and by 51% for loads between 500 and 550 N to 47.18%.

Sensor PR4_NR_FS shows a high accuracy of 99% up to a measurement level of 400 N as well. After exceeding the measuring range, the sensor signal changes significantly. A significant reduction in accuracy of up to 37% can be analysed in the following measurement levels up to 550 N to an accuracy of 72%.

This significant trend is also evident with sensor PR8_SSI_FS. The accuracy of 97.79% is exclusively achievable up to a measurement level of 300 N. The following measuring levels show a significant reduction of the measuring accuracy of 33% for a measuring range up to 400 N as well as a reduction of greater 39% for the measuring stages from 450 N to 500 N down to a 58% measurement accuracy. The PR6_R_FS and PR9_DV_FS sensors have revealed the lowest individual measuring accuracy of all tested sensors. In addition to a strong creeping sensor output signal, the sensors show a low measuring accuracy when high forces are applied. Great accuracies of 91% (PR6_R_FS) are only achieved in the low force range up to 150 N. For forces of 200N and more the achievable accuracy decreases significantly by more than 50%. A worse measuring result was observed by sensor PR9_DV_FS. The sensor achieved a high accuracy of >90% only in the first measuring stage of 50 N. Further tests on accuracy with greater force applications show accuracies of less than 62.24%.

The best consistent accuracy over the entire measuring range was analysed by sensor PR1_IHG_FS and sensor PR3_IRG_FS. Both sensors show a consistently high accuracy of 98% over the entire measuring range up to 550 N.

These two sensors are not only the sensors with the highest general as well as inter force level test accuracy. These sensors were also tested with the highest sensor signal repeatability of 99.1% for PR3_IRG_FS followed by 98.28% by sensor PR1_IHG_FS.

A similarly good repeatability was achieved for sensor PR7_SS_FS, with a measurement repeatability of 97.8%. Lower results on repeatability was tested for sensor PR2_IHK_FS at 95.32% and sensor PR4_NR_FS with 90.66%. The results of the tested sensors on repeatability were within the acceptable statistical range.

Four sensors have revealed resulting test values outside the acceptable range for the analysis of repeatability of force measurements. These included PR5_IRK_FS with 88.7% and PR8_SSI_FS with 84.8% of the sensors that are just below the defined acceptable statistical threshold of <90%.

Identical to the statistical analysis of the creep and accuracy tests, the PR6_R_FS and PR9_DV_FS sensors revealed the lowest repeatability values. However, as in previous tests, sensor PR6_R_FS shows a minor better result of 5.5% (73.9%) than sensor PR9_DV_FS with 68.4%.

The analysis of the hysteresis tests demonstrated a percentual hysteresis of less than 5% for three of the tested sensors after the force was applied to the sensors. The lowest hysteresis detectable was observed for the sensor PR1_IHG_FS with a hysteresis percentage of 1.91%. Sensors PR6_R_FS and PR7_SS_FS demonstrated similar to sensor PR1_IHG_FS a percentage of hysteresis below 5%, with 2.56% and 4.62%. A percentual hysteresis below 10% was detected for the sensors PR5_IRK_FS, with a hysteresis of 5.5%, PR2_IHK_FS with 6.79% as well as sensor PR8_SSI_FS with 9.44%. A percentage hysteresis of over 10% was shown by sensor PR3_IRG_FS with 12.69%. The strongest percentage hysteresis was tested by sensors PR9_DV_FS with 23.7% and sensor PR4_NR_FS with 26.55%. The results of the hysteresis tests are presented graphically in the Figure 29 to Figure 37.

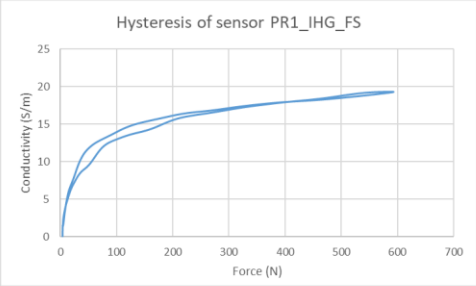


Figure 29: Hysteresis of PR1_IHG_FS

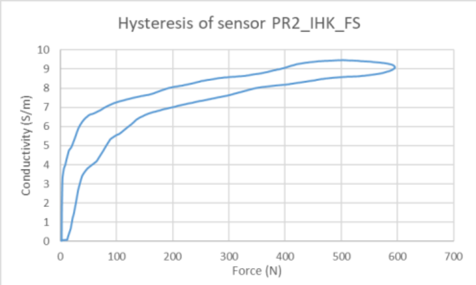


Figure 30: Hysteresis of PR2_IHK_FS

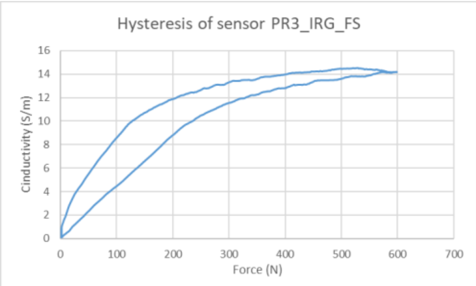


Figure 31: Hysteresis of PR3_IRG_FS

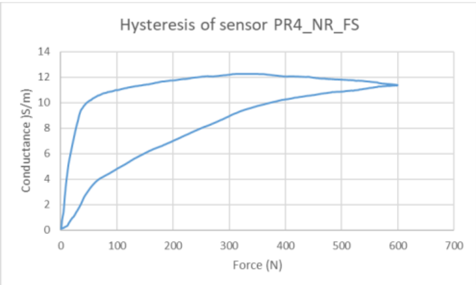


Figure 32: Hysteresis of PR4_NR_FS

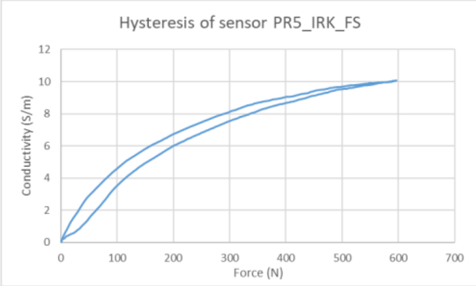


Figure 33: Hysteresis of PR5_IRK_FS

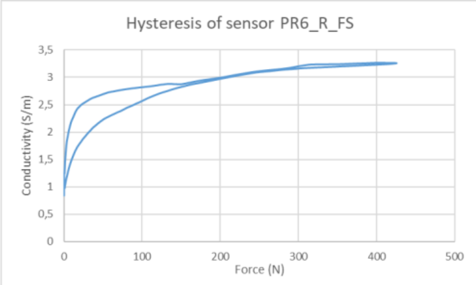


Figure 34: Hysteresis of PR6_R_FS

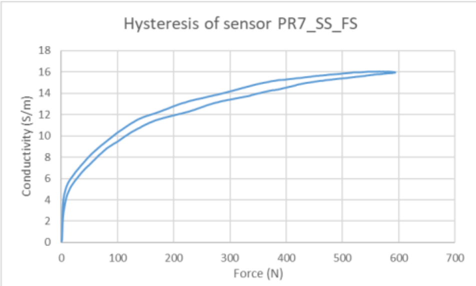


Figure 35: Hysteresis of PR7_SS_FS

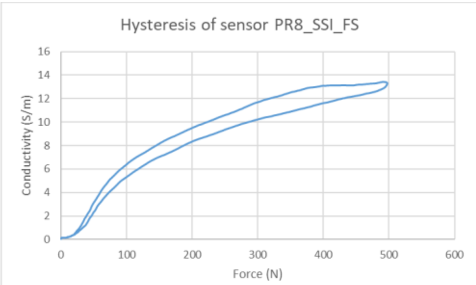


Figure 36: Hysteresis of PR8_SSI_FS

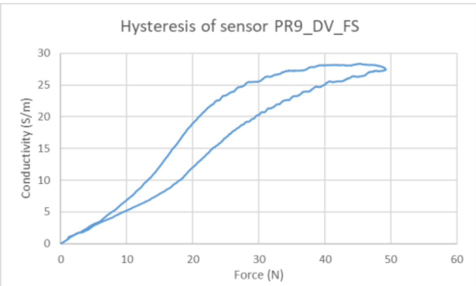


Figure 37: Hysteresis of PR9_DV_FS

On the basis of the test results presented in this chapter, a sensor selection was made in order to use the sensor with the best sensing behaviour as well as best overall test results for the selection of further research work and development processes.

With an accuracy of 99.6%, sensor PR1_IHG_FS showed a very high measuring accuracy and, in a general comparison, with 0.0014% a marginally lower accuracy than sensor PR7_SS_FS of 99.74%. This measuring accuracy could be reproduced over the entire measuring range up to 550N without reaching sensor saturation or a loss in measuring accuracy. Besides the measurement accuracy the sensor exhibits the best results in terms of the sensor creep behaviour. Here the sensor showed the best results in the comparison of all tested sensors in regards of creep reduction percentage (99.99%) as well as the shortest time needed for creep reduction, with <0.3 seconds.

The analysis of the reproducibility of the measurement shows similar results. Sensor PR1_IHG_FS with 98.28% has a repeatability of 0.8% less than the best tested sensor PR3_IRG_FS with 99.1% of this testing category.

In addition, the hysteresis of the sensor is very low at 1.91%, compared to the other sensors with hysteresis values ranging from 2.56% up to 26.55%.

The results presented outline that sensor PR1_IHG_FS is the sensor with the best measuring behaviour and test results for the requirements of further research work planned.

3.3.3.4 Calibration method

After the sensor properties were extensively tested and the sensor with the best sensor properties was selected for further research work, a calibration method for determining the sensor-derived force was developed. In the course of the development work different calibration methods were tested, validated in terms of their applicability and used in laboratory as well as field tests to proof their final applicability. In the following, three calibration methods are presented, that were developed, tested and modified consecutively. To discuss the calibration methods, the advantages and disadvantages of the methods used are described in the following.

The main objective of the research work is defined in the study of biomechanical parameters such as the study of maximum impact forces during a boxing punch. As a result of the research focus on maximum impact forces, the aim of the first calibration method is the analysis of the maximum sensor output values in comparison to the maximum force values determined by the Kistler force plate.

For this purpose, impact tests were carried out on a Kistler force plate and recorded using Vicon Nexus software for motion capture in life sciences. A following evaluation of the recorded data of both, the sensor and force plate data are executed using MATLAB R2018b analysis software.

Figure 38 shows the evaluation of 32 executed impacts with an impact range of 50 to 900N tested with sensor PR1_IHG_FS. These results outline furthermore that the selected sensor does not experience saturation even if the maximum conceivable impact force of 550N on an area of 4.7cm^2 are significantly exceeded. For the development of the correlation equation, the expectable impact range up to 550N was covered as comprehensively as possible. Tests have shown that the analysis of a comprehensive force range for the development of a sensor-specific calibration equation leads to an improvement of the subsequent validation results and therefore an improved overall sensor accuracy. The peak value correlation method as illustrated by the correlation analysis presented in Figure 38, shows a coefficient of determination of R^2 = 0.99 (SD = 0.03) between the sensor-derived conductance and force plate derived force using a fourth order polynomial function.

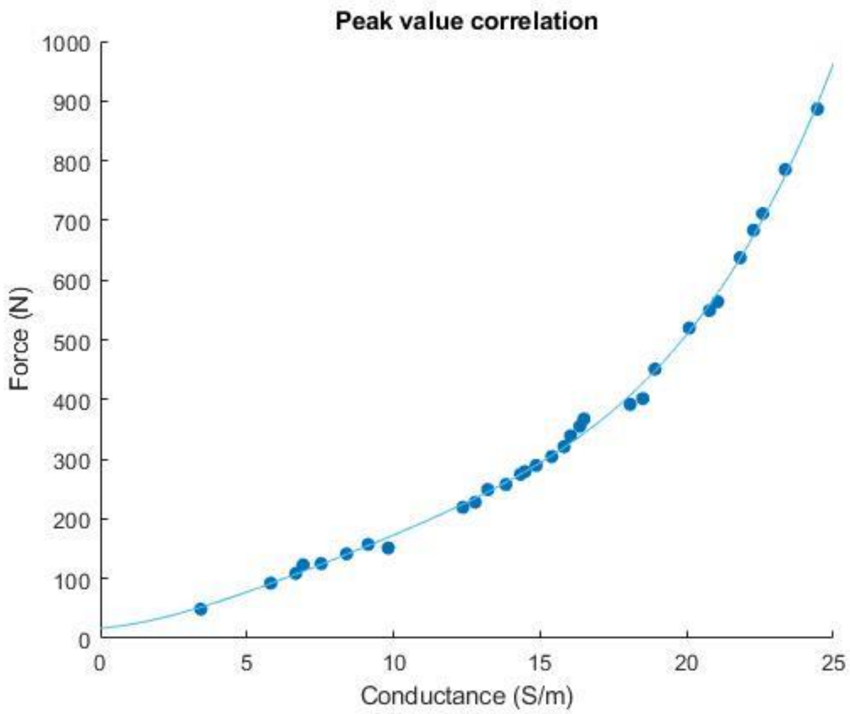


Figure 38: Peak value correlation method

The peak value correlation method has the advantage of a fast outcome generation. With the help of a programmed peak value detection algorithm, the peak data is directly evaluated by the microelectronics connected to the sensor and transferred to MATLAB.

Statistical analysis of the maximum force values of the Kistler force plate and sensor conductance using the coefficient of determination shows a high correlation between the two variables. A disadvantage of this method is the processing of a small number of calibration data. This disadvantage is due to the fact that the calibration method insists on the calculation of maximum peak values and therefore only one corresponding value per stroke is provided for the creation of a calibration routine and later on for the determination of punch force prediction.

To circumvent this limitation of the peak value correlation method, a new method was developed and tested. In the second calibration method, that builds up on the first one, the entire data set of the impact course of the force plate and the sensor is used to develop a sensor-specific calibration equation.

The second calibration method presented includes the analysis of the loading and unloading phases of the individually performed impact tests. For the generation of calibration data, similar to the peak value calibration method, impacts were performed with the sensor placed on a Kistler force plate with the addition of a spacer to achieve a uniform force distribution over the sensors sensitive area. The force range covered the entire potential force spectrum up to 550 N.

In the first step of creating a new calibration method, the entire data of the loading phase of the sensor and the Kistler force plate were examined. For this purpose, in contrast to the method presented before, the entire impact sequence was recorded using the connected microelectronics. Other than in the previous method the automatic calculation of the maximum values using the internal microcontroller was avoided. Instead, the maximum peak value finding routine was used to identify the loading phase and to separate this phase from the unloading phase. The creation of the new calibration routine was again performed using MATLAB. Due to a minor shift of the measurement start of the sensor compared to the force plate, the measuring time and time intervals of the individual force plate and sensor measurements had to be aligned in a first preceding analyses step. Figure 39 presents the loading phase based on the sensor-derived conductance (S/m) compared with the Kistler force plate derived force in Newtons, for a force measurement spectrum up to a maximum of exactly 550 N. The calculated fourth order polynomial fit shows a coefficient of determination of the generated data of $R^2 = 0.99$. The method shows a similarly high correlation as calculated for the previously presented peak value correlation method.

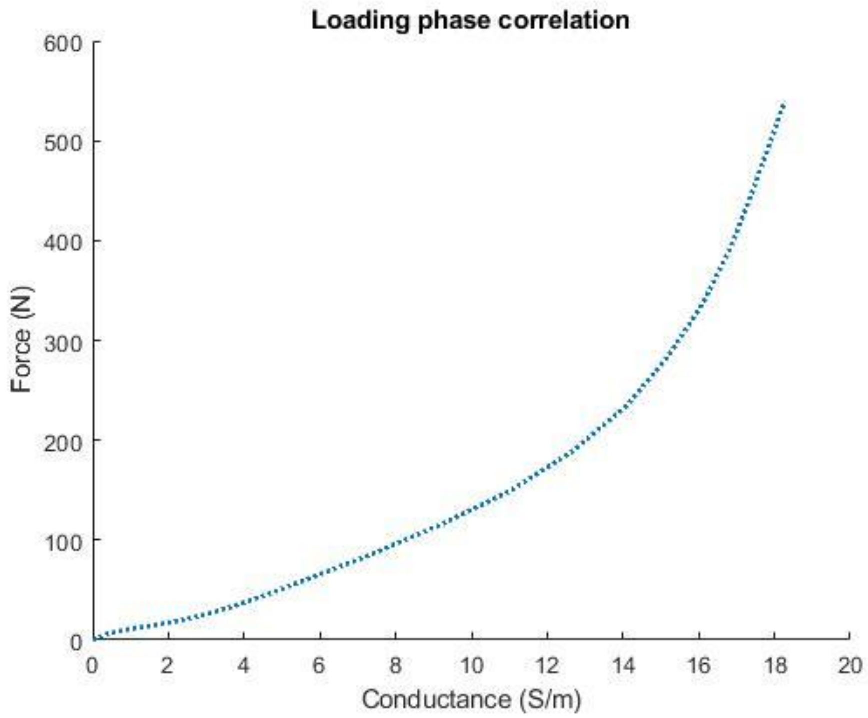


Figure 39: Loading phase correlation method

For a more detailed analysis of the impact pattern the method was extended in a further step. Therefore, the unloading phase was subsequently also taken into account in addition to the loading phase. For this purpose, the correlation was separately calculated for the unloading phase in a second step. The investigation of the unloading phase is illustrated in Figure 40. The data shows an equally high correlation of the analysed correlation between the sensor-derived output and force plate derived output of R^2 = 0.99. This correlation is in fact marginally better than for the loading phase.

The new calibration routine is used to extend the amount of measurement data included in the calibration routine, because unlike the peak value calibration method, the entire data set of the loading as well as the unloading phase is used. This extension of the data range creates a more stable calibration routine against outlier recorded e.g. in the peak value calibration routine. In addition, the method serves to extend the data understanding of the overall impact pattern and the holistic investigation of the stroke course.

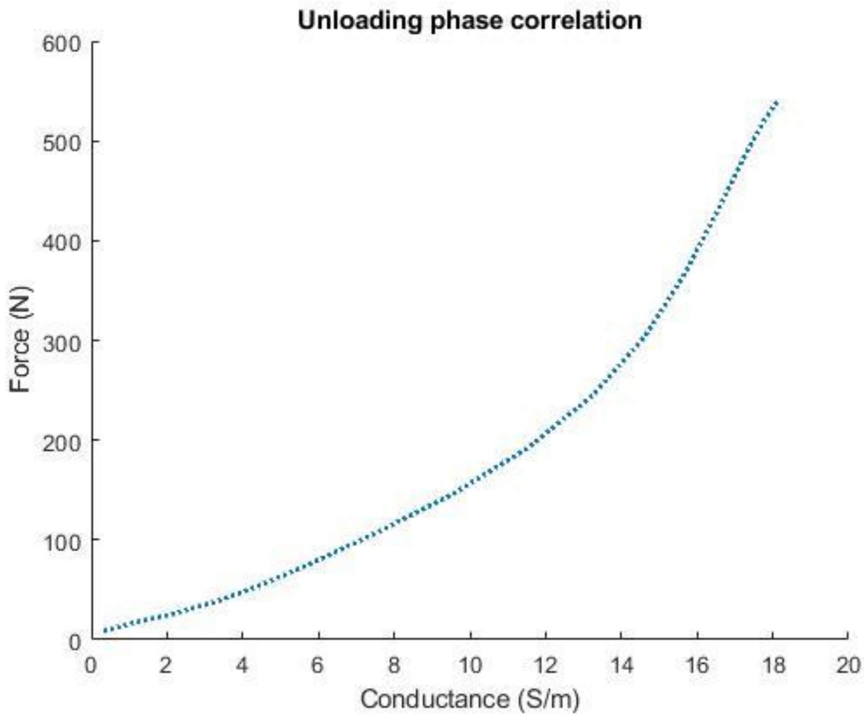


Figure 40: Unloading phase correlation method

A disadvantage of the separated loading and unloading calibration method is the process-related time-consuming data processing. This process-related time expenditure becomes apparent as soon as the calibration routine has to be processed on the internal working memory of the microcontroller. The time expenditure is a result of the separation into the two loading and unloading phases in order to use separated specific calibration routines during the sensor operation.

The collected findings from the development of a calibration routine were incorporated into the further development of a new calibration routine. The new calibration method should above all enable easier data processing with an unchanged correlation result.

As a result, a uniform calibration routine was developed, that takes both phases into account, loading and unloading and uses the entire data set to combine it into one calibration routine. A fourth order polynomial fit function is used for the correlation of the loading and unloading phase of the new calibration routine as presented in Figure 41. The result shows an equally high coefficient of determination value of $R^2 = 0.99$ between the force plate derived and sensor-derived measurement output. The statistical results were not significantly lower than the two calibration routines presented before.

Moreover, the routine has important advantages to the previous methods. The increased amount of data points used, makes the calibration routine more stable and repeatable. Furthermore, the routine shows a faster data processing. The faster data processing is due to the fact that the collected data no longer have to be separated for calculation and only one overall calibration routine is used for further calculations and embedded data processing.

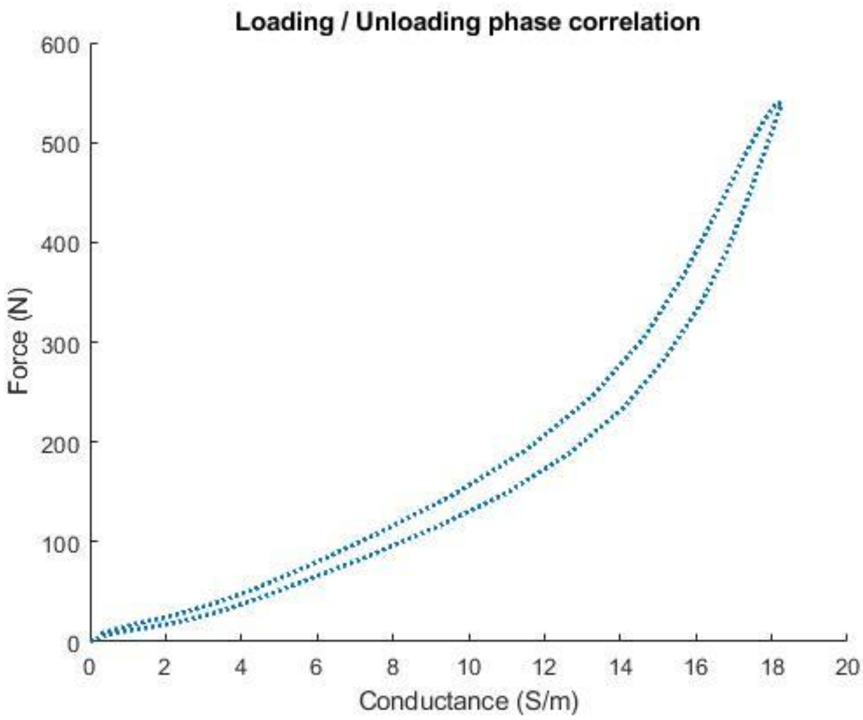


Figure 41: Loading and unloading calibration routine

3.3 Three-dimensional motion determination with inertial and magnetic sensors

An important part for the measurement and analysis of boxing related biomechanical parameters is the determination of the boxer's fist movement in three-dimensional space as it is the most important body part for the sport of boxing when striking the opponent. Except the determination of punch forces for the measurement and analysis of boxing biomechanics it is of great interest to investigate the kinetic motion of the fist in three-dimensional space to quantify performance, technique and furthermore emerging injuries. Therefore, inertial measurement sensors are used to determine the motion of the boxing glove in action within a portable monitoring tool. The movement in three-dimensional space is constituted by the two mechanisms of translational and rotational motion.

A movement in three-dimensional space is the resultant displacement within the six degrees of freedom around the three translational and rotational axes of the body in x, y and z. The positioning and orientation of the glove can be determined if all movements of the body are detected within the time interval Δt.

The translational locomotion is defined as a rectilinear displacement in which a body moves on a straight line or on an arbitrarily arched curve in space. Thereby all mass points are dragged on parallel lines (Wick, 2009). The displacement can take place in positive or negative direction depending on the reference system setup. This displacement is characterized by the rate of change of the position in space. A typical translational movement in the sport of boxing is the cross punch, which is characterized by a predominantly straight acceleration of the fist to the target. A representation and detailed description of the coordinate system is presented in chapter 3.4.

Specific sensor systems are required in order to be able to determine the motion and orientation of the boxing glove in three-dimensional space by the presented mathematical methods in the following chapter. For this purpose, a set of microelectromechanical systems (MEMS) were selected to achieve the best results.

The term inertial sensor is used for sensors based on the principle of the mass moment of inertia to measure forces. These forces are translational and rotational forces that are measured by an accelerometer and gyroscope. The two sensor systems are used in a first stage during the work of this doctoral thesis. Subsequently, the developed sensor system was extended by a magnetometer sensor and a second accelerometer. Therefore, chapter 3.3 presents the technical principle as well as the applied calibration and validation methods of the selected embedded sensors into the developed monitoring system.

3.3.1 Design and development of an angular rotation validation device

In order to verify the programmed inertial sensor system for the determination of the rotational accuracy, it was necessary to check the entire rotational spectrum by 360° in all three axes x, y and z. This step was executed, after first tests with prefabricated wooden appliances were performed. For these requirements an angular rotation validation device was designed and constructed as presented in Figure 42. The primary goal of the device is to allow a 360° rotation in three axes of the sensor without external interference in order to be able to make quick adjustments in the programming of the developed wearable device. The device was used for a quick check of the rotation angles before an all-encompassing and sports-oriented validation with a Vicon motion capture system was performed. The design of the testing device is based on a cardanic suspension. The mounting plate is a rotation disk that carries the actual structure of the gimbal. This suspension has a fixed outer part that carries two further components. The two additional suspensions are each displaced by 90° in their mounting axes. Bearings are used to ensure friction free rotation of the individual core elements of the cardanic suspension. The entire device is designed in order that each element can be rotated about 360° without being restricted by the respective outer suspensions. The inertial sensor is attached to the innermost suspension by means of a sensor holder, thus enabling a contact-free rotation.

The angular validation device is constructed without ferrous materials that can cause errors to the magnetic sensor due to soft- and hard iron interferences. The test apparatus was therefore constructed with materials such as aluminium and extruded dark grey PVC-U, that relative magnetic permeability is as low as possible to avoid material interferences. In addition, a stand of 750 millimetre length is used to reduce the effect of ferrous materials build in floors such as steel beams or power cords that cause an electromagnetic field that is affecting the magnetometer reading and therefore the measuring accuracy of the sensor device following the recommendations by Bachmann et al. (2004).

The design of the adjustment disc allows the validation of static angular rotation steps of 15°, instead of angular rotation steps of 45° as it was achieved with the wooden appliance used in the previous step. This allows a more detailed validation and furthermore, the ability for static testings over a long period of time without change in angular displacement. In addition, adjustment pins are used to prevent over rotation of the individual gimbals and therefore lowering the cause of validation errors.

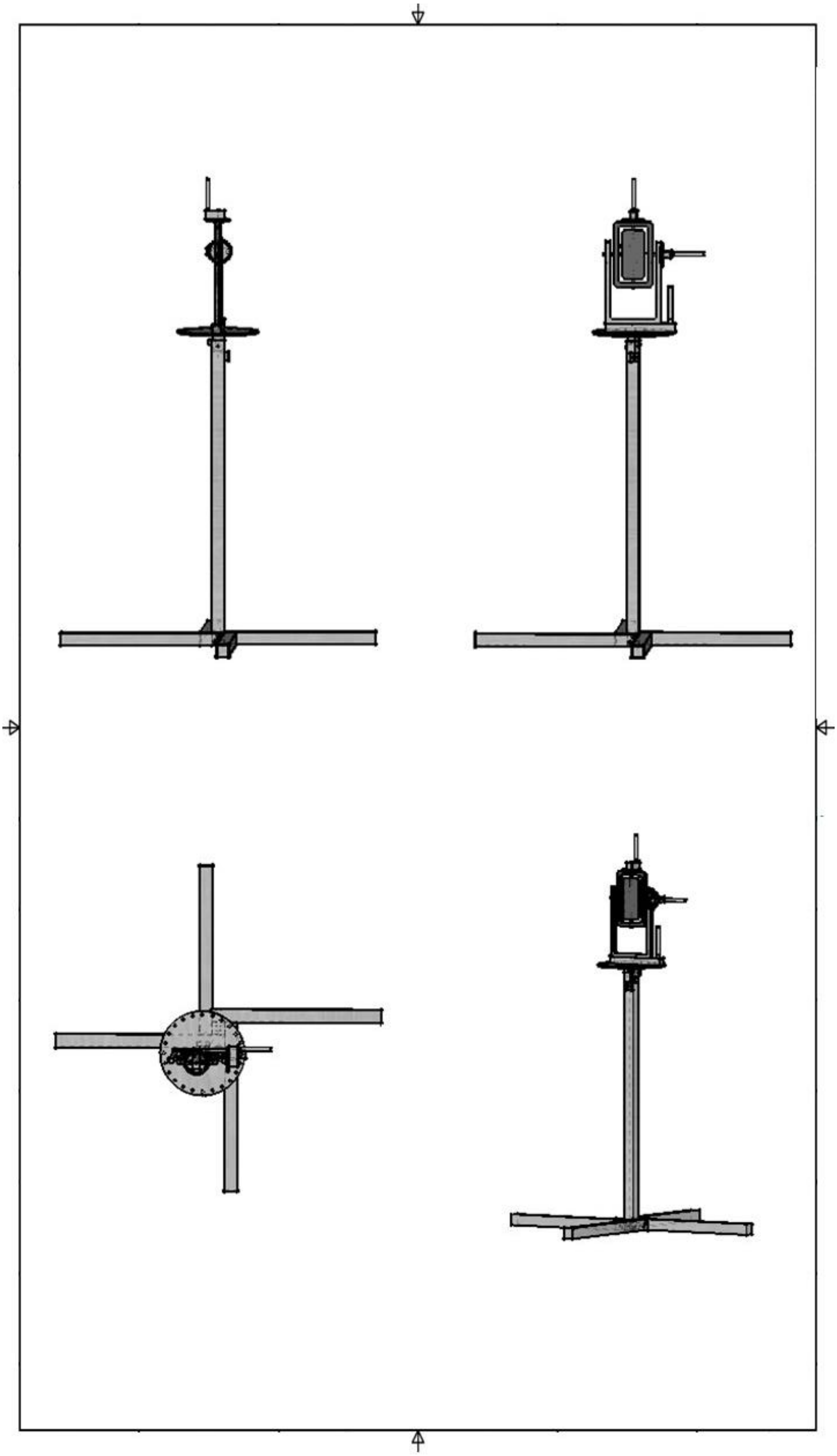


Figure 42: Angular rotation validation device

3.3.2 Design and development of an acceleration validation device

In sports, acceleration sensors are subjected to great levels of acceleration. Martial arts disciplines in particular have a large dynamic acceleration range due to the explosive striking movements of the fists. For a comprehensive validation of the acceleration sensor, the developed wearable sensor needs to be validated on its entire possible acceleration range that it can be subjected to during a boxing punch with an additional buffer. In the presented application, for an acceleration range of ± 200g.

For the validation of the acceleration, the sensor must be accelerated linearly with a constant acceleration over a defined period of time to generate sufficient measurement data for validation purposes. To achieve this, the ideal setup would be to accelerate the sensor along a straight line at the desired acceleration rate. Since this is not possible, a special validation device is required due to the large dynamic measuring range. A practical approach to validate the acceleration sensor is to use a rotational centrifuge (Acar & Shkel, 2003; Dong et al., 2018; Revel, 2011; Sporn, 1961). The use of a rotary centrifuge takes advantage of the centripetal acceleration that occurs when an object is rotated at a distance, greater than zero, from the axis of rotation (equation 12).

$$a = \omega^2 \cdot r$$

Equation 12: Centripetal acceleration

Therefore, the purpose of chapter 3.3.2 is the detailed description of the designed and developed validation device for the validation of the full measuring range of the acceleration sensors used.

The constructed and designed centrifugal device is presented by Figure 43. The materials used were carefully selected to ensure that the centrifuge did not produce hard and soft iron effects that could falsify the extraction of the gravitational acceleration within the inertial measurement unit. In addition, the design was a lightweight construction to avoid additional load on the motor by the weight of the rotating disc. The materials used to manufacture the validation device was mainly extruded dark grey PVC-U plastic. In addition, drawn aluminium (AlCuMgPb) and rolled aluminium (AlZnMgCu1.5) were used for the mounting of the motor and the ball bearing drive shaft of the motor.

The mounting of the centrifuge and the motor was fixed on a plastic PVC-U base plate. A VEXTA® Brushless DC Motor (AXH015K-A) from Oriental Motor's USA Co. Ltd. (Torrance, CA, USA) drove the centrifuge plate from the base plate via a ball-bearing shaft. The ball-bearing shaft enabled the transmission of the rotational movement of the motor to the sensor platform without interference, even at high revolutions per minute (RPM). This design construction enabled the acceleration generation without stressing the engine shaft and causing damages to the motor or a deterioration of the exact rotational transmission. The entire design of the turntable was made from extruded dark gray PVC-U plastic to reduce the overall weight and mass moment of inertia of the turntable, which must be driven by the motor.

The rotation plate consists of a rotation disk that allows the acceleration sensor to be mounted in two ways. On the one hand, the sensor can be mounted flat on the centrifuge plate or with the help of a 45° mount on the rotation disc. With the help of the 45° sensor mount, the centrifuge allows the generation of measurement data of several axes at the same time. Thus, the device allows a sensor to be run flat for individual acceleration validation of each axis individually, or the sensor can be tested in several axes simultaneously using the 45° adapter.

During the design of the sensor system on the centrifuge plate, it was ensured that the deviation of the sensor would maintain the same distance from the centre of rotation in all axes by using a mounting template to which the sensor was attached. Consequently, in any configuration of the individual axes, the sensor is 83 mm in distance, with a maximum deviation of ± 2 mm from the centre of the rotational axis. Based on the distance r to the center of rotation and the 14 acceleration levels determined for validation and data generation, Table 4 presents the number of revolutions the system has reached for the individual acceleration levels.

Due to the characteristics of the motor used, a validation in two steps was already planned during the development of the rotary centrifuge. These two steps describe the acceleration in positive and negative direction of the respective sensor axes. This is due to the fact that the motor is slowly increasing the acceleration from low RPM for the lower acceleration ranges up to a rotational acceleration of 200g. After completion of the first validation phase, the centrifuge is brought to a standstill and the sensor is prepared for validation in negative direction.

To ensure the generation of sufficient data points of the individual acceleration stages a constant feedback loop is necessary to control the motor acceleration. This ensures that as soon as an acceleration stage is reached, the microelectronics maintain the motor at a constant rotational speed. At rotational revolutions per minute of up to 1468 RPM the centrifuge requires a special mounting and support to prevent vibrations and deflections of the centrifuge. For this purpose, the centrifuge was fastened with the application of screw clamps to a laboratory table anchored in the floor and reinforced with struts. This mounting allows to avoid the vibrations of the motor on the platform and thus to prevent measuring inaccuracies detected by the acceleration sensors.

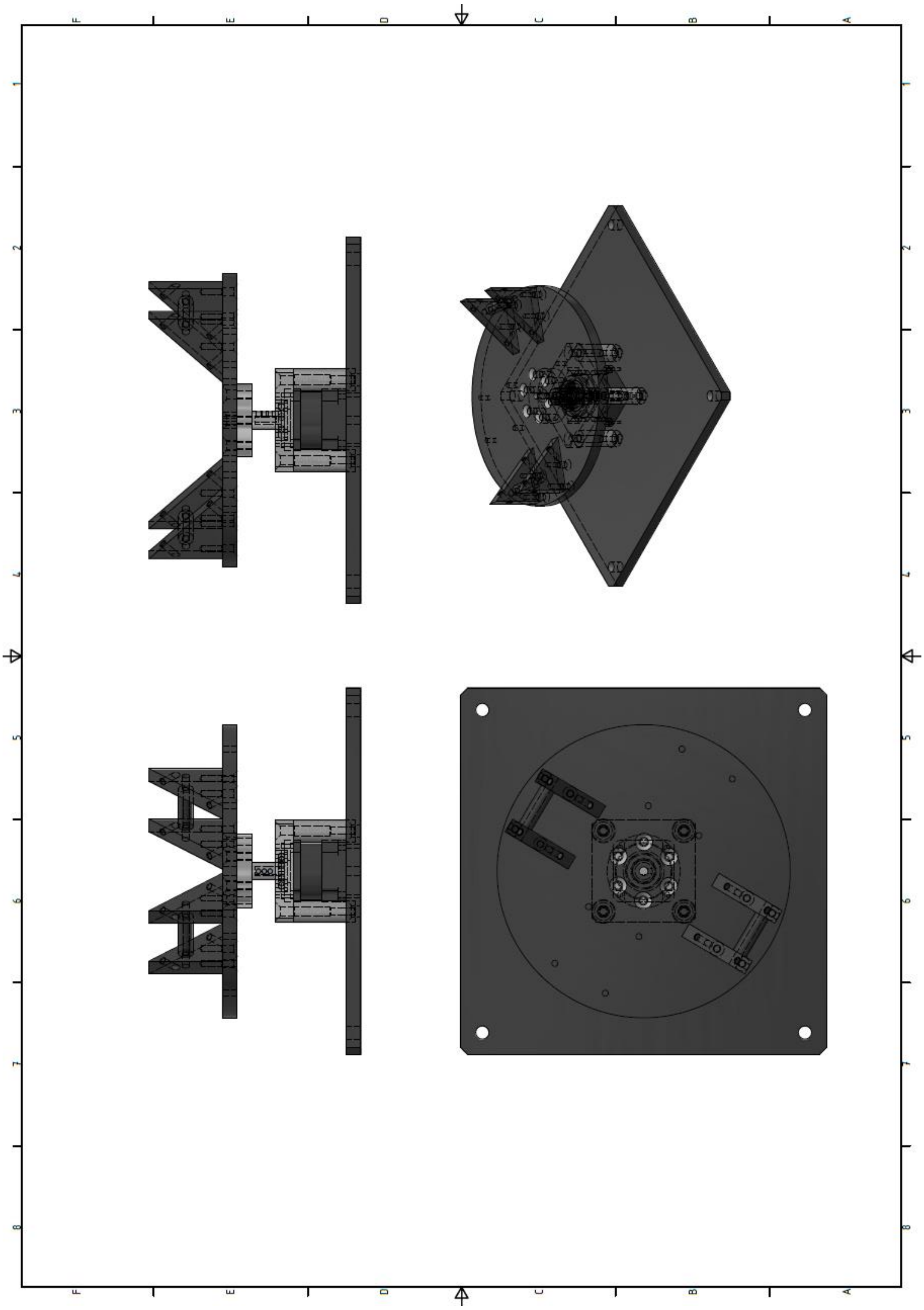


Figure 43: Design of angular acceleration validation device (centrifuge)

Table 4: Desired acceleration in RPM for the developed centrifugal device

Desired Acceleration (G)	Angular Velocity (°/s)	RPM
200.00	8812.53	1468.76
180.00	8360.30	1393.38
160.00	7882.17	1313.69
140.00	7373.09	1228.85
120.00	6826.16	1137.69
100.00	6231.40	1038.57
80.00	5573.53	928.92
60.00	4826.82	804.47
40.00	3941.08	656.85
20.00	2786.77	464.46
16.00	2492.56	415.43
12.00	2158.62	359.77
8.00	1762.51	293.75
4.00	1246.28	207.71
0.00	0.00	0.00
-4.00	1246.28	207.71
-8.00	1762.51	293.75
-12.00	2158.62	359.77
-16.00	2492.56	415.43
-20.00	2786.77	464.46
-40.00	3941.08	656.85
-60.00	4826.82	804.47
-80.00	5573.53	928.92
-100.00	6231.40	1038.57
-120.00	6826.16	1137.69
-140.00	7373.09	1228.85
-160.00	7882.17	1313.69
-180.00	8360.30	1393.38
-200.00	8812.53	1468.76

3.3.3 Accelerometers

The first sensor used within the inertial measurement unit is an acceleration sensor. These types of sensors are used, to measure an objects acceleration in motion along the reference axes. The measurement of physical activity using accelerometers is a common method since the acceleration is proportional to the extrinsic force and thus can be used to reflect the intensity and frequency of physical locomotion (Yang & Hsu, 2010).

3.3.3.1 Technical principle

The term acceleration a describes the change in velocity d_v of an object and is determined by the first derivation of the velocity over time dt (Hering & Schönfelder, 2018). This acceleration can also be defined as translational acceleration a_{trans} (equation 13).

$$a(t) \ or \ a_{trans} = \frac{dv(t)}{dt} = \frac{d^2x(t)}{dt^2}$$

Equation 13: Translational acceleration

a acceleration

dv change in velocity over time t

dt period of change of velocity s

x distance travelled within time t

In addition, the rotational acceleration (equation 14) a_{rot} can be calculated by the derivation of the angular velocity w over time dt. The angular velocity is therefore calculated by the derivation of the angel φ over time t.

$$a(t) \ or \ a_{rot} = \frac{dw}{dt} = \frac{d^2\varphi}{dt^2}$$

Equation 14: Rotational acceleration

The acceleration is essentially based on Newton´s second law of motion (equation 15) that states, the change in motion is always proportional to the applied driving force and occurs in the direction of the corresponding line in which the force is applied to. Therefore, F is representing the accelerating force that is measured and m is defining the accelerated mass of the accelerating object (Newton, 1729).

$$F_a = m \cdot a = m \cdot \frac{d^2x}{dt^2}$$

Equation 15: Newtons second law of motion

Acceleration can be measured in positive direction as well as in negative direction. Both orientations are important for the biomechanical analysis of a punch thrown to analyse the acceleration of the fist until impact as well as the retraction phase back in to the defensive position.

These days, accelerometers are one of the most common sensor systems used in industry. Acceleration sensors can be distinguished among capacitive, piezoelectric and piezoresistive sensor devices. Although the theoretical assumption of all acceleration sensors is the mass-spring principle.

A problem when working with piezoelectric acceleration sensors is the type of current used. Piezoelectric accelerometer devices use an alternating current. Especially when working with microelectromechanical systems where direct current is used, alternating current poses, due to its incompatibility with direct current, a major drawback. Benefits of capacitive differential accelerometers include low power consumption, high output level and response to motion. Due to the low noise level of capacitive sensing, superior sensitivity is achieved (Yang & Hsu, 2010). For this reason, as well as the use of direct current, a capacitive accelerometer unit was selected for the incorporation into the developed monitoring system.

Capacitive acceleration sensor systems consist of a seismic mass in the centre of the sensor device. The seismic mass is connected by polysilicon springs with a known suspension rate to the casing of the inertial measurement unit. Furthermore, the sensor is attached to a specific cushioning appliance or surrounded by damping material as for example air, that encompasses the mass unit.

The inertia of the mass causes the spring to be stretched or compressed if the accelerometer is put into motion (Hering & Schönfelder, 2018). The sensor is following Hooke’s law of elasticity as long as the spring force is proportional to the change in length of the spring. The theorem of Hooke´s law states that the force F which causes an expansion or compression, is linked to the change in length (Δx) by a proportional constant k (equation 16). The constant k is the constant of the spring used within the spring mass principle of the acceleration sensor (Hering & Schönfelder, 2018).

$$F_s = k \cdot \Delta x$$

Equation 16: Hooke´s law

Hooke's law is occasionally formulated as (equation 17). Where F no longer represents the applied force, but the equal and opposite restoring force that causes elastic materials to recover to their original dimensions (Britannica, 2019b).

$$F_s = -k \cdot \Delta$$

Equation 17: Hooke’s law

The motion of the seismic mass of the accelerometer is affected by the damping appliance or material used. In most applications air is used as damping material. Therefore, air is exerting a damping constant λ to the seismic mass. The damping force F_D, exerted inside the sensor, can be calculated by multiplying the applied velocity v by the damping constant λ. The force and velocity vector elements appeal in opposite direction to each other (equation 18).

$$F_D = -\lambda \cdot \mathrm{v} = -\lambda \cdot \frac{\Delta x}{\Delta t}$$

Equation 18: Damping force

The spring pendulum represents in combination with the damping appliance and the acting force a classical 2nd order mechanical oscillation system (Hering & Schönfelder, 2018).

$$F_{ext} = m \cdot a = m\frac{\Delta x^2}{\Delta t^2} + \lambda\frac{\Delta x}{\Delta t} + k \cdot x$$

The presented equations are used to describe the physical principle of capacitive acceleration sensors. For the determination of acceleration, it is necessary to convert the physical values into electrically measurable values that allow the quantification of the acceleration within an electrical setup. Capacitive acceleration sensors are based on the spring mass principle. Therefore, the mass is connected as an electrode between two parallel-plate capacitors C_1 and C_2. The two parallel-plate capacitors are connected to the case whereas the seismic mass is connected by a spring that moves between two parallel-plate capacitors and is therefore flexible. The capacitors are aligned along the sensitive axis to detect a displacement of the seismic mass by a change of capacity. Both parallel-plate capacitors have the same distance to the mass as well as the same capacity C, that is the quotient of the electric charge Q and the electric voltage V, or the dielectric constant ε, the distance d and the surface area A, if no force and therefore no acceleration is applied to the sensor (equation 19) (Demtröder, 2013).

$$C = \frac{Q}{V} = \varepsilon_0 \cdot \frac{A}{d}$$

Equation 19: Electrical capacity

The distance of the capacitors to the seismic mass can be defined as d_0 when no force is applied. Once a force is applied that causes a displacement of the seismic mass, both distances of the capacitors to the mass are changed by the equal proportion d (equation 22). The capacity for the capacitors is calculated by equation 20.

$$C_1 = C_0 + \Delta C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d_0 - \Delta d} \quad C_2 = C_0 + \Delta C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d_0 + \Delta d}$$

Equation 20: Electrical capacity of two capacitors within capacitive acceleration sensor

ε_0 is representing the absolute permittivity of free space and ε_r the relative permittivity of free space to allows the calculation of the permittivity ε (equation 21).

$$\varepsilon = \varepsilon_0 \cdot \varepsilon_r$$

Equation 21: Permittivity

The absolute displacement can be calculated by rearrangement and the equation of the capacities $C_1(d_0 + d) = C_2(d_0 - d)$ to calculate the absolute displacement of the seismic mass for the determination of acceleration by equation 22.

$$d = d_0 \frac{C_2 - C_1}{C_1 + C_2}$$

Equation 22: Absolute displacement

The two selected 3-axis accelerometers using each three accelerometers in an orthogonal direction to each other with separate test masses for every axis. The acceleration along one particular axis leads to a displacement of the corresponding test mass, where the capacitive sensors detect the displacement for the measurement of the objects acceleration in x, y, and z direction (InvenSense Inc., 2014).

Not only the mechanically determined displacement Δd has a hyperbolic dependency on the sensor's capacity. In addition, the displacement and its effect on the capacitors alter the output voltage V_o within the accelerometers bridge circuit.

$$V_o = \frac{V_I}{2} - V_I \frac{\frac{1}{C_2}}{\frac{1}{C_2} + \frac{1}{C_1}} = V_I \left(\frac{1}{2} - \frac{C_1}{C_2 + C_1} \right) = \frac{V_I}{2} \left(\frac{C_2 - C_1}{C_2 + C_1} \right)$$

Equation 23: Output voltage

By rearranging equation 23 under consideration of equation 20 it is possible to calculate the linear dependency of the output Voltage from the displacement of the spring mass principle. This displacement is proportional to the force of inertia (equation 15) and allows the direct measurement of the acceleration with the known seismic mass of the sensor (Schmidt, 2007).

$$V_o = -V_o \frac{\Delta x}{2d_0}$$

Equation 24: Output voltage

MEMS acceleration sensors are micronized sensors. Therefore, the provoked displacement is in a micrometre range with a small change in capacity. To increase and maximize the detected change in capacity, the sensors are built with parallel connected capacitors as shown in Figure 44.

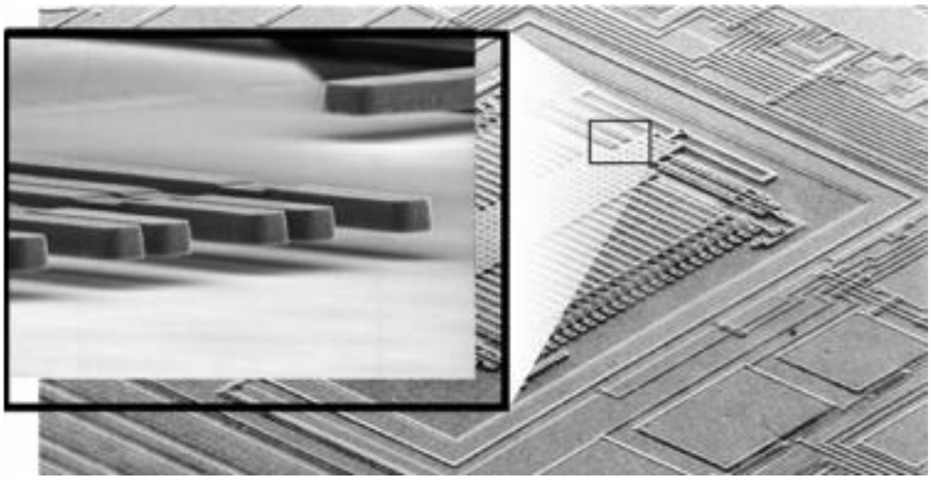


Figure 44: A scanning electron microscope (SEM) image of an inertial MEMS accelerometer (Spencer, 2019).

3.3.3.2 Calibration

In order to guarantee a high measuring accuracy and reliability of the measuring system to be developed, the acceleration sensors used must be calibrated. A precise calibration of the sensors is important to compensate for systematic errors in the system, such as bias and scale factor errors. During the calibration process, the raw data of the acceleration sensors are corrected for errors in order to achieve a higher measurement accuracy. The calibration of the acceleration sensors was performed by determining the individual axis dependent bias for the x, y and z axes and the sensitivity specific resolution of the sensors at a 1,000 Hz measuring frequency and the use of a 200 Hz low-pass filter. The bias of the acceleration sensor is defined as the offset of the output signal from the actual real acceleration. The offset bias is independent of external forces. It is possible to calculate the offset bias and compensate for this type of error by calculating a long-term average of the individual axis output signals when the sensors are at rest. The calibration equation used for the calibrated acceleration sensor output can be expressed as equation 25.

$$A_c = A_{raw} \times A_{res} - A_{bias}$$

Equation 25: Calibrated acceleration output

The final calibrated acceleration sensor output value, A_c, is therefore calculated from the measured raw value, A_{raw}. For this purpose, the acceleration raw value, A_{raw}, is multiplied by the sensor specific resolution, A_{res} and subtracted by the axes individual offset bias A_{bias}. The calculation of the sensor specific resolution depends on the scale factor of the sensor used, provided by the manufacturer and allows for the compensation of scale factor errors. The scale factor is divided by 32768.0, declared as an unsigned 16-Bit integer, for the calculation of the sensor resolution (equation 26).

$$A_{res} = \frac{Scale\ factor}{32768.0}$$

Equation 26: Acceleration resolution

The sensor offset bias of the acceleration value is calculated by the sum of the measured raw output data while the sensor is at rest. The summed acceleration bias is then divided by the number of data points measured to calculate the average of the determined data and divided once again by the sensitivity scale factor pre-defined by the manufacturer (equation 27).

$$A_{bias} = \left(\frac{\sum_{i=1}^{n} xi}{n}\right) / \ Scale\ factor$$

Equation 27: Acceleration bias

The presented calibration process was applied to all three axes x, y and z. Figure 45 is presenting the calibrated acceleration data obtained for the three axis.

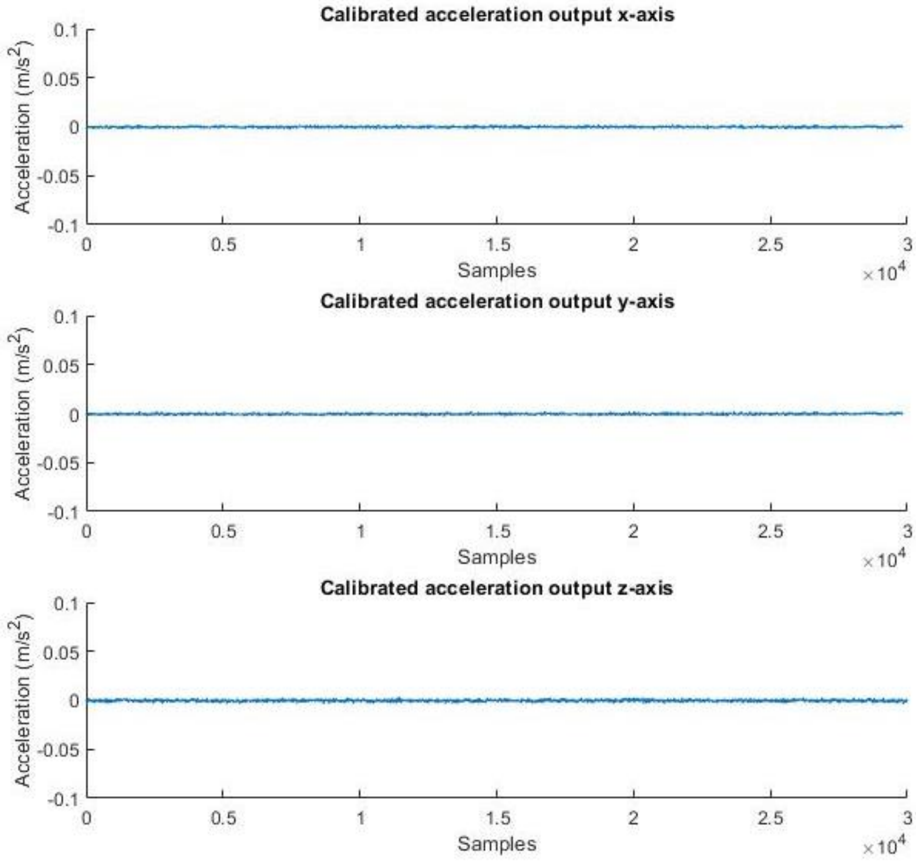


Figure 45: Calibrated acceleration output x, y and z-axis

3.3.4 Gyroscopes

To determine the orientation of the boxing glove in three-dimensional space it is important to detect the angular movement of the system. The following chapter is used to give an introduction about angular rate sensors, so-called gyroscopes and their physical measurement principle that is important to consider for the calibration and validation process and ultimate use of the sensor for the determination of the fist orientation in three-dimensional space.

3.3.4.1 Technical principle

Angular rate sensors were first discovered by Johann Gottlieb Friedrich von Bohnenberger, a professor of physics, mathematics and astronomy at the University of Tübingen, Germany in 1817 for the tilt determination of ships in relative position to the sun. The developed angular rate sensor was simply called a machine and was therefore introduced as the “machine of Bohnenberger” (Wagner & Trierenberg, 2010, p. 1). A few years later the nowadays known term of a gyroscope was introduced. The term gyroscope is based on the two Greek words “scopeein” with the meaning to display and “gyros” the Greek term for rotation. The French scientist Léon Foucault has created in the early stage of the 19th century the coinage “gyroscope” by combining these two terms. Foucault used the principle of Bohnenberger’s machine to demonstrate earth rotation, before other industries started to further develop and use gyroscopes in the early years of the 20th century (Acar & Shkel, 2009). The first gyroscopes, such as the Sperry gyroscope, together with many modern gyroscopes, use a rotating impulse wheel attached to a gimbal structure. Rotating wheel gyroscopes, nonetheless, had many disadvantages, especially in terms of bearing friction and wear. Gyroscopes based on vibration technology, such as the Hemispherical Resonator Gyroscope (HRG) and Tuning-Fork Gyroscopes, offered an effective solution to the bearing problems by avoiding the need for rotating elements. Advanced alternative technologies like fiber optic gyroscope (FOG) and ring laser gyroscope (RLG) operating on the Sagnac effect were also developed. Overcoming virtually all mechanical constraints such as vibration and shock sensitivity as well as friction, the optical gyroscope is used in many high-end applications even though they are very expensive (Acar & Shkel, 2009, pp. 4–5).

The most common used and for this thesis selected gyroscope is the micro electro mechanical system (MEMS) type gyroscope. This type of sensor was selected due to its small size, weight, low cost, power consumption, production costs and great reliability. Key factors for the technical development of wearable systems.

Gyroscope systems measure angular rate in rad per second, expressed in degrees per second (equation 28).

$$(1\frac{rad}{s} = \frac{360°}{2\pi} = \frac{180°}{\pi} \approx 57.296°/s)$$

Equation 28: Rad to degrees per second

The angular rate is detected within the body frame, with respect to the inertial frame. The operating principle of most of the MEMS gyroscopes is the use of mechanical vibrating elements. An important effect for the execution of MEMS gyroscopes is the sinusoidal Coriolis force F_C, named after the French scientist and engineer G. G. de Coriolis (1792-1843) (Yazdi et al., 1998). The Coriolis force is an apparent force that occurs in a relatively moving, rotating reference system that causes a lateral deflection of an oscillating mass and is proportional to the degree of rotation (Yazdi et al., 1998). The Coriolis force F_C can be calculated by the oscillating mass m, the angular velocity of the reference system ω and the velocity of the body v under consideration of the reference system by equation 29 (Tipler & Mosca, 2015, p. 128).

$$\vec{F_c} = m \cdot a_c = -2m \cdot (\vec{v} \times \vec{\omega})$$

Equation 29: Coriolis force

The amplitude A and frequency f of the oscillating mass of the gyroscope sensor is necessary to determine the angular velocity by equation 30 (Füldner, 2012, p. 25).

$$\omega = \frac{a_c}{4 \cdot \pi \cdot f \cdot A}$$

Equation 30: Angular velocity

Vibrating gyroscopes operating by the use of a proof mass similar to the technical design of an acceleration sensor. Earlier MEMS gyroscopes have used vibrating quartz crystals to produce the necessary motion. Nowadays, the vibrating structured elements are poured into silicon for the mechanical design (Acar & Shkel, 2009).

The foundation of all vibratory gyroscopes is the energy transfer between two modes of vibration within the gyroscopes structure, as a result of the Coriolis acceleration (a_c). The Coriolis acceleration being an apparent acceleration, that occurs in a rotating reference frame and is to be measured proportional to the rotational speed (Yazdi et al., 1998).

In terms of the mechanical design of gyroscope sensors, the proof mass is connected by flexible elements to the case allowing the proof mass to oscillate versatile in two orthogonal directions. The two orthogonal directions are called the drive and the sense direction. The drive direction is working as a vibratory oscillator and the sense direction as a Coriolis accelerator. The general dynamic system corresponds to a simple mass-spring-damper system with two degrees of freedom (2-DOF) (Acar & Shkel, 2009) similar to the accelerometer as outlined in chapter 3.3.3.

The implementation of spinning gyroscopes for MEMS sensors never became successful due to the rotary parts that use bearings to prevent friction and wear (Acar & Shkel, 2009).

A mass-independent equation for the Coriolis acceleration a_C can be generated since the mass m of the measuring unit on which the Coriolis force F_C is induced can be assumed to be known (equation 31).

$$\vec{a}_c = 2 \cdot (\vec{v} \times \vec{\omega})$$

Equation 31: Coriolis acceleration

Once a rotating force is applied to the sensor that causes an angular rotation, the gyroscopes proof mass is resonating in one direction, creating a force in perpendicular direction due to the Coriolis effect. The sensor plates that are decoupled from the proof mass are orientated in a perpendicular direction to the oscillating alignment to measure the acting Coriolis acceleration a_C. The Coriolis acceleration is increasing, as the proof mass is displaced further from the center of rotation.

A change in capacity is detected by means of a capacitive system, as it is used in an acceleration sensor and stated in chapter 3.3.3. The oscillating mass provides different values on the opposite sides of rotation of the proof mass in which the change in capacity produced, is proportional to the rotational rate.

Based on this, the rotation velocity can be determined as a current that is induced as force by the Coriolis effect, due to the proportional rate of rotation. The signal is forwarded either as an analog signal that is equivalent to the rotation rate, or as a digital signal through an internal analog-to-digital converter (ADC).

The illustration Figure 46 of a modern gyroscope indicates that this type of system measures the rotational velocity only in one direction. The operating principle of a modern gyroscope is that, if the gyroscope rotates to an angular direction, a sinusoidal Coriolis force is induced at the frequency of the drive mode oscillation in the direction of sense. Thereby, the Coriolis force excites the sensing mode and causes the proof mass to respond in the direction of sense. As a result, the sinusoidal Coriolis response is detected by the sensing electrodes and transferred into an electric output (Acar & Shkel, 2009).

Therefore, three gyroscopes are required to measure the rotation velocity in all three degrees of freedom. The gyroscopes are therefore arranged in perpendicular orientation to each other to measure the angular rotation in x, y and z direction. This assembly of sensors is important for the determination in 3-dimensional space.

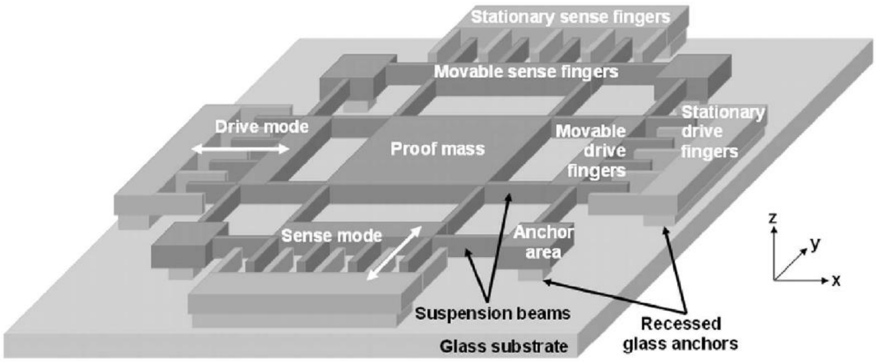


Figure 46: Illustration of MEMS gyroscope (Alper & Akin, 2005, p. 708)

Finally, the integration of the angular rate ω measured in degrees per second with respect to the time interval Δt results in the measured path angle (InvenSense Inc., 2019), indicated by degrees (equation 32). Equation 33 to 34 are used to determine the angle respectively to the yaw (ψ), pitch (ϕ) and roll (θ) angles of all three axes.

$$\alpha = \int_{t_0}^{t} \omega \cdot \Delta t$$

Equation 32: Angular rate

$$\psi = \int_{t_0}^{t} \omega_{\psi} \cdot \Delta t$$

Equation 33: Angular rate yaw

$$\phi = \int_{t_0}^{t} \omega_{\phi} \cdot \Delta t$$

Equation 34: Angular rate pitch

$$\theta = \int_{t_0}^{t} \omega_{\theta} \cdot \Delta t$$

Equation 35: Angular rate roll

3.3.4.2 Calibration

Before the measurement system to be developed can meet the requirements of high measurement accuracy and reliability, the gyroscope used must be calibrated similar to the acceleration sensor. The calibration of the angular rate sensor is used to compensate for systematic errors in the system, such as bias and scale factor errors. During the calibration process, the raw data of the angular rate sensor is adjusted for errors to achieve the required measurement accuracy for the determination of the fist orientation in three-dimensional space. The calibration of the angular rate sensor was performed in the identical procedure as the calibration process was conducted for the acceleration sensors at a 1,000 Hz measuring frequency and by use of a 200 Hz low-pass filter. The calibration of the three orthogonal axes x, y and z is based on the sensitivity specific resolution and the gyro offset bias. The offset bias of the angular rate sensor is defined as the deviation of the real angular rate when the sensor is in idle state. As with the calibration of the acceleration sensor, the gyroscope offset bias is calculated by taking a long-term average of the individual axis output signals. The equation used to calibrate the angular rate sensor can be expressed as equation 36.

$$G_c = G_{raw} \times G_{res} - G_{bias}$$

Equation 36: Calibrated gyroscope output

Consequently, the calibrated output value of the gyroscope, G_c, is calculated from the gyroscope raw value, G_{raw}, multiplied by the gyroscope resolution, G_{res}. Additionally, the calculated offset bias, G_{bias}, is then subtracted. The gyroscope resolution depends on the sensor specific scale factor and the programmed rotational rate. To calculate the gyroscope resolution, the scale factor provided by the manufacturer is divided by 32768.0 due to the value of an unsigned 16-Bit integer (equation 37).

$$G_{res} = \frac{Scale\ factor}{32768.0}$$

Equation 37: Gyroscope resolution

The gyroscope offset bias is calculated by the sum of the measured raw output data while the sensor is at rest. The average offset bias of the calibration data collection is calculated by dividing the obtained data by the number of data points collected. To calculate the gyroscope offset bias, the result is further divided by the scale factor specified by the manufacturer (equation 38).

$$G_{bias} = \left(\frac{\sum_{i=1}^{n} xi}{n}\right) / \, Scale\ factor$$

Equation 38: Gyroscope bias

The calibrated gyroscope data for the three axes is illustrated in Figure 47.

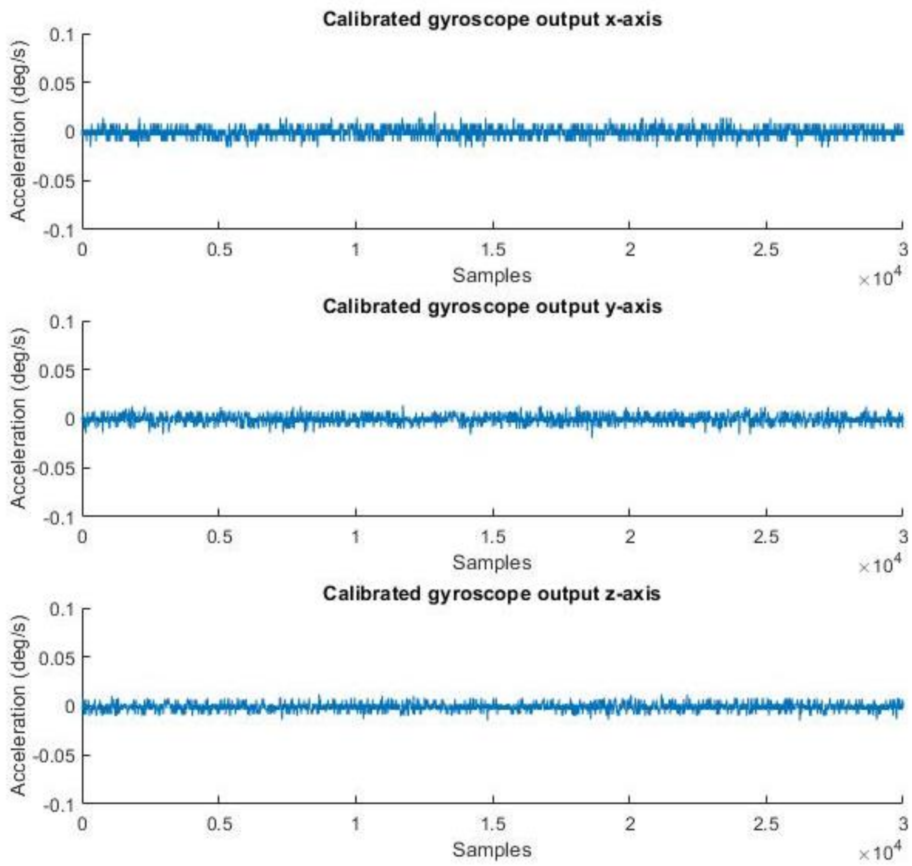


Figure 47: Calibrated gyroscope output x, y and z-axis

3.3.5 Magnetometers

In order to detect the orientation of the boxing glove in three-dimensional space including the heading orientation, also called as the yaw angle, it is necessary to incorporate a magnetometer sensor to the developed monitoring system. The magnetometer is used to correct for drift of the estimated heading orientation. In this case, the inertial sensor unit is referred to as MARG (Magnetic Angular Rate and Gravity Sensor) sensor (Cirillo et al., 2016).

Therefore, subchapter 3.3.5 presents the third and ultimate MEMS sensor that is incorporated to the developed monitoring system during the research process for the determination of the fists orientation in three-dimensional space.

3.3.5.1 Technical principle

The magnetometer also referred as magnetic compass was used for navigation purposes since ancient times (Demtröder, 2013). Modern electric compasses feature many advantages compared to conventional needle compasses or gimbal compensated compasses, such as shock and vibration resistance, electronic compensation of stray field effects, and a digital interface to computerized navigation systems (Caruso, 1997).

The magnetometer is an environment-dependent sensor system, in contrast to the environment independent acceleration and gyroscope measurement methods. The magnetic field is measured in units of micro-Teslas (μT) or in unit of Gauss (1 Gauss = 100 μT).

Magnetic sensing techniques ranging from Hall effect magnetometer, rotating coil magnetometer, magneto resistive magnetometer, fluxgate magnetometer, superconducting quantum interference device magnetometer (SQUID), atomic magnetometers, fiber-optic magnetometer, magnetodiode magnetometers and many more (Caruso, 1997; Elbel, 1996; Zheng, 2018). For the research presented by this thesis, a Hall effect magnetometer sensor was selected due to good availability, low cost, small size and sufficient measurement range. In addition, Hall effect based magnetic devices provide great technical benefits such as durability, high speed and high repeatable operation and a broad temperature range for a wide range of application (Honeywell Inc., n.d.).

Magnetic sensor devices taking advantage of the existing geomagnetic field that is created by convective current of the highly ferrous liquid earth core and for a smaller proportion of the electric currents created by the ionosphere and the magnetosphere (Demtröder, 2013). The magnetic measurement devices measuring the earth´s magnetic field strength at its current position. The earth magnetic field can be considered as a sort of magnetic dipole in its center in which the direction of the geo magnetic field is proceeding from the southern hemisphere to the orientation of the northern hemisphere (Figure 48). For accurate orientation determination it has to be considered that the angle of the magnetic field to the earth´s surface is called the inclination or dip angle, that varies on the different locations and has to be considered during the calibration process (Figure 49) (Caruso, 1997). Furthermore, the earth dipole axis is declined by approximately 11.4° in relation to the earth rotational axis with a dipole moment $p_{mg} \approx 8 \cdot 10^{22}$ (Demtröder, 2013, p. 117) (Figure 48). This is important when working with magnetic sensing devices that has to be considered for the calibration process.

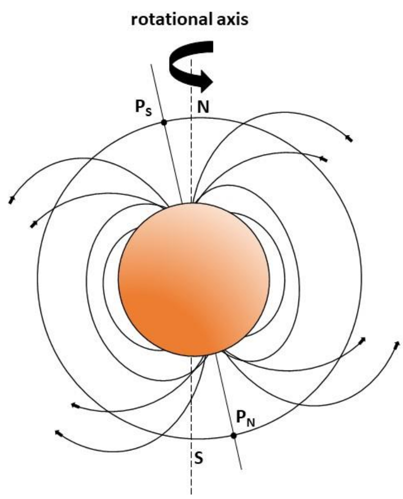


Figure 48: Earth magnetic field. Earth's magnetic field. The sources of the field are in the inner part of the earth. The penetration points PS and PN of the dipole axis through the earth's surface are called geomagnetic poles (Demtröder, 2013, p. 117).

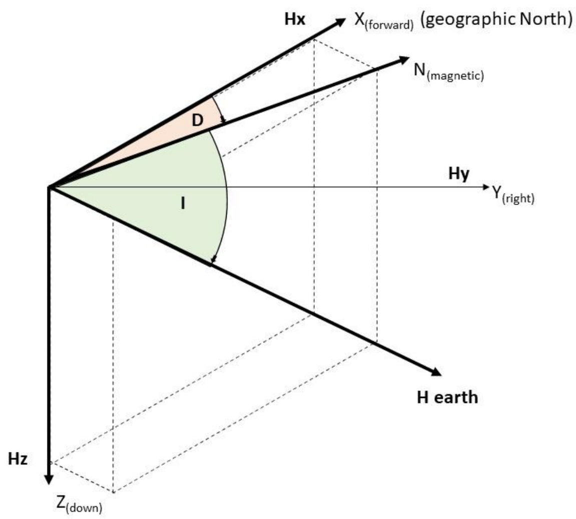


Figure 49: Magnetic earth coordinates with inclination (I) and declination (D)

In addition to the measurement of the direction of the magnetic north, it is possible to measure the magnetic flux density of the magnetometers current position. Therefore, magnetometer sensors can be distinguished between scalar and vector sensors.

Scalar magnetometers enable merely the measurement of the magnetic flux densities magnitude. On the other hand, vector magnetometers indicate in addition to the magnetic flux densities magnitude, information about the device orientation and enable therefore the determination of the sensors heading direction (Webster, 1999). For the purpose of heading orientation detection, a vector magnetometer sensor device is selected that is introduced to the research development. To enable a three-dimensional orientation determination, the selected sensor device incorporates three orthogonally aligned sensors.

The selected magnetometer and its technical principle are based on the Hall effect as mentioned before. The Hall effect principle is the most common used method for mobile magnetic electronics (InvenSense Inc., 2019). The effect was first discovered by the American physicist Edwin Herbert Hall in 1879 (Schaumburg, 1992). The Hall effect is similar as the Gauss´s effect, a galvanomagnetic effect of the charge transport in an electrically conductive material, that occurs under the influence of a magnetic field. The physical cause of the galvanomagnetic effects is the dynamic effect on moving charge carriers in the agent magnetic field (Elbel, 1996). The Hall element consists of a thin plate of conductive material with output connectors that are perpendicular to the direction of current flow. When the elements are exposed to a magnetic field, they react with an output voltage that is proportional to the strength of the magnetic field. As the output voltage is very low (μV), additional electronics are required to obtain usable voltage levels (Honeywell Inc., n.d.).

The basic principle of the Hall effect is depicted in Figure 50 showing an illustration of a current carrying conductor with current (I), magnetic field (Bz), length (l) and width (b). The upper conductor is representing a current carrying conductor without disturbance of a magnetic field with $Bz = 0$. If there is no magnetic field in place, the current distribution is uniform and there is no potential difference at the output (Honeywell Inc., n.d.).

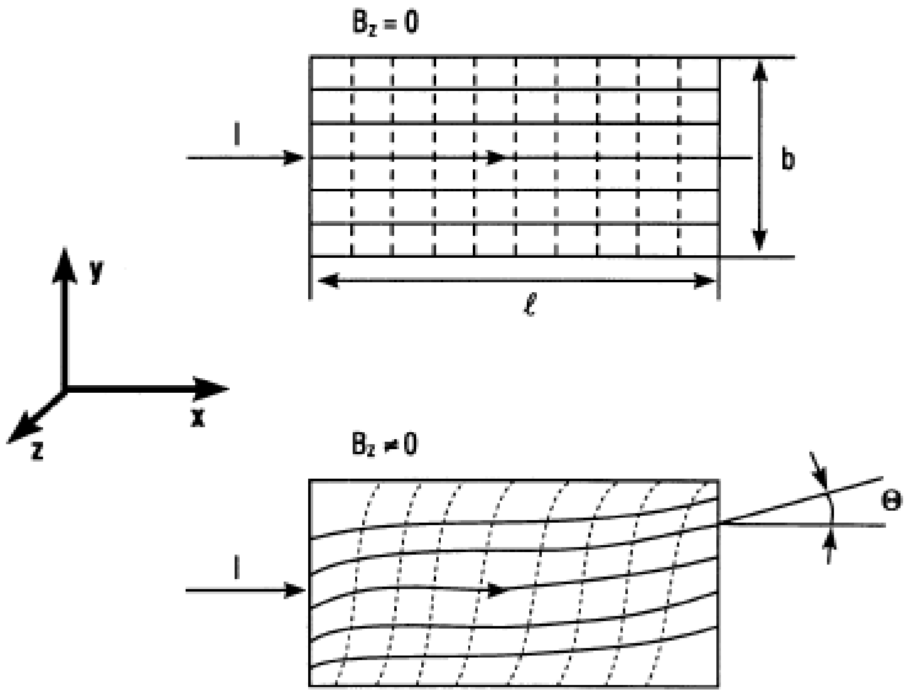


Figure 50: Current and equipotential lines of a current carrying conductor through which current I flows in the x-direction without magnetic field (a) and with magnetic field (b) figure (Elbel, 1996, p. 110)

In the case of an existing magnetic field, represented by Figure 50 (b) of the current carrying conductor, the current will be disturbed and a Lorentz force (FL) consisting of the charge (q), velocity of the charge carrier (v_x) and the magnetic field (B_Z) (equation 39) is exerted.

$$F_L = -q\ v_x\ B_z$$

Equation 39: Lorentz force (Hering & Schönfelder, 2018, p. 47)

The Lorentz force shifts the charge carriers in the y direction by a certain angle from their rectilinear direction. This angle is called the Hall angle (θ). Its size depends on the mobility of the charge carriers and the magnetic induction (equation 40) (Elbel, 1996, p. 111).

$$tan\theta = \mu \cdot B$$

Equation 40: Hall angle (Elbel, 1996, p. 111)

As shown in Figure 50, there is an excess of electrons leading to the top and resulting in an electron deficiency at the bottom. As a result, an electric opposing field (F_{el}) is built. The electric opposing field is calculated by the electric field strength (E_y) and the charge (q) (equation 41).

$$F_{el} = -q\ E_y$$

Equation 41: Electric field strength (Hering & Schönfelder, 2018, p. 47)

The Lorentz force counteracts the electric force until an equilibrium is reached (equation 42).

$$-q\ E_y = -q\ v_x\ B_z$$

Equation 42: Lorentz force and electric field strength equilibrium (Hering & Schönfelder, 2018, p. 47)

The velocity of the charge carrier (v_x) depends on the electric current density ($\vec{S}$) (equation 43).

$$\vec{S} = q \cdot n \cdot v_x$$

Equation 43: Electric current density (Elbel, 1996)

$$v_x = \frac{\vec{S}}{q \cdot n}$$

Equation 44: Charge carrier velocity (Elbel, 1996)

The electric field strength can be calculated by use of the electric current density ($\vec{S}$), the Hall constant of the sensor (R_H) and the existing magnetic field (Bz).

$$E_H = R_H \cdot S \cdot B_z$$

Equation 45: Scalar field strength (Elbel, 1996)

The charge carrier disturbance leads to a potential difference (voltage) at the output. These voltages are referred to as Hall voltages (V_H)" (Honeywell Inc., n.d.) and can be determined on the sides of the current carrying conductor, in the direction of the generated electric field strength (Elbel, 1996).

$$E_H = \frac{U_H}{b}$$

Equation 46: Hall electric field strength (Elbel, 1996)

$$S = \frac{I}{b \cdot d}$$

Equation 47: Electric current density (Elbel, 1996)

Combining the scalar field strength equation with the Hall electric field strength and the electric current density, the derivation allows the calculation of the Hall voltage (V_H). The Hall voltage is inversely proportional to the current carrying conductor diameter and directly proportional to the Hall coefficient, current and the magnetic induction (Elbel, 1996; Honeywell Inc., n.d.). This allows to determine the magnetic flux, by use of the Hall theorem, with the current (I) known.

$$\frac{U_H}{b} = R_H \cdot \frac{I}{b \cdot d} \cdot B$$

$$U_H = \frac{R_H}{d} \cdot I \cdot B$$

Equation 48: Hall voltage (Elbel, 1996)

3.3.5.2 Calibration

When working with magnetometer sensors it is important to conduct a soft- and hard-Iron calibration with the sensor used and within the testing environment as the sensor suffers, other than the acceleration or gyroscope sensor, from environmental distortions.

The magnetometer measures the strength and direction of the local magnetic field in relation to the earth magnetic field. If the magnetometer is rotated around 360 degrees in a distortion free environment each measurement of the compass would lie on a sphere centered around the origin (0x, 0y, 0z) with Earth's magnetic field as the radius. Since ferrous materials such as iron is creating a strong magnetic field, the readings of the magnetometer can be heavily influenced. More precisely the magnetic field measure will be a combination of the earth's magnetic field and the magnetic field of the ferrous object in the immediate surrounding. Ferrous materials such as carbon steel, cast iron or alloy steel occur in various types in the environment and can have a major impact on the measurement accuracy. Hard iron distortions remain steady and in a constant position relative to the compass in all directional orientations (Caruso, n.d.). Furthermore, hard iron effects adding a permanent magnetic field component on each sensor axes of the sensors output that can be subtracted as an offset. Besides, the location of the sensor on the platform itself plays an important role as the distortion varies by the location. Components like the microcontroller or the gyroscope is creating a magnetic field proportional to the electric current that flows through the module (cf. Konvalin, 2008). To conduct a valid calibration, it is necessary to mount the magnetometer permanently to its platform. If the magnetometer is positioned differently on the platform a new calibration is required.

The hard iron calibration process includes the accumulation of magnetometer data in a specific time frame. During this collection phase the magnetometer is moved slowly around 360° in all of the three axes. The minimum and maximum values along the three axes x, y, and z are measured and the average of each axis is calculated as an offset bias. The calculated offset biases are then subtracted from the subsequent magnetometer data (equation 49) (Konvalin, 2009). This results in a recentered circle around the origin (0x, 0y, 0z). The calibration process should be repeated if the environment of the sensor is changed. Otherwise, the offsets can be stored in the on-board memory of the device for further testing's.

$$bias = \frac{(axis_{max} + \ axis_{min})}{2}$$

$$axis_{cal} = data - bias$$

Equation 49: Hard iron offset calculation

In contrast to hard iron distortion, soft iron interferences are a result of materials that influences the compass without generating a magnetic field itself. Hence it is not additive to the magnetometer readings, these distortions stretch the magnetic field depending on the direction of the material relative to the sensor from an ideal circle to an ellipse shaped magnetometer reading as illustrated in Figure 51. Materials like iron or nickel generating a soft-iron distortion to the sensor reading.

Based on the approach for soft and hard iron interference compensation by Konvalin (2009), the soft iron calibration was conducted as follows.

The first step in the soft iron compensation is to determine the angle of rotation, θ, of the correspondingly shifted axis to be calibrated. In order to calculate the rotational displacement of the magnetometer data (equation 51) the magnitude of the line segment r must be calculated (equation 50).

$$r = \sqrt{(x_1)^2} + \ (y_1)^2$$

Equation 50: Magnitude of the line segment r

$$\theta = \arcsin\left(\frac{y_1}{r}\right)$$

Equation 51: Rotational displacement θ

After determining the rotational displacement, θ, the rotation matrix (equation 52) is applied for further calculation to the magnetometer vector values of the x and y axes to turn the ellipse by use of the rotational matrix (equation 53).

$$R = \begin{matrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{matrix}$$

Equation 52: Rotation matrix displacement

$$\hat{v} = R_v$$

Equation 53: Re-aligned rotational matrix

Once rotated, the ellipse formed by the magnetometer data is adapted to the coordinate system and scaled. To scale the magnetometer data from the ellipsoid shape to a circle, a scaling factor, σ, is determined. The scaling factor is calculated by the ratio of the length of the major axis to the length of the minor axis (equation 54).

$$\sigma = \frac{q}{r}$$

Equation 54: Soft-iron scale factor

To complete the soft-iron calibration, a final rotation must be performed, using a negative θ of the equation 52 and 53 (Konvalin, 2009).

Figure 51 presents the raw magnetometer reading that is formed in an ellipsoid shape, highlighted in red, before the hard- and soft-iron calibration is performed. The center of the raw magnetometer data is shifted on both the x- and the y-axis. To re-center the readings a soft-iron calibration is conducted to reshape the ellipsoid to a spherical centered circle (Figure 52). Based on hard iron distortions the sphere is not aligned with its origin at 0x and 0y. By running the hard iron calibration function, the drift from its origin is aligned to 0x and 0y (Figure 53). This enables the magnetometer reading to be used for further orientation algorithms to detect the angular rotation by forming a perfectly shaped sphere, when plotting a three-dimensional figure of all axes x, y and z combined (Figure 54).

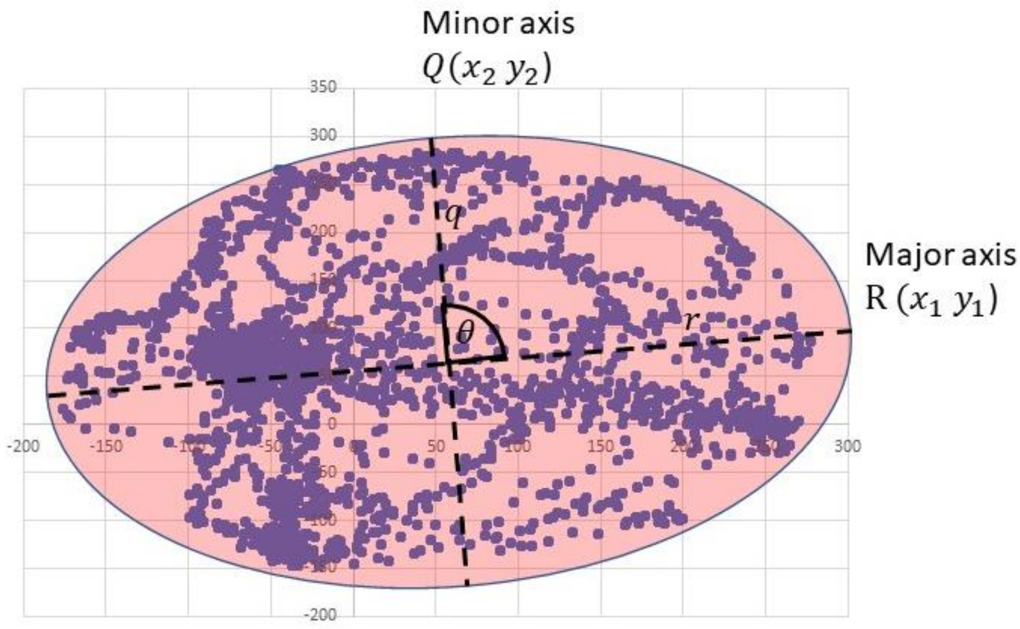


Figure 51: Non-calibrated magnetometer data

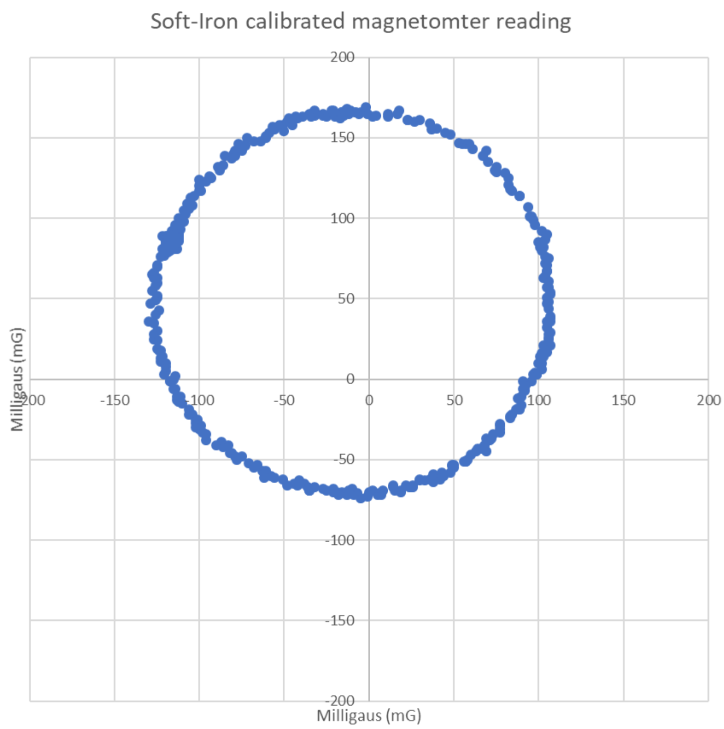


Figure 52: Soft-iron calibrated magnetometer reading

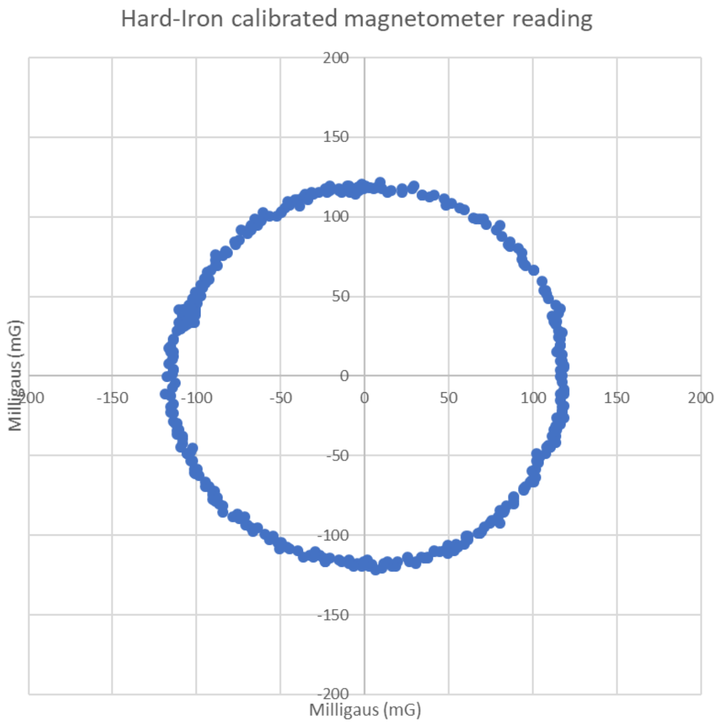


Figure 53: Soft and hard-iron calibrated magnetometer reading

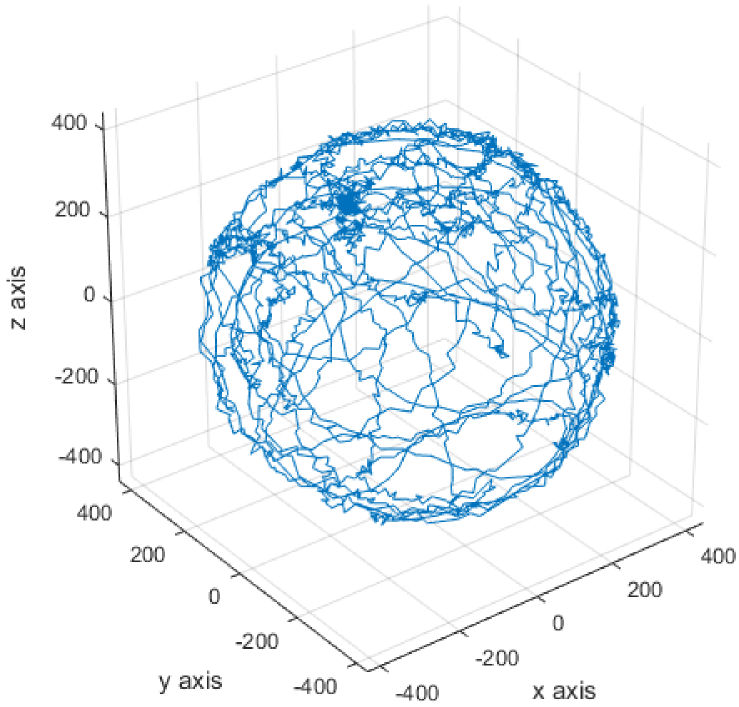


Figure 54: 3D plot x, y and z axes magnetometer in milligauss

3.3.6 Sensor fusion

As described in the previous chapters, the sensor system employs inertial measuring instruments of an accelerometer, gyroscope and magnetometer to determine the fist orientation in three-dimensional space. The underlying problem of using single sensors is based on the individual characteristics of the sensors for obtaining valid measurement results. According to the physical measuring principle, gyroscopes are able to compute the rotational movement by integrating the measured data. This type of sensor provides good measurement results for a short-term. The problem with this type of sensor is that through integration, interfering signals accumulate over time resulting in a drift of the sensor signal and a distorted reading for long term measurements (Günthner, 2008, p. 22). Rotations along the transverse and sagittal axes can theoretically be determined by means of an acceleration sensor. However, this data is also strongly influenced by interference signals. Whereas the measurement of the rotation around the longitudinal axis is only possible with a magnetometer. It turns out that the exact determination of the three-dimensional orientation in space is not possible using the sensor outputs individually. In order to bypass the limitations of the individual sensors and to compensate for the errors described in the previous chapters, to obtain reliable results, the fusion of the individual sensor unit outputs is necessary. The application of a sensor fusion enables to use the best information of the individual sensors and thus to obtain accurate measurement results for the determination of the fist orientation in three-dimensional space (Figure 55). For this purpose, the measurement data obtained with the gyroscope is used for short-term angle determination and the acceleration and magnetic field sensor data for long term stability (Günthner, 2008, p. 22).

In this work a Madgwick sensor fusion algorithm was used to fuse the individual sensor output signals.

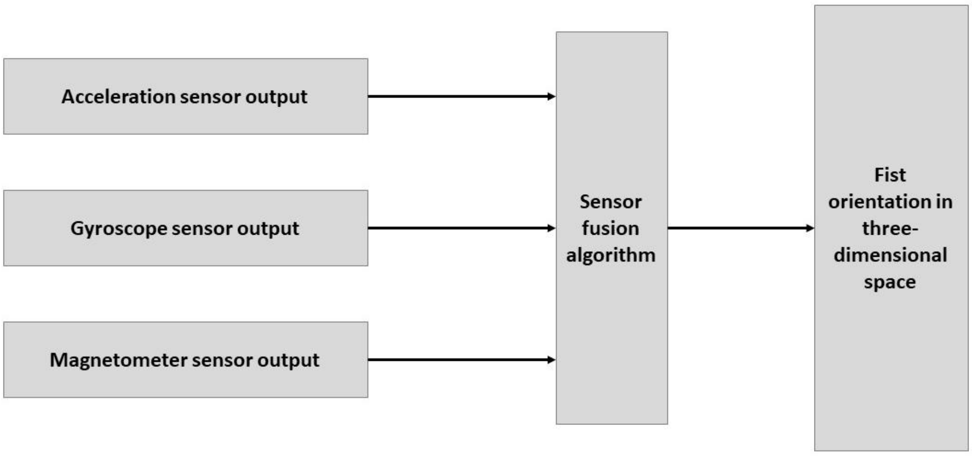


Figure 55: Sensor fusion of individual sensor output signals

3.4.6.1 Madgwick filter

The Madgwick sensor fusion filter is based on a quaternion representation. This has the advantage of avoiding the limitations observed with Euler angle representations, such as singularity effects, while determining the three-dimensional orientation of the fist in space while throwing a punch. A detailed description of this problem is presented in the following chapter 3.5. Furthermore, the Madgwick sensor fusion filter exhibits a reduced implementation complexity, that is particularly important for limited power and processing applications, as well as it provides a good handling for low and high sampling rates (Madgwick et al., 2011; Shepherd et al., 2017). The Madgwick sensor fusion filter combines the three sensor output signals of the tri-axis accelerometer, gyroscope and magnetometer to form a comprehensive MARG (Magnetic, Angular Rate and Gravity) system, also known as AHRS (Attitude and Heading Reference System) for the determination of the fist orientation in three-dimensional space. In addition to the fusion of the three sensor signals, the Madgwick filter contains a compensation of error signals caused by magnetic distortion. For the gyroscope angle determination, the acceleration and magnetometer sensor outputs are used by an optimized and analytically derived gradient descent algorithm. This enables the direction of the gyroscope measurement error to be determined exactly by a quaternion derivative. For this purpose, the data collected by the gyroscope sensor are corrected in a first step by means of a filter gain ζ. The filter parameter ζ represents the convergence rate, that is used to eliminate measurement errors of the gyroscope. According to Madgwick (2010), the filter gain ζ is determined by means of the estimated rate of gyroscope bias drift of the individual axes using the formula presented in equation 56 and is expressed as the magnitude of a Quaternion derivative. The correction algorithm is used to correct the sensor signal from biases and drift errors to determine the initial sensor orientation. Subsequently, the magnetometer and accelerometer data are merged using the gradient descent algorithm. During the fusion of the rotation angles, the accelerometer and magnetometer data are weighted with a filter parameter β. The filter parameter β, also expressed as the magnitude of a quaternion derivative, is used to represent the estimated mean zero gyroscope measurement error of the individual rotation axes (equation 55) (Madgwick, 2010, p. 13). To determine the orientation in three-dimensional space, the result of the gradient descent algorithm is used to correct the angles measured by the gyroscope.

$$\beta = \left\| \frac{1}{2} \hat{q} \otimes \left[0 \ \tilde{\omega}_\beta \ \tilde{\omega}_\beta \ \tilde{\omega}_\beta \right] \right\| = \sqrt{\frac{3}{4}\,\tilde{\omega}_\beta}$$

Equation 55: Madgwick filter gain β

$$\zeta = \sqrt{\frac{3}{4}\,\tilde{\dot{\omega}}_\zeta}$$

Equation 56: Madgwick filter gain ζ

The block diagram shown in Figure 56 presents the complete Madgwick filter used for the sensor fusion of the accelerometer, gyroscope and magnetometer data for the final determination of the three-dimensional orientation of the fist in space. The Madgwick sensor fusion filter used in this work was selected as it allows the determination of angles in the three axes of rotation (yaw, pitch and roll) with a dynamic RMS error of less than

1.7° with respect to gravity and the earth's magnetic field (Madgwick et al., 2011), thus providing better results than a Kalman-based algorithm (Madgwick, 2010). In addition to its advantages described at the beginning of this chapter, the filter has proven its applicability in the sports context, especially in boxing (Shepherd et al., 2016, 2017).

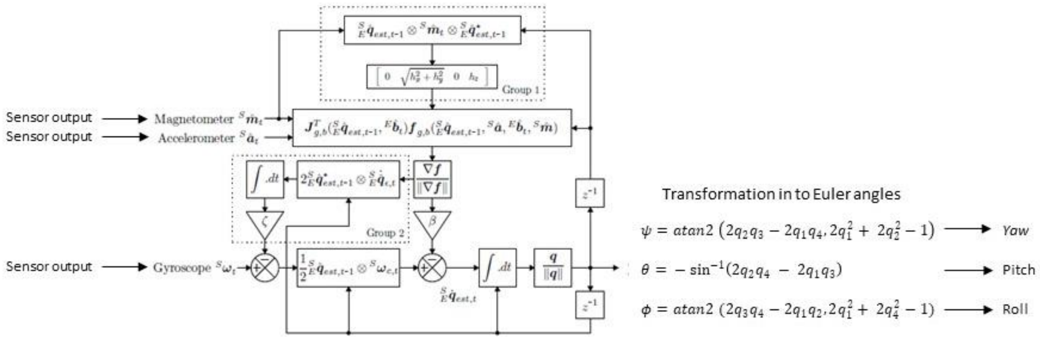


Figure 56: Block diagram presentation of Madgwick sensor fusion modified from Madgwick (2010, p. 13)

3.4 Coordinate system

A fundamental part of performance monitoring is the motion analysis. To determine the orientation and movement of the punch in three-dimensional space it is imperative to define the movement within two reference coordinate systems. The two selected coordinate systems are called the inertial and the body-fixed frame. Both frames are right-handed orthogonal Cartesian systems. The following two subchapter are used to describe the selected frames and to present the applied coordinate system.

3.4.1 Inertial frame

To determine the position and orientation of the developed sensor system in three-dimensional space it is necessary to detect the motion of the developed sensor and its body coordinate frame in relation to a reference coordinate system. The selected reference frame is the inertial coordinate system.

Other possible reference frames are a field or boxing ring fixed coordinate frame that has its origin at the center or a corner of the boxing ring. The second possible reference frame is an earth coordinate frame, that corresponds with the inertial frame but is changing in respect to the earth rotation.

The inertial frame was selected as the most suitable frame as a result of its good accountability. Furthermore, it was selected due to the fact that the inertial measurement unit is measuring acceleration and angular velocity with respect to the inertial frame. The inertial frame is denoted ψ_I and is a stationary coordinate system. The frames origin is located at the earth center. The earth's surface is representing the x-axis that passes the equator and its orthogonal counterpart the y-axis. In an orthogonal orientation to the x-axis and y-axis is the z-axis pointing downwards in a positive direction to the earth center. The inertial coordinate system is a dextral system with the direction of rotation expressed clockwise.

3.4.2 Body-fixed frame

The body coordinate frame is the coordinate frame of the moving sensor system and its containing inertial measurement unit. The body coordinate frame is denoted ψ_B. The inertial sensor units frame origin is located in the center of the inertial measurement unit and is pre-defined by the manufacturer to its housing. For a simplified data visualization and data processing it is of great advantage if the body-fixed frame is aligned to the sport specific direction of motion. Therefore, considering the technical usage of the system, the sensor unit is re-aligned on the developed sensor circuit board, that the body-fixed x-axis is pointing forward in the direction of the punching area of the boxing glove, the body-fixed y-axis is pointing sideways to the medial and lateral direction, in the case when the glove is lying flat on the ground and the body-fixed z-axis is pointing downwards and upwards to the ground as displayed in Figure 57.

This setup is following the configuration suggested by Diebel (2006), that "the home position [θ, ϕ, ψ] = [0, 0, 0,], is flat and level, pointing forward along the world x-axis. The non-intuitive downward-pointing z-axis is chosen in order to make a positive change in θ correspond to pitching upward" (Diebel, 2006a, p. 11).

The origin of the defined body coordinate system is located at the center of the developed sensor unit circuit board. The body frame is a body fixed coordinate frame and is rotating with the gyration of the sensor. When the developed sensor system is moving, the body-fixed frame moves with respect to the inertial coordinate system.

Figure 57 is illustrating a graphical representation of the defined body coordinate system with respect to the inertial frame of the implemented developed sensor within the boxing glove.

The grey highlighted coordinate system in Figure 57 is the original body coordinate system of the boxing glove. A translational motion is performed when the glove is moving along the x-axis in positive direction to the new coordinate system, that is presented in blue with the axis X', Y' and Z'.

Rotational motion is described by the movement around a pivot point or rotation axis in which all mass points of the segment are rotated around concentric circles of the common axis of rotation. Rotational motion of the boxer's fist can be observed in most of the bouts thrown around the boxer's forearm as presented in chapter two. As presented in Figure 57, point P is turned with an angle $\Delta\psi$ to the point P' at a time Δt. The result is a rotation of all points of the coordinate system by an angle of $\Delta\psi$ (Richard et al., 2013).

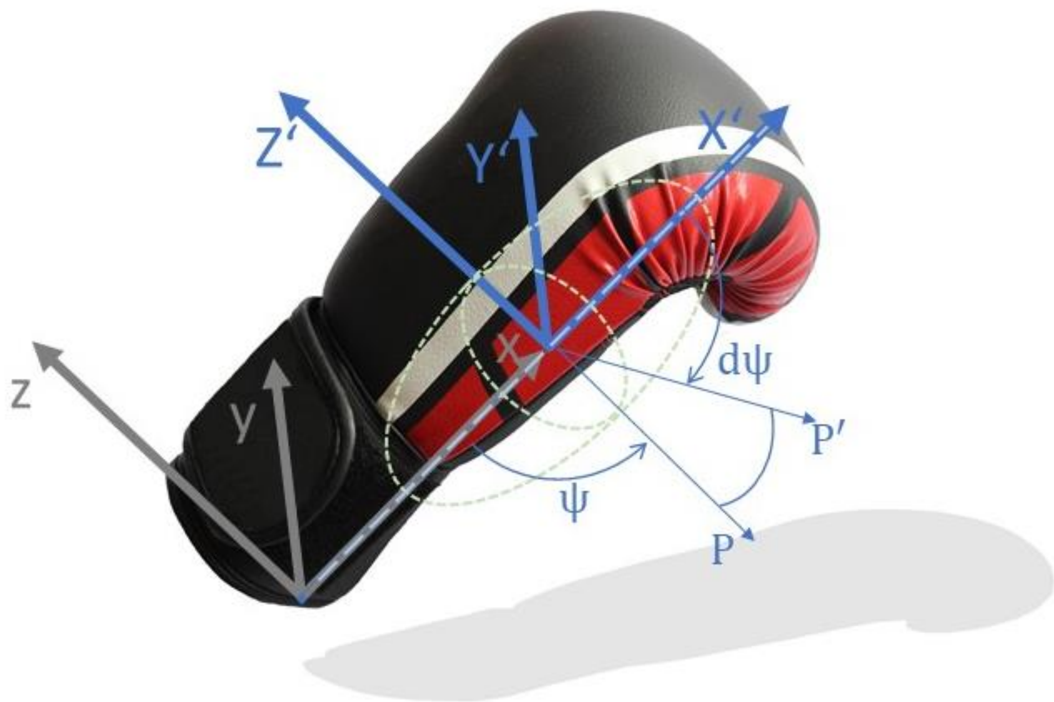


Figure 57: Body coordinate system of the implemented developed sensor system

3.5 Representation of rotation

Rotations can be expressed and evaluated mathematically in different ways. The main and most common methods are the Euler and Quaternion method. Both types of angle presentation forms are used during the work throughout the research conducted, to represent the rotational motion of the fist in three-dimensional space.

3.5.1 Euler angles

The Euler angle theorem is named after the swiss mathematician Leonhard Euler (Britannica, 2019a). By means of the Euler theorem it is possible to express the orientation of an object in space. The angles are used to describe a rotation around a specific axis of the object that is displaying a transformation of the global coordinate frame to the body coordinate frame and contrarily. The rotational axes and the order in which the rotation is conducted can vary in different situations especially in a sportif context where athletes have to respond to their contest environment and take advantage of the body's entire range of motion. This is leading to many different possible but equivalent angular rotational solutions. Therefore, rotational matrices are used for the mathematical expression of these angular rotations and enable the transversion of a coordinate frame into another. This process is of great advantage when working with sensors that measure a vectoral absolute reference, that is related to a reference frame from where the collected data has to be transferred into the operating coordinate system. This is a common problem that occurs when working with magnetometer sensors.

Euler angles have the advantage that once they are determined they are simple to present by their rotation around the pitch (θ), roll (ϕ) and yaw (ψ) angles or respectively known as bank, attitude and heading angles (Diebel, 2006a).

- Pitch (θ): The pitch angle is the rotation about the perpendicular axis of the longitudinal axis and therefore defined as the rotation around the transverse lateral y-axis.

- Roll (ϕ): The roll or bank angle is defined as the angular rotation around the longitudinal x-axis of the object.
- Yaw (ψ): The yaw or heading angle is the rotation around the vertical z-axis perpendicular to the x- and y-axes.

Euler angles are used initially during the work of this thesis as it is a fundamental method for determining angular rotations. They are easy to implement and allow to generate a descriptive result. Although that the Euler angle theorem is a fundamental approach, it contains some drawbacks that have to be considered for determining the systems angular motion in three-dimensional space.

A problem when computing Euler angles by use of a microcontroller is the requirement of great random-access memory since the calculation of sine and cosine curves requires a lot of performance and can become unmanageable very quickly, especially when implemented on low-cost hardware that is needed for the rotation matrices of the yaw, pitch and roll rotation (Fresk & Nikolakopoulos, 2013). Another drawback when working with the Euler angle theorem is the problem of singularity errors, also referred to “gimbal lock” errors. These errors were experienced while conducting initial experiments with the developed sensor system and led to changes in the selected method for the representation of rotation.

The gimbal lock or singularity error is an error that occurs after a series of rotations, when two of the rotational axes align together. This can be the case if the second Euler angle is at a critical value for example if the pitch angle is at 90°. This causes that the roll and yaw angles cannot be determined as they rotate around the same spin axis (Diebel, 2006a). The problem with the singularity problem is stated and expressed by Fresk and Nikolakopoulos (2013) by the statement that the Euler theorem

> *“is solely based on Euler angles, which have the merit of being intuitive, but per definition these angles cannot define certain orientations as it suffers from singularities that result in a problem known as “gimbal lock”. This problem is the loss of one degree of freedom in a three-dimensional space”* (Fresk & Nikolakopoulos, 2013, p. 1).

As a result of singularity, the two aligned rotations degenerating and come into a single rotation. Therefore, the angular derivates can become infinite and thus corrupt the measured punching motion.

3.5.1.1 Euler rotation

To calculate the movement around the yaw (ϕ), pitch (θ) and roll (ψ) angles it is necessary to express the orientation by a combination of rotations around the three axes to generate trigonometrical rotation matrices. The rotation around the three axes are defined by the presented rotation matrices (equation 57 – 59).

Rotation matrix of the x-axis:

$$R_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix}$$

Equation 57: Rotation matrix of the x-axis

Rotation matrix of the y-axis:

$$R_y(\theta) = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & cos(\theta) \end{bmatrix}$$

Equation 58: Rotation matrix of the y-axis

Rotation matrix of the z-axis:

$$R_z(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Equation 59: Rotation matrix of the z-axis

The multiplication of a presented rotational matrix with a vector leads to a rotation of the vector. This means that the vector ω is calculated by the initial point $\vec{v}$ with the multiplication of the rotation matrix R_n, in which n is expressing the axis of rotation and ψ is depicting the rotational angle. The new vector $\vec{\omega}$ is created with equation 60.

$$\vec{\omega} = R_n\ (\psi)\ (\vec{v})$$

Equation 60: Rotation vector

In order to rotate the system around an arbitrary angle, the rotation matrix corresponds to the matrix product of the three rotation matrices about the x, y and z-axis (equation 61).

$$R_{\vec{n}} = R_x \cdot R_y \cdot R_z$$

Equation 61: Matrix product

The rotation matrix that maps the vector of Euler angles to the corresponding rotation matrix is expressed as:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -sin(\phi) \\ 0 & sin(\phi) & cos(\phi) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} \cos(\theta)\cos(\psi) & \cos(\theta)\sin(\psi) & -\sin(\theta) \\ \sin(\phi)\sin(\theta)\cos(\psi) - \cos(\phi)\sin(\psi) & \sin(\phi)\sin(\theta)\sin(\psi) + \cos(\phi)\cos(\psi) & \cos(\theta)\, sin(\phi) \\ \cos(\phi)\sin(\theta)\cos(\psi) + \sin(\phi)\sin(\psi) & \cos(\phi)\sin(\theta)\sin\,)\psi) - sin(\phi)\cos(\psi) & \cos(\theta)\, cos(\phi) \end{bmatrix}$$

Equation 62: Rotation matrix for all three axes

The rotation matrix can be depicted as a simplified rotation matrix of $R_{\vec{n}}$ (equation 63).

$$R_x \cdot R_y \cdot R_z = \begin{bmatrix} 1 & \psi & -\theta \\ -\psi & 1 & \phi \\ \theta & -\phi & 1 \end{bmatrix}.$$

Equation 63: Simplified rotation matrix of $\mathrm{R}_{\vec{\mathrm{n}}}$

The rotation matrix presented is outlining a rotation sequence around the roll ϕ, pitch θ and yaw ψ axis as presented in Figure 58.

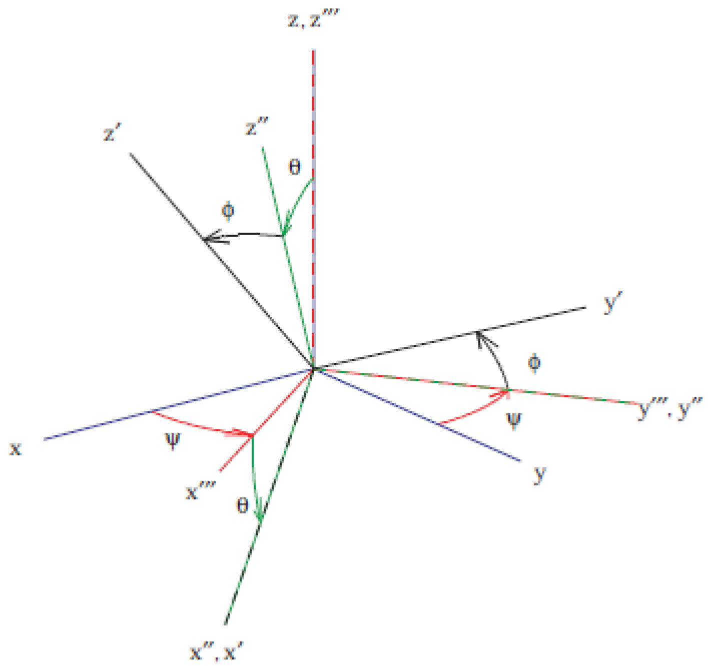


Figure 58: Euler angle rotation sequence (Diebel, 2006a, p. 12)

3.5.2 Quaternions

In order to avoid singularity effects by the use of the Euler angle theorem as experienced in a first attempt during the experimental measurement phase and described by e.g. Yun and Bachmann (2006), Zhang et al. (2012) and Fresk and Nikolakopoulos (2013), the calculation of quaternions is used for the determination of the sensor's angular rotation in three-dimensional space. The use of quaternions provides greater information about the biomechanical processes of combat sports, allowing athletes and coaches to use this information to enhance their performance for technical improvement (Worsey et al., 2019). The mathematical theorem of quaternions is an extension of complex numbers that was discovered in 1843 and was first published by the Irish mathematician Sir William Rowan Hamilton in 1844 (Hamilton, 1844). Quaternions are a form of non-commutative algebra that are rank four hyper complex numbers (Ell et al., 2014). Quaternions $q \in H$ consists of a real part q_0 and additionally a vectorial imaginary part q_1, q_2 und q_3, whose components are each multiplied by their own imaginary unit i, j and k (equation 64).

$$q = q_0 + \boldsymbol{i}q_1 + \boldsymbol{j}q_2 + \boldsymbol{k}q_3$$

Equation 64: Quaternion (Kuipers, 1999, p. 105)

Quaternions can be further specified as vector and scalar part as shown in equation 65.

$$q = S(q) + V\,(q)$$

Equation 65: Quaternion (Ell et al., 2014, p. 1)

The imaginary units are defined like the complex numbers and are denoted as components. The three imaginary units i, j, and k are resulting in the square root of -1. In addition, the product of two imaginary units will result in the third imaginary unit, in which the resulting expression is anti-commutative (Kuipers, 1999).

$$i^2 = j^2 = k^2 = ijk = -1$$

$$ij = -ji = k$$

$$ki = -ik = j$$

$$jk = -kj = i$$

Equation 66: Hamilton rules (Ell et al., 2014, p. 1)

The imaginary units i, j, and k are used to represent the standard orthogonal three-dimensional base (Kuipers, 1999).

$$i = (1, 0, 0)$$

$$j = (0, 1, 0)$$

$$k = (0, 0, 1)$$

Equation 67: Standard orthogonal three-dimensional basis

The sum of two quaternions is calculated component-wise and follows the rules of addition of complex numbers (Kuipers, 1999).

$$\begin{aligned} q + p &= (q_0 + iq_1 + jq_2 + kq_3) + (p_0 + ip_1 + jp_2 + kp_3) \\ &= (q_0 + p_0) + (q_1 + p_1)i + (q_2 + p_2)j + (q_3 + p_3)k \end{aligned}$$

Equation 68: Addition of quaternion

When multiplying the quaternions, the signs of the products of the imaginary units must be taken into account (Valenti et al., 2015).

$$q\,p = (q_0 + iq_1 + jq_1 + kq_1) \cdot (p_2 + ip_2 + jp_2 + kp_2)$$
$$= (q_0p_0 - q_1p_1 - q_2p_2 - q_3p_3) + (q_0p_1 + q_1p_0 + q_2p_3$$
$$- q_3p_2)i + (q_0p_2 - q_1p_3 + q_2p_0 + q_3p_1)j + (q_0p_3 + q_1p_2$$
$$- q_2p_1 + q_3p_0)k$$

Equation 69: Quaternion multiplication

As with complex numbers, the conjugated quaternion is generated by negating the imaginary unit (equation 70) and corresponds to its product (Ell et al., 2014).

$$\bar{q} = \overline{q_0 + \imath q_1 + \jmath q_2 + kq_3} = q_0 - (iq_1 + jq_2 + kq_3)$$
$$= q_0 - iq_1 - jq_2 - kq_3$$

$$q \cdot \bar{p} = (q_0 + iq_1 + jq_2 + kq_3) \cdot (p_0 - ip_1 - jp_2 - kp_3)$$
$$= (q_0p_0 + q_1p_1 + q_2p_2 + q_3p_3) + (-q_0p_2 + q_1p_3 + q_2p_0$$
$$- q_3p_2)i + (-q_0p_2 + q_1p_3 + q_2p_0 - q_3p_1)j + (-q_0p_3 - q_1p_2$$
$$+ q_2p_1 + q_3p_0)k = {p_0}^2 + {p_1}^2 + {p_2}^2 + {p_3}^2$$

Equation 70: Conjugated quaternions

The quaternion product corresponds to a scalar (equation 71) (Ell et al., 2014).

$$|q| = \sqrt{q \cdot \bar{q}} = \sqrt{{q_0}^2 + {q_1}^2 + {q_2}^2 + {q_3}^2}$$

Equation 71: Quaternion’s norm

Quaternions with a size other than zero are called unit or normalized quaternions and can be converted into the respective unit quaternion by dividing their magnitude (Ell et al., 2014).

$$q = \frac{q}{|q|} = \frac{q_0}{|q|} + i\frac{q_1}{|q|} + j\frac{q_2}{|q|} + k\frac{q_3}{|q|}$$

Equation 72: Form of a unit quaternion

3.5.2.1 Quaternion rotation

Starting from the unit quaternion, the angle of rotation as well as the corresponding axis of rotation can be calculated. The angle of rotation is calculated from the real part of the quaternion (Diebel, 2006). The real part can be calculated from the cosine of half the rotational angle. The angle of rotation can thus be transformed according to Ξ and results in formula 73.

$$q_R = q_0 + iq_1 + jq_2 + kq_3$$
$$= \cos\left(\frac{\Xi}{2}\right) + n_x \cdot \sin\left(\frac{\Xi}{2}\right)i + n_y \cdot \sin\left(\frac{\Xi}{2}\right)j + n_z \cdot \sin\left(\frac{\Xi}{2}\right)k$$

$$\alpha = \cos\left(\frac{\Xi}{2}\right)$$

$$\Xi = 2\arccos(\alpha)$$

Equation 73: Quaternion calculation of rotational angle

Based on the angle of rotation, the axis of rotation can be calculated. For this, the imaginary parts of the unit quaternion are converted to n_x, n_y and n_z.

$$iq_1 + jq_2 + kq_3 = n_x \cdot \sin\left(\frac{\Xi}{2}\right)i + n_y \cdot \sin\left(\frac{\Xi}{2}\right)j + n_z \cdot \sin\left(\frac{\Xi}{2}\right)k$$

$$n = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} \dfrac{q_1}{\sin\left(\frac{\Xi}{2}\right)} \\ \dfrac{q_2}{\sin\left(\frac{\Xi}{2}\right)} \\ \dfrac{q_3}{\sin\left(\frac{\Xi}{2}\right)} \end{bmatrix}$$

Equation 74: Quaternion calculation of rotational axis

In order to calculate the Euler angles for visual representation, the transformation matrix must be created from the quaternions in a following step. For this purpose, a three-dimensional vector is transformed from the general coordinate system into the sensor specific coordinate system. In this process the vector v_1, of the general coordinate system, becomes the vector v_2 of the sensor specific coordinate system. To provide the vectors with a fourth element needed for quaternion calculations, an additional element is added at the first position with a magnitude of 0 (Madgwick, 2010).

$$v_2 = q \cdot v_1 \cdot \bar{p}$$

The rotation is represented by the rotation matrix (equation 75) (Madgwick, 2010).

$$= \begin{bmatrix} 2q_1^2 - 1 + 2q_2^2 & 2(q_2 q_3 + q_1 q_4) & 2(q_2\, q_4 - q_1\, q_3) \\ 2(q_2\, q_3 - q_1\, q_4) & 2q_1^2 - 1 + 2q_3^2 & 2(q_3\, q_4 - q_1\, q_2) \\ 2(q_2\, q_4 + q_1\, q_3) & 2(q_3\, q_4 - q_1\, q_2) & 2q_1^2 - 1 + 2q_4^2 \end{bmatrix}$$

Equation 75: Quaternion rotational matrix

Based on the rotation matrix, the angular rotation can be calculated for visual purposes as Euler angles from the rotation matrix of the quaternion components. For this purpose, the Euler angles are described in the form of rotations around the longitudinal ψ (equation 76), transverse θ (equation 77) and sagittal axis ϕ (equation 78) of the athlete's fist. Since the $arctan$ and $arcsin$ functions are programmed with results between -$\pi/2$ and $\pi/2$ only, these functions must be completed with the $atan2$ function (Madgwick, 2010).

$$\psi = atan2\,(2q_2q_3 - 2q_1q_4, 2q_1^2 + \ 2q_2^2 - 1)$$

Equation 76: Quaternion to Euler rotation longitudinal axes

$$\theta = \ -\sin^{-1}(2q_2q_4 \ - \ 2q_1q_3)$$

Equation 77: Quaternion to Euler rotation transversal axes

$$\phi = atan2\,(2q_3q_4 - 2q_1q_2, 2q_1^2 + \ 2q_4^2 - 1)$$

Equation 78: Quaternion to Euler rotation sagittal axes

4 Experimental research

Following the detailed representation of the acquired design and development of the sensor system, chapter 4 outlines the experimental part of the executed research work of the present thesis. This includes the method research approach for the analysis of boxing biomechanics by use of the developed sensor system.

The experimental research was conducted to test on the one hand the validity of the developed sensor system and to provide a proof of the developed sensor concept. Therefore, a variety of experiments were executed to test the system and its developed program and algorithms on short- and long-term sensor output in terms of accuracy, feasibility, susceptibility to errors, as well as overall functionality and direct applicability within the sport setting. In this respect, the chapter is outlining the conducted studies, including the proof of concept and the validation of the unique boxing monitoring system. The information gained of the first conducted feasibility studies offering a profound knowledge about the conceptualization of smart sport equipment. This research step was of fundamental meaning for the further course of the conducted studies and enabled the research questions and design of the executed experiments.

In addition, a number of experiments were designed and executed to test the system in laboratory as well as in-field conditions for the analysis of biomechanical performance data in the sport of boxing while punching. The aim of the conducted studies is to extend the existing state of research in the field of boxing science and to analyse the sport, by use of smart sensors in depth with a focus on sport specific biomechanics.

All experiments conducted serve the generation of unique information in to boxing biomechanics by the use of smart sport equipment. Therefore, an experimental series of tests with gauge repeatability and reproducibility was designed and built up in a laboratory as well as in-field environment. The study design covers the special requirement profile of a martial artist in a competition situation. To gain a comprehensive knowledge in to boxing biomechanics, a great number of participants are included in to the different studies conducted. The included level of experience of the participants is ranging from beginner, to intermediate up to highly experienced athletes with international experience.

The order of the experiments is planned in a way that the studies building up on each other in terms of complexity as well as depth of the research focus. This research design was applied as the sensor system was continuously developed based on the results obtained in the preceding experimental studies conducted. The structure enables to incorporate the findings of the previous experiment in the study design of subsequent studies.

The studies including, the analysis of punching technique in experienced and non-experienced athletes, the analysis of fist activity in amateur boxing while punching, the analysis of self-assessment of punching intensity in amateur boxing as well as the analysis of the centre of pressure distribution on the striking fist while punching. The research serves to illustrate and support the significance of modern sport sensor technologies, by the development and application of novel measurement techniques, that enable the definition and analysis of new fields of investigation in the field of sport science.

All studies were executed under strict observance of highest scientific quality criteria and requirements in terms of objectivity, reliability and validity of the conducted studies. The scientific studies presented were examined by the Ethics Committee of the German Sport University Cologne (Cologne, Germany) for its ethically correct applicability. Therefore, the studies were conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021).

4.1 Validation of a Unique Boxing Monitoring System

The following chapter 4.1 serves the presentation of the applied methods for the validation of the sensors used for the developed unique boxing monitoring system. The chapter is structured by outlining the objective and need for a comprehensive validation process at the start of the chapter. Following the objective of the study, the applied experimental methodology is presented. Based on the experimental methods applied, a detailed description of the obtained validation results is outlined. The chapter on the presentation of the applied methods for the validation of a unique boxing monitoring system concludes with a discussion of the experimental results and a conclusion of the developed systems outcome, that allow further research studies in the analyses of boxing biomechanics.

The study presented in this chapter is published in the sensors journal 2021 (Menzel and Potthast, 2021a, 21, 6947).

4.1.1 Objective

Significant development work and scientific research has been conducted in recent years in the field of detecting human activity and the measurement of biomechanical performance parameters using portable sensor technologies, so called ‘wearables’ (Andreoni et al., 2017; Olguín & Pentland, 2006).

The development, marketing and demand for novel and modern wearables in the sport and health care sector has shown a strong worldwide increase in a short duration of time. This development is reflected in the number of sales of wearable products worldwide from 2014 to 2018. There was an increase predicted by 597.91% over a four-year period from 28.8 million units sold in 2014 to 172.2 million units sold in 2018 (Tenzer, 2019). According to a prognosis from 2019, published by the International Data Corporation (IDC), global sales for wearable sensor technologies are expected to continue to grow, up to a volume of 279 million units sold in the upcoming years until 2023 (Shirer et al., 2019).

Despite the strong growth and ongoing development work, users remain largely unaware of the extent to which the data provided by wearable sensor technologies is reliable and to what grade the output of the measured data is accurate (Pires et al., 2016).

An underlying problem is based on the fact that little information is known about the available measurement systems on the market. There are not many publications or studies published by manufacturers on novel measurement systems that show how the data from the sensor systems provided are processed (Pires et al., 2016). This problem is based on the circumstance, that from a scientific perspective, only a few wearable devices were rigorously tested to ensure accurate, reliable and valid data. Numerous companies in the field of developing and selling sports/fitness technology did not adequately validate their measurement systems, but perfected their marketing to increase profit margins without scientifically substantiating the accuracy of the systems provided (Halson et al., 2016).

The lack of information about the validity in terms of reliability and accuracy of developed wearable sensor technologies as well as the need for their validation to evaluate the effectiveness of the sensors for the athletes has been discussed by many authors as a crucial part of the development process (Andreoni et al., 2017; Bassett et al., 2012; Evenson et al., 2015; Kooiman et al., 2015; Meyer, 2017; Olguín & Pentland, 2006; Seshadri et al., 2019).

Crucial to the development of the sensor system is the validation of the sensor data, with existing measurement systems, such as Kistler force plate and Vicon motion capture systems, that are considered as so-called gold standard according to the current state of research, before the developed device can be used for field study experiments (Andreoni et al., 2017; Pires et al., 2016; Prescott & Garthwaite, 2002; Roell et al., 2019).

The information gained from the validation studies presented in this chapter are of great importance and the foundation for the further scientific work. In the case that the predefined accuracies are not met, the sensor technology and the algorithms must be adapted in order to meet the high scientific validation criteria for scientific field studies in the research area of combat sports.

The validation process described in the following is therefore of great importance for the developed measuring system and the presented development step. Additionally, further reasons are justified to the importance stated from scientific literature by, on the one hand, the increasing number of wearables that are introduced to the market every year. The literature research of the presented chapter shows a large discrepancy in the validity of a great range of measurement systems and the lack of disclosure of testing methods and therefore the importance of validity depiction for the presented work. A further aspect is the ever-increasing demand from the perspective of users and the effect that the collected personal performance data can have on the user’s health, if non validated data and sensor systems are used.

The objective of the experimental study design of chapter 4.1 is, as it is outlined, the validation of the developed sensor designs proof of concept. Therefore, a special focus is on the validation of the systems sensor components, developed calibration algorithms and sensor configuration with respect on accuracy and error / limitation determination for in-field applications.

The validation process of the sensor system for the determination of biomechanical parameters in the sport boxing and other martial arts is divided into two parts.

The first part serves the statistical analysis for the validation of the developed calibration algorithms for impact force measurement, by use of the developed piezoresistive pressure sensors. It is of great importance to test the derived calibration algorithms on their applicability in the instrumentalized state of the sport equipment. To validate the accuracy of the measurement, impact tests were performed to simulate the actual field of application.

The second part serves to validate the inertial sensor technology implemented within the glove. The large dynamic movements of fists during a boxing match require a special measuring method, because the gold standard motion capture system requires marker-based motion tracking with the help of camera systems to produce accurate measurements. This method is not practical as it involves a high risk of injury and high probability of losing markers during the match. Therefore, the developed sensor system measures the trajectory and movement of the fist by incorporating calibrated inertial sensors. For this purpose, the validity of the programmed inertial sensors was analysed by means of statistical tests regarding acceleration and angular rotation for three-dimensional motion analysis in this experimental study. In addition, the sensor behaviour was analysed for long-term applications.

4.1.2 Methodology

The following chapter is used to present the applied methodologies for the validation of the sensors used for the development of a unique boxing monitoring system. Therefore, the experimental setup and protocol, data analysis and statistical analysis is outlined in detail.

a) Ethics statement

The investigation of the validity of the developed boxing monitoring system includes no data collection of specific human research data. For this reason, it was not necessary to examine the ethical approval of an ethic committee for the first part of the testings. For the second part, the scientific study was examined by the Ethics Committee of the German Sport University Cologne (Cologne, Germany) for its ethically correct applicability. Therefore, the study was conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021).

b) Participants

Two participants were observed in the presented study. The average male boxer mass (mean ± SD) was 79.25 KG ± 0.95 with an average boxer height of 177.5 ± 2.5 cm. The majority of the study was conducted utilizing material testing devices such as a Zwick/Roell material testing machine and the developed validation devices such as the centrifugal apparatus.

c) Experimental setup and protocol

The first part of the validation study is used to examine the validation of the impact force determination. A special focus was set on the validation of the calibration algorithms developed and presented in chapter 3.2 for the determination of punch forces with piezo-resistive pressure sensors. The measurement setup of this study included the verification of the impact force with the use of a Kistler force plate, which, according to Roell et al. (2019), is the gold standard in the evaluation of the force measurement in biomechanical data systems. To validate the impact force, impacts were applied by straight punches to a Kistler force plate (Figure 59). The sensor system as well as the microelectronics used for the validation were integrated into a 12-ounce (340.194 g) AIBA certified Adidas boxing glove (2017 model) as described in chapter 3.1.3 about the sensor assembly and instrumentalization of the sport equipment. The microelectronics used is, as well as the sensor system, built into the boxing glove. A sampling frequency of 1000 Hz was used to measure the acting impact forces. This setup enabled an interference-free and high data transmission rate for the completion of sensor validation to detect the entire impact course.

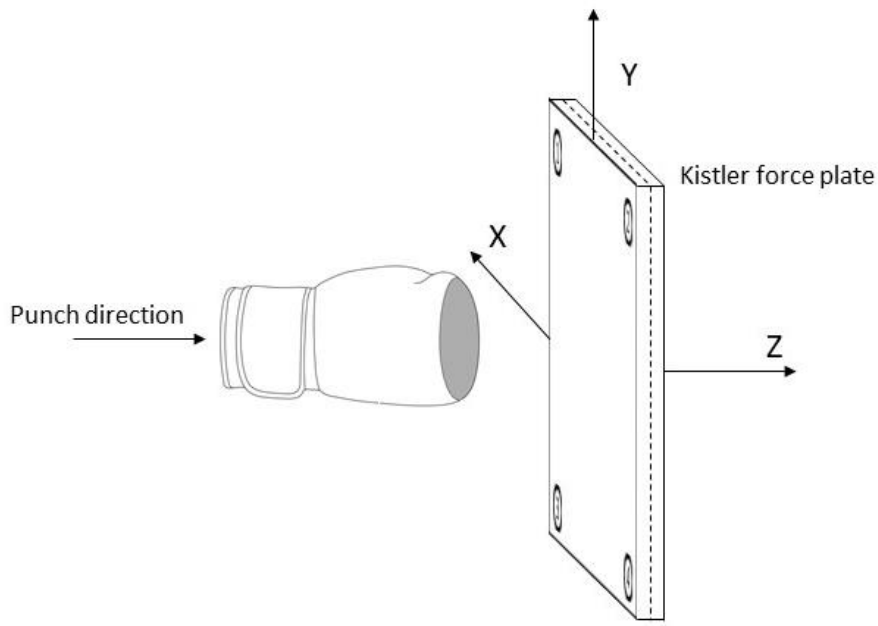


Figure 59: Test setup schematic.

The data acquisition of the Kistler force plate was conducted with a frequency of 10,000 Hz. The Kistler data processing was performed using Vicon Nexus software for motion capture in life sciences. Based on the existing scientific literature on the validation of wearable sensor technologies, there is no commonly accepted experimental protocol available for the validation of wearable sensors, as discussed in detail in the objective of this chapter (Halson et al., 2016; Loosemore et al., 2015). This lack is, as described, due to the large individual variability of the variously applied sensor technologies. Due to this fact and the given circumstances that the wearable technology to be validated in this case is a unique measurement system, a specially developed validation protocol was established.

The experimental protocol is based on the application-related properties of the sensors used.

The measurement protocol consisted of four validation runs which were conducted on two consecutive days. For each of the four measurement runs, fifteen impact sequences were performed on the designated Kistler force plate. The cross punch was determined as the most repeatable punching technique and, consequently, selected for the experiment. In order to validate the most extensive range of impact force possible, as it is to be expected in field, impact forces with a range from 200 N to 2500 N were executed. The data collection started with the low force range of approximately 200 N. The impact intensities were continuously increased by about 200 N in each of the individual measuring cycles up to a 2500 N punching intensity in the last impact cycle performed.

The second part of the study examines the measurement validity of the inertial sensors used. For this purpose, the sensors used and the programmed embedded software were tested on validity. Due to the inertial sensor technology used, the second part of the validation study was further divided into the validation of the sensing acceleration and the validation of the rotational angle.

As already mentioned for the validation of the impact force determination, a specific test protocol was again developed for the validation of inertial sensor technologies. In the first step, the programmed acceleration sensors were validated. During the development three different validation methods were applied. The first validation method was used while programming the embedded hardware. A straightforward and simple to accomplish drop test was performed to check the sensors signal validity.

The verification of the embedded sensor programming by means of drop tests is a straightforward way to perform a preliminary signal validation and to optimize the embedded hardware programming of the used sensor technology without extensive experiments or the development of validation devices. For the validation method using drop tests, the sensor was attached to a 50 x 40 mm wide and 200 mm long wooden block at the top side. The attachment to the wooden block ensures that the sensor does not rotate in free fall and thus the acceleration is measured exclusively in one sensor axis of the sensor. This method is based on the principle that the sensor is dropped from a fixed height without additional acceleration. The only acceleration the sensor is exposed to during free fall is the acceleration of the earth's gravitational acceleration in the longitudinal axis of 1 g or 9.81 $m \cdot s^{-2}$ (Tipler & Mosca, 2015). Using this method, the sensor was accelerated from a height of 80 cm in free fall and decelerated on a foam cushion to reduce the impact intensity. These drop tests were performed for all three axes in positive as well as in negative direction for the first acceleration validation testing. In contrast to the analysis of the impact validation, the data transfer in this experiment was carried out via a wireless Bluetooth connection. This method of data transmission was performed with a recording frequency of 100 Hz.

Based on the results of the preliminary drop test validation and the optimization of the sensor output, a comprehensive validation of the acceleration sensors was carried out. As described for the first drop test validation method of the acceleration sensors, a known acceleration must be given for the validation of the acceleration. In order to validate the entire potential measuring range of +/- 200g, an extension of the validation method is therefore of elementary importance. For this purpose, a special validation device was developed based on the principle of a centrifugal device as presented in chapter 3.3.2. Based on preliminary tests, the sensor range of ±200 g was evaluated as sufficient. The maximum acceleration at impact was measured up to 160 g for internationally experienced athletes.

The design of the validation device enabled the adjustment of the input acceleration needed in the form of a rotational movement created by an electric motor. The concept of the validation device consisted of a fixed motor that accelerated a turntable and the sensor unit mounted on top via a ball-bearing shaft (Figure 60).

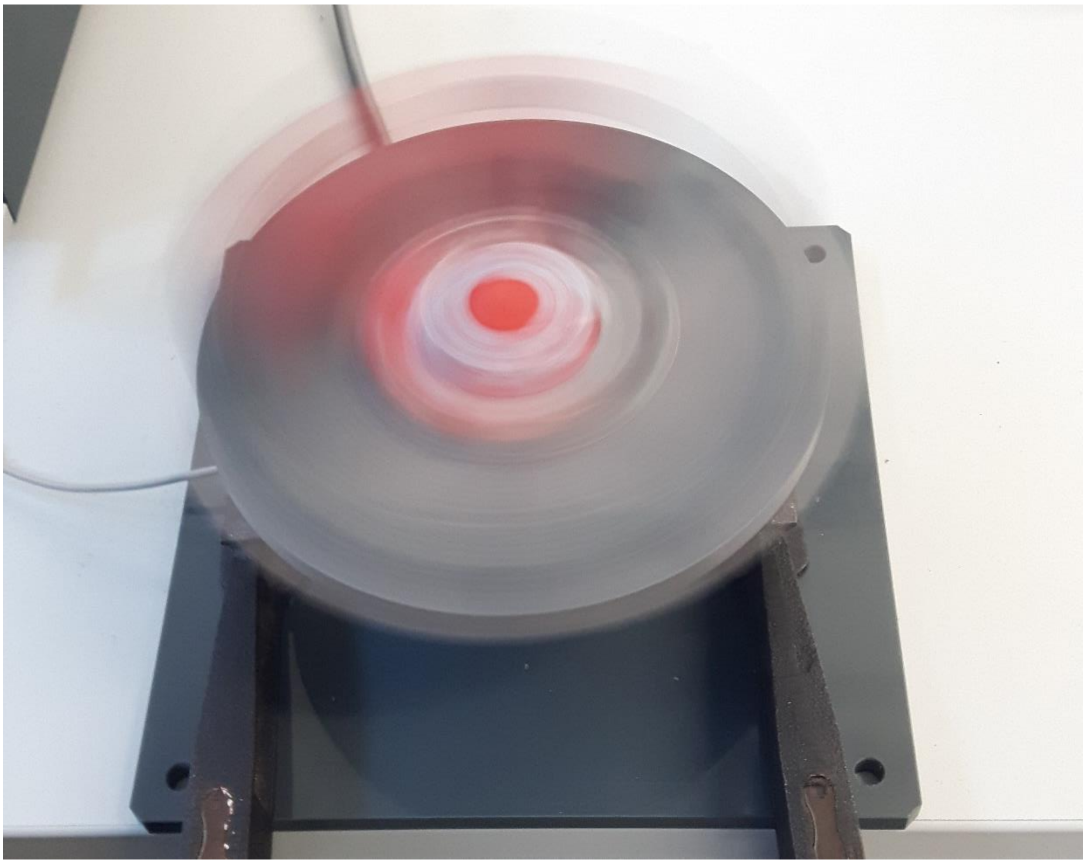


Figure 60: Centrifuge measurement data acquisition

The change in acceleration can be adjusted in two ways. First of all, by changing the distance of the sensor to the centre of rotation and secondly by changing the number of rotational revolutions per minute (RPM). In the presented experimental setup, the motor and thus the acceleration of the platform is continuously controlled by an electronic control unit to not influence the position of the sensor for accurate validation results. The sensor is mounted on the turntable by means of a sensor attachment and a fixed distance of 12 cm from the centre of rotation. The sensor mounting allows the angular position of the sensor to be changed from a flat position with 0° inclination up to an inclination of 45°. This setting allows the acceleration to be measured in one axis when the sensor is mounted with 0° inclination or over several axes without having to change the sensor attachment when the sensor is mounted with an inclination of 45° (Figure 43).

The experimental protocol of the acceleration validation by the developed centrifugal device consisted of 20 measuring cycles in each of the experimental runs. The measurement was from −200 g up to +200 g with a predefined increase of the acceleration rates for all three axes. Each of the measurement levels was held for a data acquisition period of a minimum of 50 s to collect a considerable number of data samples before accelerating to the next measurement level. This measurement protocol was repeated five times to analyse the system's repeatability. Similar to the drop test validation protocol, the data transfer in this experiment was carried out via a wireless Bluetooth connection with a transmission rate of 100 Hz.

Following the acceleration validation process, the sensor system was validated through the orientation of the sensor in three-dimensional space. This validation process was carried out in three consecutive steps. In a first preliminary validation, the sensor output was tested by use of an analogue goniometer device. The preliminary testing was conducted throughout the programming phase that allows to make direct changes to the embedded programming without the direct need of designing a new validation device. The validation protocol consists of eight measurement cycles with a change of rotation from 0° to 360° with an increase of 45° per cycle. The data transmission was conducted using a wired data transmission of 1,000Hz.

Following the preliminary validation, a comprehensive validation process was executed by use of a designed and developed gimbal device as presented in detail in chapter 3.3.1.

The designed validation apparatus allows to rotate the sensor around all three axes (yaw, pitch and roll) 360° without affecting the sensor positioning on the inner sensor mount. Potentiometers were used to generate a reference value to validate the rotation angle of the sensor around the respective axes against the rotation determined by the electrical signal of the potentiometer.

The data was transferred using a wireless Bluetooth connectivity with a measuring frequency of again 100 Hz from the sensor unit to a stationary laboratory computer. The measuring protocol consists of three runs with a rotation of 360° for each of the three axes.

In the experimental setup, punches against a boxing bag with a defined weight were performed. A 40 kg punching bag made out of leather from

Paffen Sport (Paffen Sport GmbH & Co. KG, Cologne, Germany) was used on a wall-mounted suspension to perform the punches, against a defined and stationary target. The three-dimensional movement execution of the glove was recorded utilizing a marker-based Vicon motion capture camera system (VICON MXF40, Vicon Motion Systems Ltd., Oxford, UK) (Figure 61).

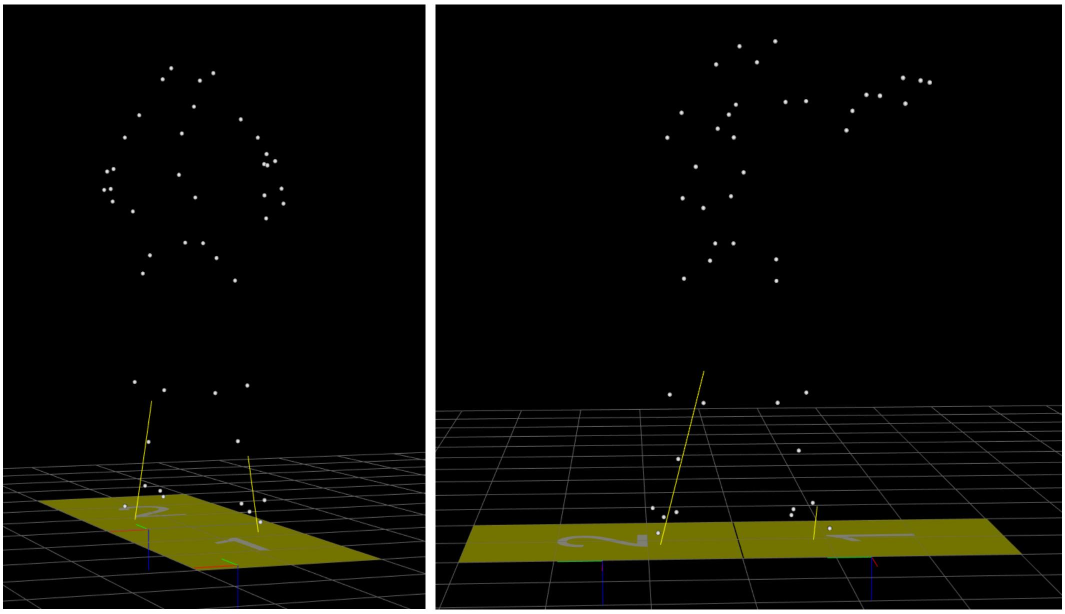


Figure 61: Vicon motion capture testing a) preparation phase b) throwing phase

Drift tests were conducted in a subsequent step following the results of the punch force, angle and acceleration validation experiments. The drift tests were used to validate the system on drift occurring over time in action. Thereafter, the system was tested over a period of five, fifteen and finally forty-five min, according to the maximum length of a boxing match.

d) Data analysis

To compare the acquired punch force validation data of the Kistler force plate with the sensor device, the sensor data had to be interpolated to perform a holistic analysis of the force–time curve between both measurement systems, due to different data acquisition frequencies between the developed sensor system with a frequency of 1,000 Hz, the force plate frequency of 10,000 Hz and the Vicon Motion Capture System with a frequency of 1,000 Hz. The data processing and further data analysis were performed using custom-built MATLAB (2018b) routines (The MathWorks, Natick, MA, USA) for all tests conducted during the experimental validation study.

The data analysis to validate the incorporated inertial sensors was performed in an identical manner. Due to the differences in recording frequencies, the sensor data were matched by means of data interpolation. The coordinate system for the execution of the drop tests was aligned in the direction of the sensor axis to be validated in drop test direction (gravitational acceleration) as presented in Figure 62.

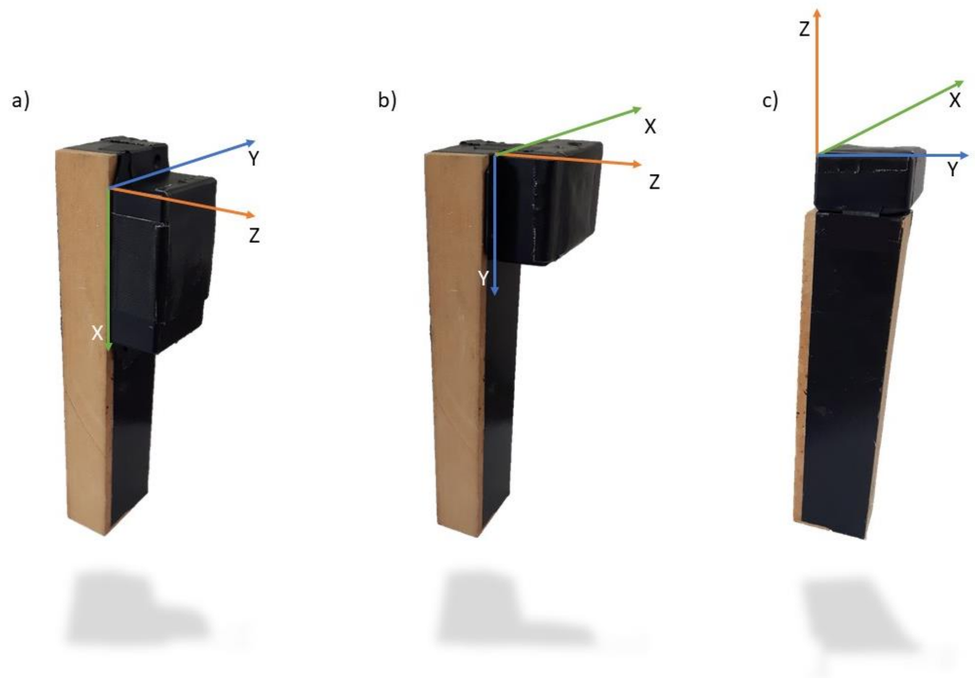


Figure 62: Aligned axes a) x-axis; b) y-axis; c) z-axis

For the validation of the entire range of acceleration using the centrifugal device, the sensor axis to be validated (a_n) was aligned in the direction of the centrifugal force, orthogonally to the direction of the tangential acceleration (a_t) as shown in Figure 63. Whereas the orientation of the coordinate system for the validation of the orientation in a three-dimensional space using the developed angular rotation validation device was aligned with the x-axis pointing upwards, the y-axis pointing sideways and the z-axis pointing forward. This initial position was chosen as it is similar to the starting position of the boxing glove while the fist remains in the defensive position and before it is tilted in a forward direction by 45° around the y-axis, in the direction of the object to be hit, thus, assuming the punching orientation.

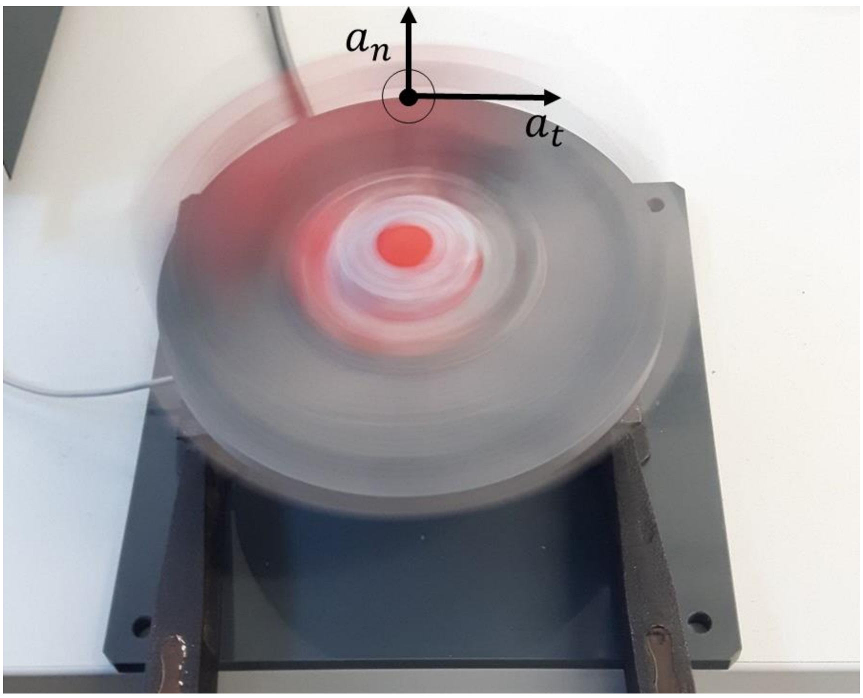


Figure 63: Centrifugal device aligned axis

To validate the acceleration, the centrifugal acceleration of the centrifuge was calculated. The acceleration occurs when the sensor is rotated around a certain radius at a specific rotational frequency. The general equation for the calculation of the centrifugal acceleration is given by equation 79.

$$a = \omega^2 \cdot r$$

Equation 79: Centrifugal acceleration

ω is the angular velocity and r the distance of the sensor centre to the centre of the rotational axis of the centrifugal device. By use of the equation, it can be observed, that increasing the sensor distance to the axis of rotation, is leading to an increased angular acceleration. In order to keep the radius for all axes tested at the same distance to the centrifuges centre, the sensor mount assembly orientation was changed without affecting the sensor positioning on the sensor fixture. By transforming the equation (79), the angular acceleration is calculated using a pre-defined acceleration (equation 80).

$$\omega = \sqrt{\frac{a}{r}}$$

Equation 80: Angular acceleration

The determination of the required revolution per minute for each axis, to generate a certain acceleration for the validation process, was calculated using equation 81 (Stephenson & Mahlke, 2011).

$$RPM = 100 \cdot \sqrt{\frac{a(g)}{(11.18 \cdot r(m)}}$$

Equation 81: Revolution per minute of the centrifugal device

e) Statistical Analysis

The statistical data analysis of the individual validation experiments presented in this chapter is following the preliminary data processing and was performed using the analysis software, IBM SPSS Statistics for Windows, Version 23.0 (IBM Corporation, New York, USA).

To analyze the validity of the predicted punch force determination using the developed sensor system, a linear regression was performed based on the punch force data from the Kistler force plate. Linear regression analysis was also performed to validate the acceleration in g's and angular rotation in degrees, as determined by the inertial sensor. A Pearson correlation coefficient analysis was conducted to analyze the sensor systems validity. For the visualization of the statistical analysis, a scatter plot is used to show linear correlation between sensor-derived punch force (N) and Kistler force plate-derived punch force (N). Scatter plots were used to show linear regression between inertial sensor-determined acceleration (g) and centrifugal-derived acceleration (g) as well as inertial sensor-determined rotation (°) versus potentiometer-derived rotation (°). The same statistical analysis method was conducted to test the incorporated inertial sensor unit in the second step against the Vicon motion capture system. In addition to the Pearson correlation coefficient, the root means square error (RMSE) as well as the standard deviation (SD) was calculated to evaluate the statistical data from the experimental validation results to provide detailed information about the magnitude of measurement errors. To analyse the significance of the measurement results, an ANOVA statistic was carried out, to test on the statistical analysis of statistically significance with a selected alpha level of 0.05.

The data were further analyzed on the homoscedasticity of the residuals. A Durbin–Watson statistic was taken into account to analyze the correlation of the residual error values. For the presentation of homoscedasticity, ZRESID versus ZPRED graphs were utilized. Furthermore, a P-P plot of regression standardized residuals with a generated regression line and a histogram chart was used. A histogram was also used to test the data on normal distribution.

4.1.3 Results

Experimental results of the punch force determination validation

The statistical results of the validity of the predicted punch force determination using the developed sensor system compared to the determination of punch force by the Kistler force plate demonstrated a high linear regression between the two measurement methods.

The correlation analysis according to a Pearson product–moment correlation coefficient showed a high positive correlation of R = 0.995 between the force plate-derived force and sensor-derived force. A further analysis showed an adjusted R^2 of 0.99 (Table 5) with a RMSE of 59.84 N.

Table 5: Regression analysis summary for the validation of sensor-derived punch force determination

Variable	B	95% CI	ß	t	p
Constant	-10.164	[-32.05 11.72]		-0.92	0.36
Kistler Force Plate	1.00	[0.98 1.02]	0.99	105.44	0.00

Note. R^2 adjusted = 0.99. CI = Confidence interval for B.

The significance of the validation results is shown by means of an ANOVA. The performed F statistics showed a high significance of $p < 0.001$ with a confidence interval of 95% (F (1.123) = 11117.55, $p < 0.001$). The sensor-derived force is equal to

$$Punch\,force\ (y) = -10.16\ +\ 1.00\ N\ \cdot x$$

Equation 82: Validation linear regression

Figure 64 presents the validation results for the peak punch forces determined by the developed boxing monitoring system compared to the Kistler force plate-determined peak punch forces with a displayed alpha of

5% confidence interval of the linear regression model, for a total of 125 punches thrown with a punch force ranging from 242 N up to 2310 N.

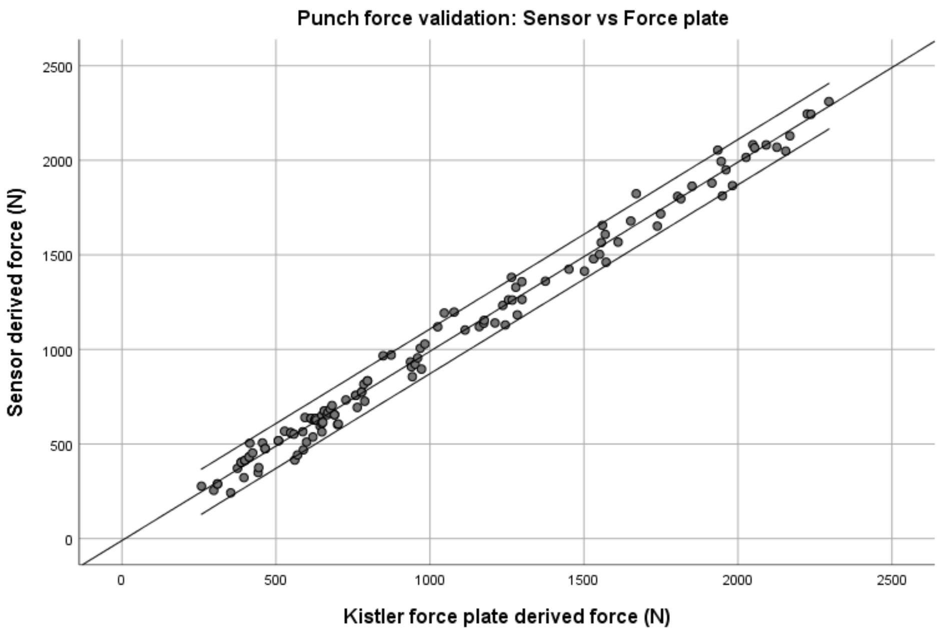


Figure 64: Punch force validation: Sensor vs Force plate derived force (N)

The statistical testing on homoscedasticity of the residuals for equal statistical variances was assessed in the following step. The review of the regression standardized residuals associated with the sensor value regressed on the predicted value showed that there is a clearly randomized data display with no error pattern of any sort evident in the scatter plot (Figure 65) for an even distribution of variance. Homoscedasticity of the experimental data was also assessed by reviewing the dependent variable histogram (Figure 66) and the regression line of the P-P plot of the regression standardized residuals (Figure 67). Additionally, Figure 66 presents the approximate normally distributed residuals. In addition, a Durbin-Watson statistic was taken into account to analyse the correlation of the residual error values. The Durbin-Watson test was analysed with a value of 1.63 to proof the independence of the residual error values and indicates that there is no evidence of autocorrelation of the residuals apparent. A root means square error of the residuals of 59.49 N was calculated. To further analyze the impact force, the time force progression of the punch force determined with the sensor (green) was analyzed with respect to the force time progression measured by the force plate (black). This analysis shows a correlation of the force–time curves of R = 0.98. The sensor-derived force-time curve shows a symmetrical leptokurtic curve pattern by comparison with the Kistler force plate-derived force-time profile in Figure 68.

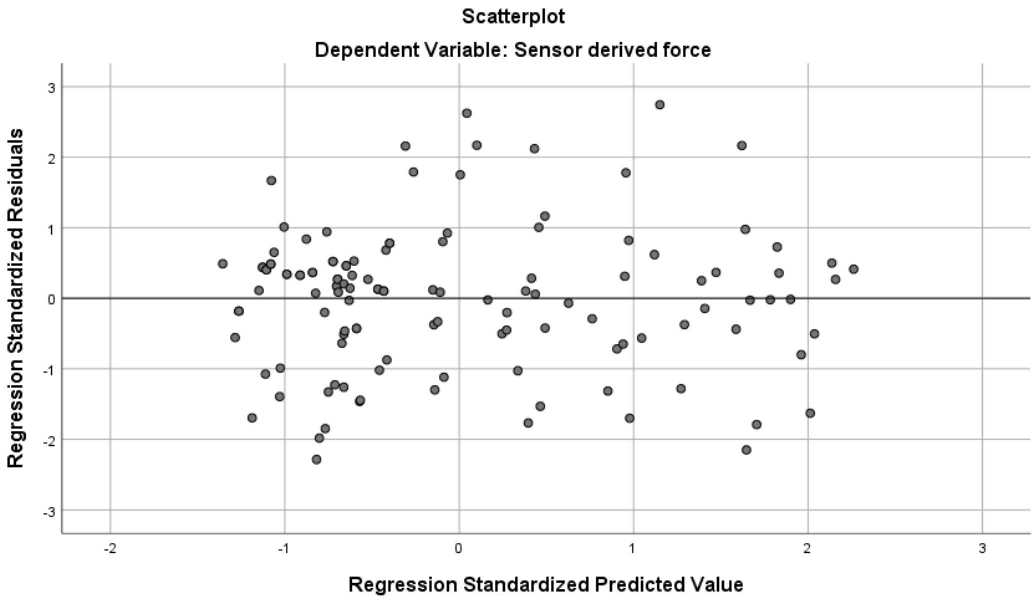


Figure 65: ZRESID vs ZPRED plot of determined punch force

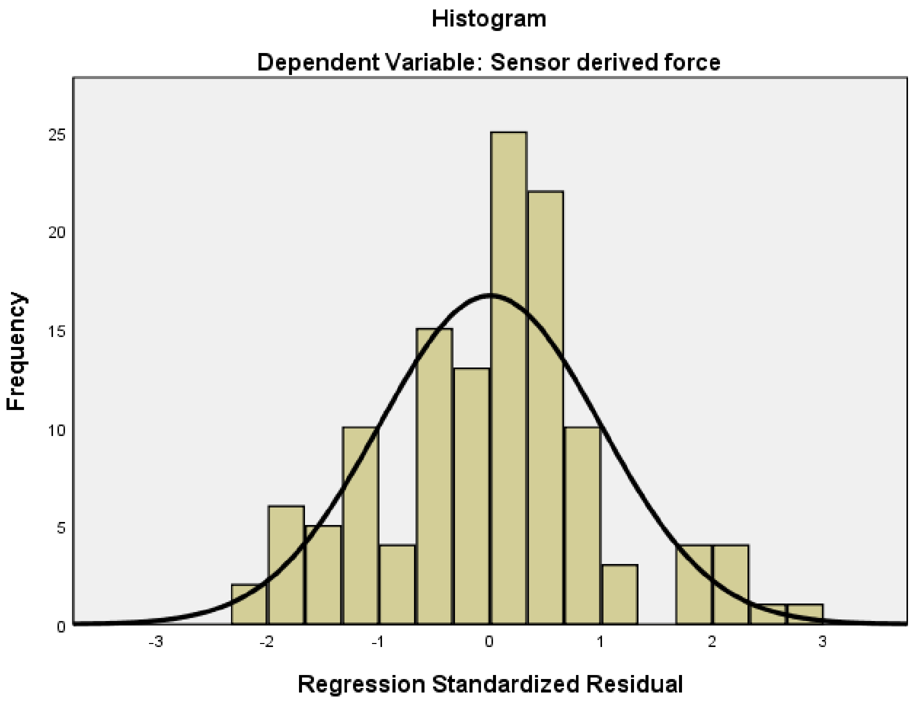


Figure 66: Histogram of sensor-derived punch force

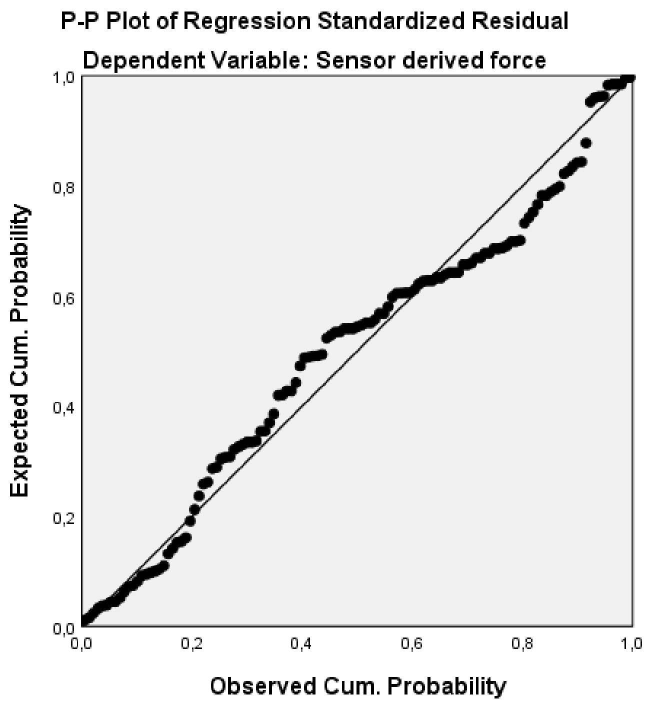


Figure 67: Regression plot of the homoscedasticity of sensor-derived punch force

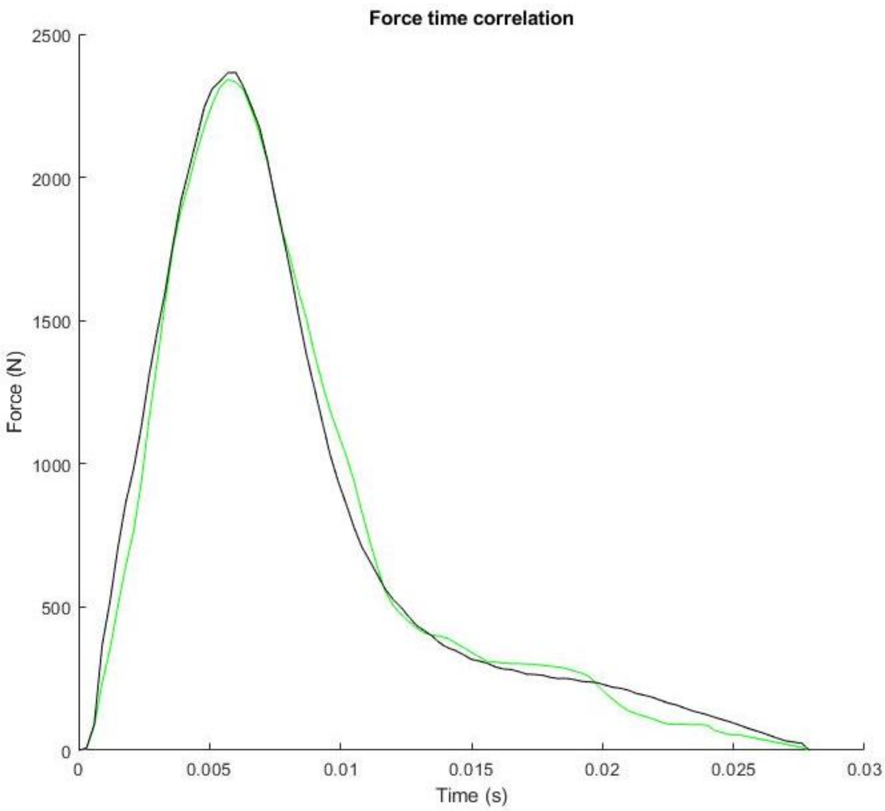


Figure 68: Force-time progression sensor (green) vs Kistler (black)

Experimental results of the inertial sensor validation

The preceding analysis of the lower acceleration range of the inertial sensor system by means of the drop tests performed shows a high significance ($p < 0.001$) in the determination of the acceleration for a +/- 2g as well as a +/- 16g sensor limit setting.

The sensor is accelerating to approximately 9.81 m/s^2 based on the physical principle of gravitational acceleration when no additional acceleration is applied to the object, until the point of ground contact. The calibrated acceleration data, shows an increasing acceleration up to +/- 9.84 m/s^2 in average with a standard deviation of SD = 0.05g in all conducted tests until the point of ground contact with an acceleration rate setting of +/- 2g.

The second sensor setting tested was at +/- 16g in the same way as the +/- 2g accelerometer setting by conducting drop tests from a height of 80 centimetre.

The results of the regression analysis show that the incorporated sensor technology determines the acceleration due to gravity with a coefficient of determination of $R^2 = 0.99$ and an average measured acceleration of 9.71 m/s^2 (SD = 0.19 m/s^2) as indicated in Figure 69.

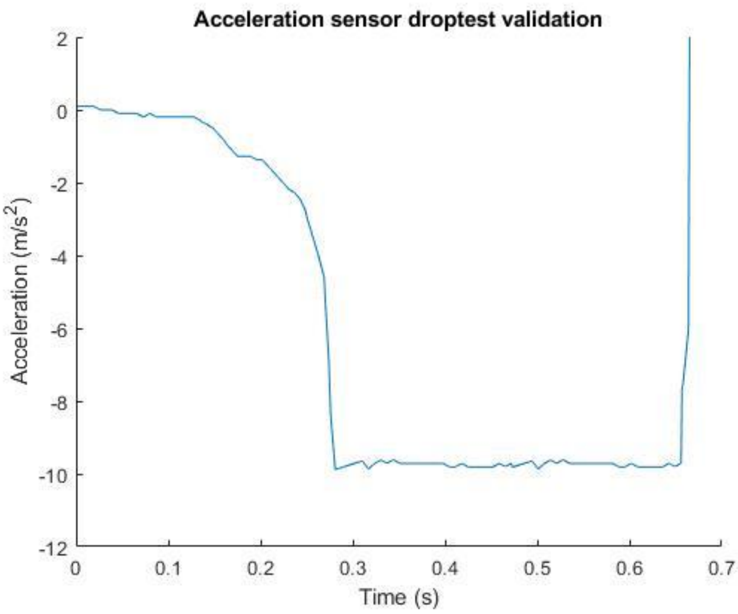


Figure 69: Acceleration sensor drop test validation

The subsequent investigation of the entire acceleration range using the validation centrifuge exhibited an identically high statistical accuracy. The statistical analysis of the impact acceleration using the built-in inertial sensors, when compared to the acceleration of the validation centrifuge, shows a high linear regression between the two measuring methods used. The correlation analysis according to Pearson shows a correlation of R = 1.0 (adjusted R^2 = 1.0) for the x-axis, a R = 1.0 (adjusted R^2 = 1.0) for the y-axis and a Pearson R = 1.0 (adjusted R^2 = 1.0) for the z-axis acceleration as presented in Figure 70 to Figure 72. The acceleration range tested ranged from −200 g to +200 g, determined by the inertial sensor and the acceleration measured by the centrifugal validation device.

The results of the F statistics show a significance of the measurement results of $p < 0.001$ with an applied confidence interval of 95% for all three axes. The acceleration determined by the measuring system is equal to

$$Acceleration\ (x) = -0.17\ +\ 1.00\ N\ \cdot x$$

Equation 83: Validation of linear regression for x-axis acceleration

$$Acceleration\ (y) = 0.43\ +\ 1.00\ N\ \cdot y$$

Equation 84: Validation of linear regression for y-axis acceleration

$$Acceleration\ (z) = 0.112\ +\ 1.00\ N\ \cdot z$$

Equation 85: Validation of linear regression for z-axis acceleration

The validation results, including an alpha of 5% are displayed in Figure 70 to Figure 72 using the regression model for a sample size of 2095 for the x-axis, 1595 for the y- axis and 1516 samples for the z-axis acceleration.

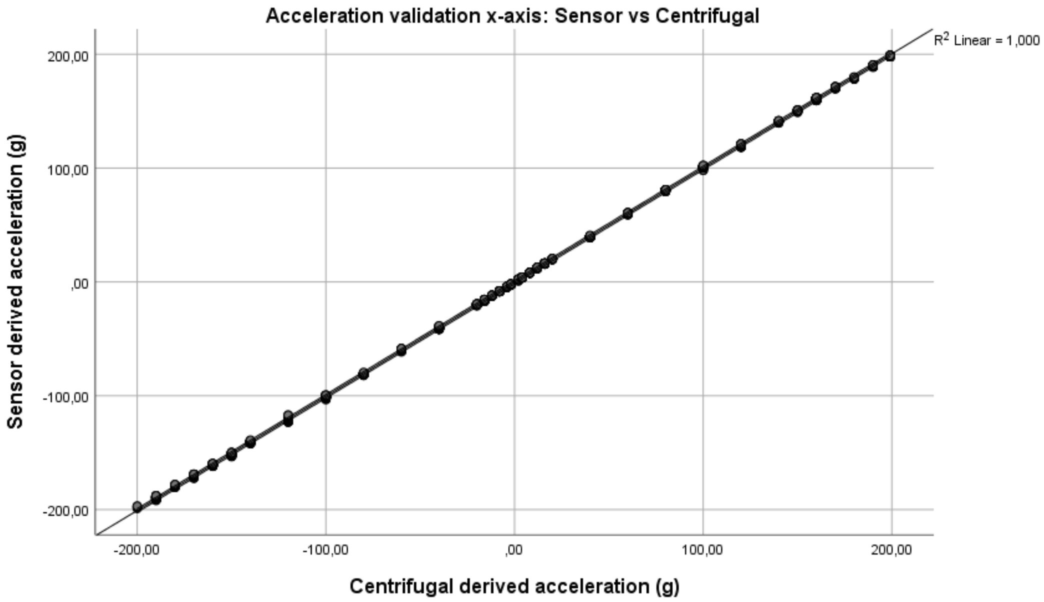


Figure 70: Acceleration validation x-axis: Sensor vs Centrifugal device

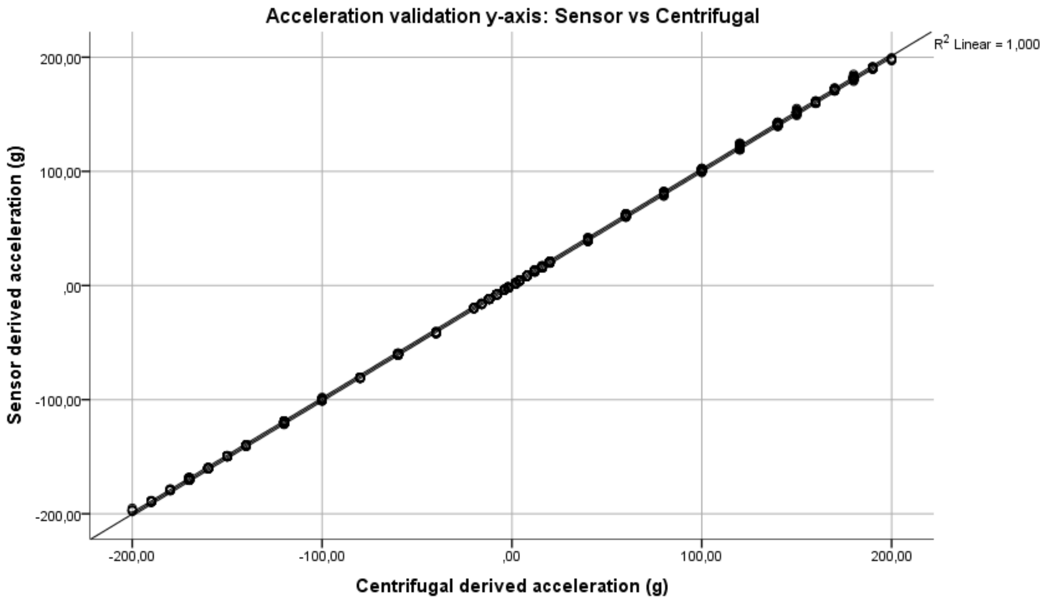


Figure 71: Acceleration validation y-axis: Sensor vs Centrifugal device

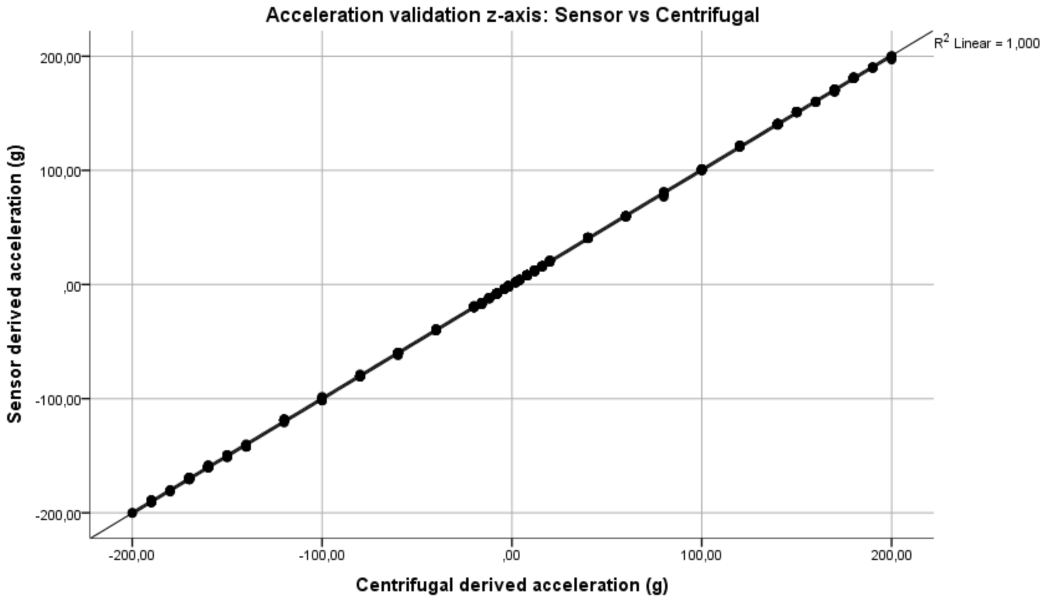


Figure 72: Acceleration validation z-axis: Sensor vs Centrifugal device

As for the Punch force determination validation, the results of the acceleration data are analysed in terms of homoscedasticity on equal statistical variances of the residuals. Homoscedasticity of the experimental data is assessed by reviewing the dependent variable histograms for the three axes individually as presented in Figure 73, Figure 75 and Figure 77 and the regression line of the P-P plots Figure 74, Figure 76 and Figure 78 of the regression standardized residuals. In addition, Figure 73, Figure 75 and Figure 77 are representing the normally distributed residuals for all three axes.

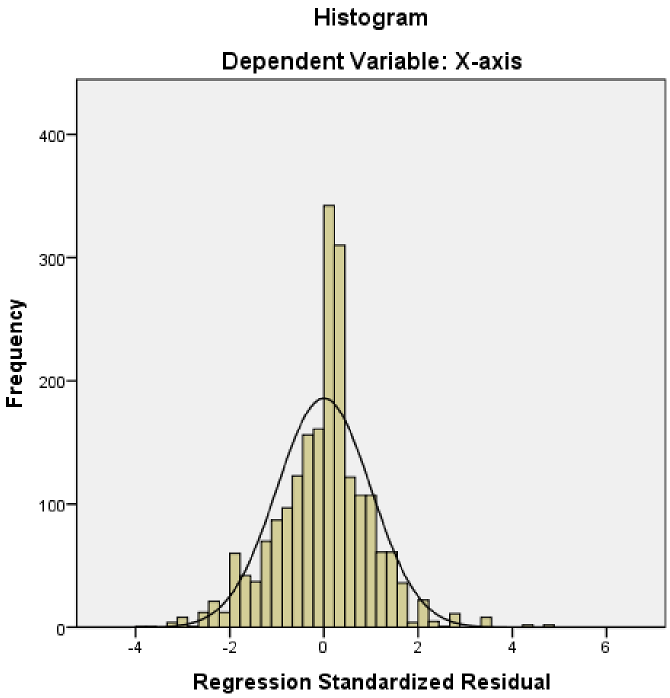


Figure 73: Histogram of acceleration sensor x-axis

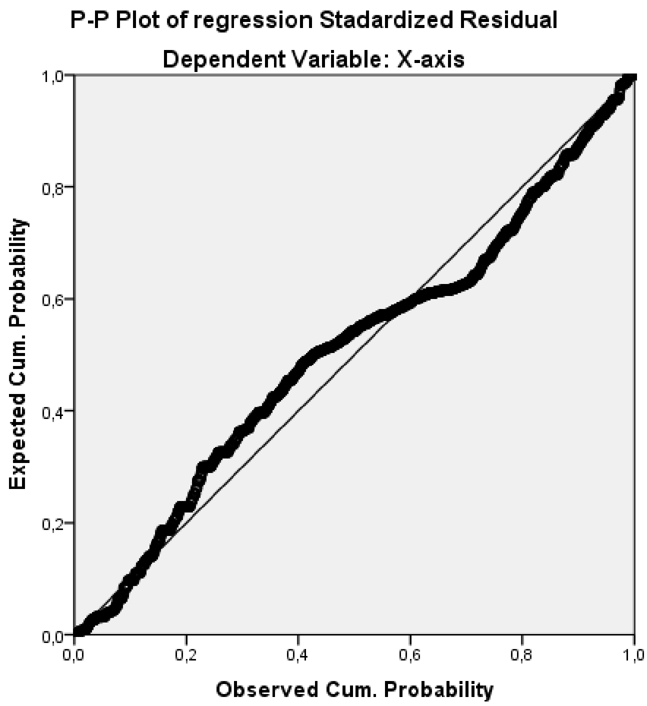


Figure 74: Regression plot of the homoscedasticity of acceleration sensor x-axis

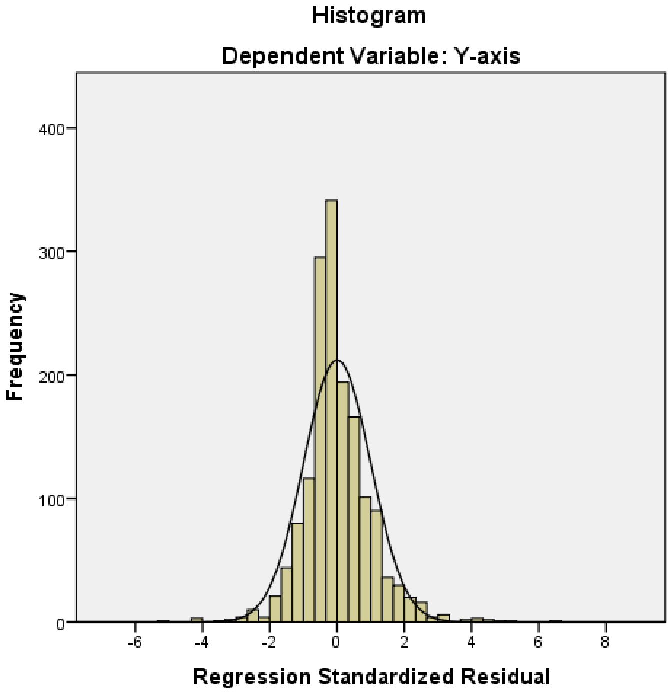


Figure 75: Histogram of acceleration sensor y-axis

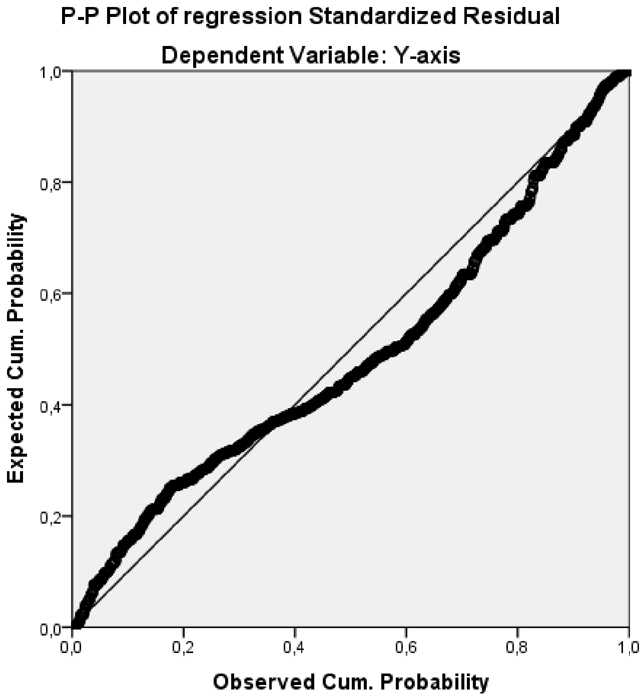


Figure 76: Regression plot of the homoscedasticity of acceleration sensor y-axis

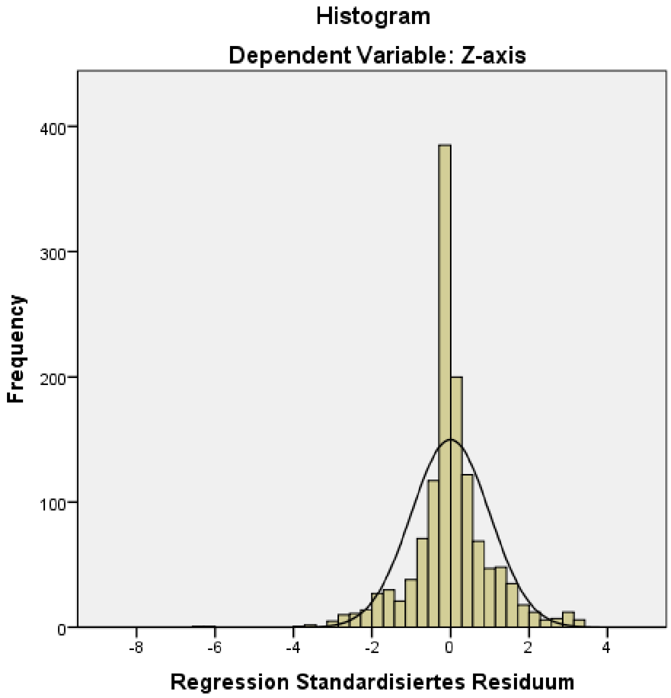


Figure 77: Histogram of acceleration sensor z-axis

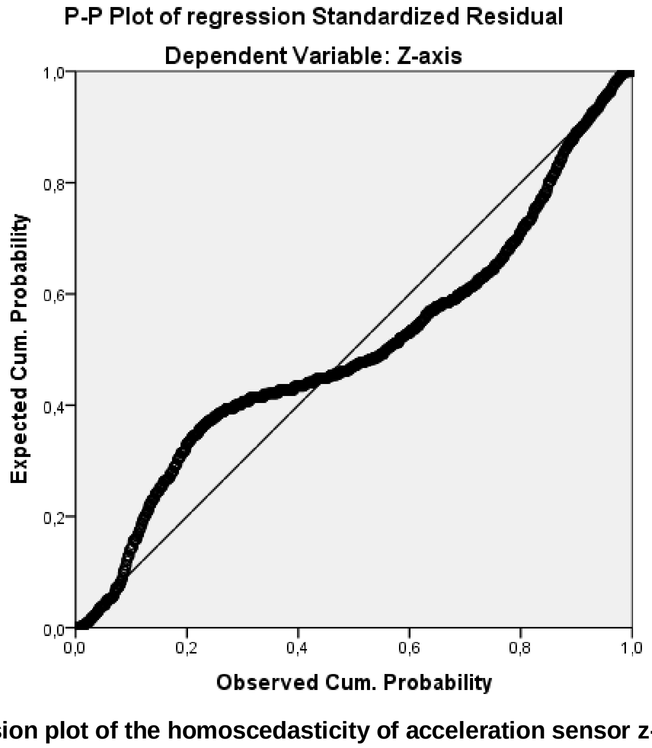


Figure 78: Regression plot of the homoscedasticity of acceleration sensor z-axis

For the x-axis, a maximum standard deviation of ±1.48 g at a centrifugal acceleration of −170 g and a maximum root mean square error of 3.21 at −200 g was observed (Table 6 and Table 7). A maximum standard deviation of ±1.51 g was measured for the y-axis at a centrifugal acceleration of −120 g and a maximum root mean square error of 3.54 at +200 g (Table 8 and Table 9). The maximum standard deviation for the z-axis was determined at ±0.83 g at a centrifugal acceleration of 80 g and a maximum root mean square error of 1.58 at +200 g (Table 10 and Table 11).

Table 6: Acceleration results x-axis positive direction

Acceleration x-axis positive direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
2 g	2.06	0.04	1.86	2.26	0.07
4 g	3.81	0.27	2.34	4.07	0.17
8 g	7.99	0.04	7.87	8.12	0.04
12 g	12.27	0.28	11.50	12.77	0.38
16 g	16.14	0.22	15.57	16.54	0.25
20 g	19.95	0.15	19.70	20.20	0.16
40 g	39.23	0.29	39.09	40.85	0.56
60 g	60.52	0.43	59.13	60.74	0.43
80 g	80.27	0.29	79.65	80.91	0.36
100 g	100.95	0.62	97.98	102.24	1.07
120 g	119.62	0.82	118.48	121.24	0.94
140 g	140.93	0.38	139.67	141.61	0.91
150 g	150.22	0.44	148.93	150.80	0.45
160 g	160.78	0.57	159.37	161.74	0.87
170 g	170.84	0.37	169.54	171.43	0.67
180 g	178.94	0.41	178.37	180.00	1.25
190 g	189.70	0.39	188.54	190.67	0.58
200 g	198.25	0.37	197.91	200.00	0.96

Table 7: Acceleration results x-axis negative direction

Acceleration x-axis negative direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
-2 g	-2.34	0.16	-2.56	-1.83	0.37
-4 g	-4.38	0.20	-4.58	-3.84	0.41
-8 g	-8.30	0.11	-8.51	-8.00	0.28
-12 g	-12.10	0.16	-12.58	-11.73	0.16
-16 g	-16.28	0.45	-17.00	-15.50	0.49
-20 g	-20.04	0.36	-21.00	-19.50	0.35
-40 g	-40.61	0.65	-41.50	-38.50	0.78
-60 g	-59.63	0.62	-61.50	-58.50	0.88
-80 g	-81.02	0.40	-82.00	-79.50	0.77
-100 g	-101.12	0.90	-103.50	-99.50	1.12
-120 g	-121.32	1.19	-123.00	-117.00	1.43
-140 g	-140.76	0.64	-142.00	-139.00	0.65
-150 g	-151.88	1.00	-153.50	-150.00	1.57
-160 g	-160.80	1.01	-162.00	-159.50	0.53
-170 g	-170.27	1.48	-172.50	-169.00	0.99
-180 g	-179.61	0.88	-180.50	-178.00	1.44
-190 g	-189.43	0.96	-192.00	-188.00	1.68
-200 g	-197.75	0.96	-199.00	-197.00	3.21

Table 8: Acceleration results y-axis positive direction

Acceleration y-axis positive direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
2 g	2.09	0.26	1.06	2.56	0.27
4 g	4.38	0.18	3.80	4.63	0.39
8 g	8.55	0.14	8.02	8.81	0.50
12 g	13.08	0.42	11.78	13.71	1.06
16 g	16.37	0.46	15.50	17.50	0.51
20 g	20.49	0.43	19.50	21.00	0.53
40 g	39.98	0.81	39.00	42.00	0.86
60 g	61.12	0.91	60.00	62.50	1.09
80 g	81.05	0.70	78.50	82.50	0.79
100 g	101.07	0.85	99.00	102.50	0.87
120 g	121.23	1.51	119.00	124.50	1.50
140 g	141.39	0.86	139.50	143.00	0.87
150 g	151.70	1.00	149.00	155.00	1.08
160 g	160.54	0.48	159.50	161.50	0.91
170 g	171.70	0.57	170.50	173.00	0.63
180 g	181.70	1.00	179.00	185.00	1.00
190 g	190.50	0.46	189.50	191.50	1.15
200 g	198.17	0.82	197.00	199.50	3.54

Table 9: Acceleration results y-axis negative direction

Acceleration y-axis negative direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
-2 g	-1.92	0.22	-2.29	-1.15	0.23
-4 g	-3.68	0.09	-3.84	-3.37	0.29
-8 g	-7.83	0.03	-7.88	-7.77	0.09
-12 g	-11.93	0.10	-12.07	-11.56	0.12
-16 g	-16.29	0.25	-16.50	-15.53	0.53
-20 g	-19.85	0.19	-20.21	-19.61	0.20
-40 g	-41.46	0.53	-42.16	-40.39	1.99
-60 g	-60.20	0.29	-60.87	-59.26	0.91
-80 g	-80.86	0.17	-81.16	-80.53	1.76
-100 g	-100.16	0.44	-101.03	-98.13	1.33
-120 g	-119.93	0.78	-121.74	-118.71	1.48
-140 g	-140.06	0.33	-140.84	-139.63	1.64
-150 g	-149.67	0.22	-150.00	-149.11	1.33
-160 g	-160.06	0.31	-160.66	-159.42	1.85
-170 g	-169.66	0.81	-170.63	-168.37	1.73
-180 g	-179.10	0.36	-179.66	-178.42	1.13
-190 g	-189.26	0.25	-189.63	-188.53	1.37
-200 g	-196.76	0.92	-197.71	-195.21	1.36

Table 10: Acceleration results z-axis positive direction

Acceleration z-axis positive direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
2 g	2.05	0.07	1.73	2.19	0.08
4 g	4.07	0.03	4.03	4.14	0.07
8 g	8.21	0.08	7.92	8.35	0.20
12 g	12.21	0.19	11.60	12.46	0.26
16 g	16.05	0.09	15.95	16.41	0.09
20 g	20.46	0.22	20.08	20.96	0.45
40 g	40.88	0.22	40.46	41.22	0.78
60 g	59.83	0.15	59.44	60.04	0.39
80 g	79.79	0.83	76.64	81.36	0.93
100 g	100.58	0.31	100.08	101.12	0.40
120 g	121.21	0.34	120.54	121.92	0.89
140 g	140.51	0.26	139.76	141.02	0.27
150 g	151.11	0.24	150.76	151.50	0.67
160 g	160.04	0.20	159.80	160.42	0.51
170 g	170.21	0.57	169.00	171.02	0.65
180 g	181.11	0.24	180.76	181.50	0.58
190 g	190.04	0.20	189.80	190.42	0.60
200 g	199.25	0.77	197.02	200.00	1.58

Table 11: Acceleration results z-axis negative direction

Acceleration z-axis negative direction					
Calc. Centrifugal acc (g)	Mean (g)	± SD (g)	Min (g)	Max (g)	RMSE (g)
-2 g	-1.92	0.33	-2.17	-1.05	0.33
-4 g	-3.92	0.04	-4.08	-3.86	0.09
-8 g	-8.02	0.04	-8.10	-7.89	0.04
-12 g	-11.94	0.23	-12.41	-11.63	0.23
-16 g	-16.73	0.28	-17.13	-16.07	0.77
-20 g	-19.65	0.24	-19.98	-18.76	0.44
-40 g	-39.85	0.38	-40.33	-39.00	0.41
-60 g	-60.26	0.46	-62.13	-59.48	0.49
-80 g	-80.16	0.30	-80.63	-78.65	0.31
-100 g	-100.82	0.65	-101.33	-98.30	0.96
-120 g	-118.75	0.55	-121.07	-118.22	1.48
-140 g	-141.43	0.48	-142.39	-139.96	1.36
-150 g	-150.24	0.50	-151.41	-149.46	0.50
-160 g	-159.70	0.41	-160.50	-158.43	0.62
-170 g	-170.17	0.55	-170.87	-169.15	0.54
-180 g	-180.60	0.70	-181.61	-180.00	0.73
-190 g	-190.09	0.62	-190.87	-188.89	0.62
-200 g	-200.14	0.20	-200.28	-200.00	0.16

A linear regression was carried out to validate the sensor-derived angular rotation in three-dimensional space against an electrical potentiometer used within the gimbal angular validation device. The results of the regression analysis for the yaw, pitch and roll angle shows a Pearson $R = 0.99$ of sensor-derived angular rotation around the yaw axes. The analyses of the pitch axes resulted in a Pearson $R = 0.99$ and an $R = 0.99$ for the roll axes. Significance was analysed with $p < .001$ for the applied F statistic using an alpha of 5% ($p < .001$) for the rotation around the yaw axes. A significance of $p < .000$ was achieved for the analysis of the pitch angular rotation validation using an alpha of 5%. The roll angular validation was analysed with an alpha of 5% ($p < .000$) with a significance of $p < .000$.

The results obtained from the angular rotation validation testing, including an alpha of 5% are displayed in Figure 79 to Figure 81 using a sample size of ~ 17,000 for each of the three-axis yaw, pitch and roll tested.

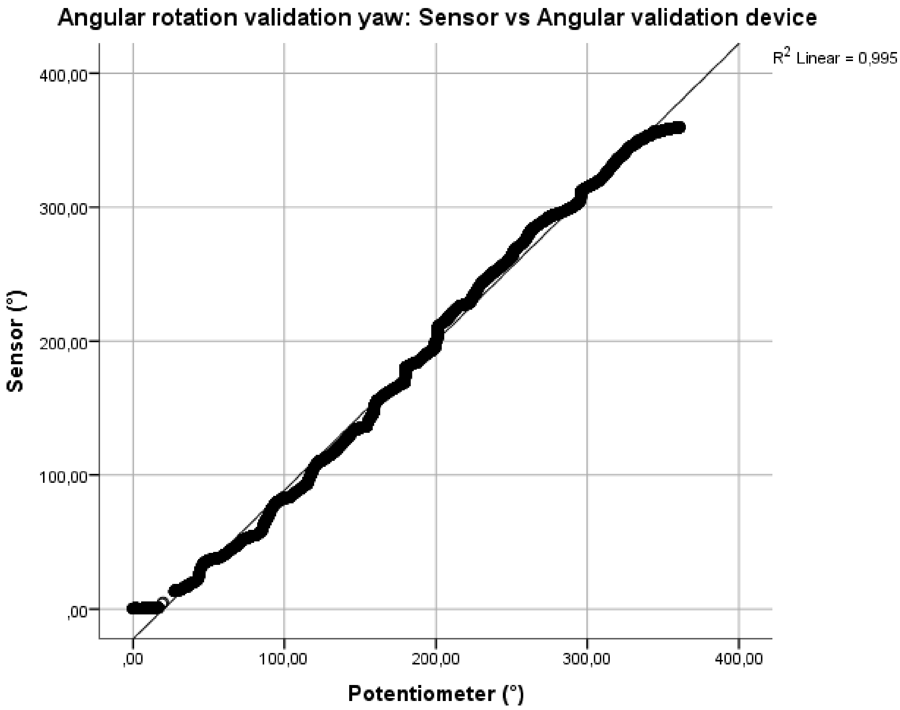


Figure 79: Angular rotation validation yaw

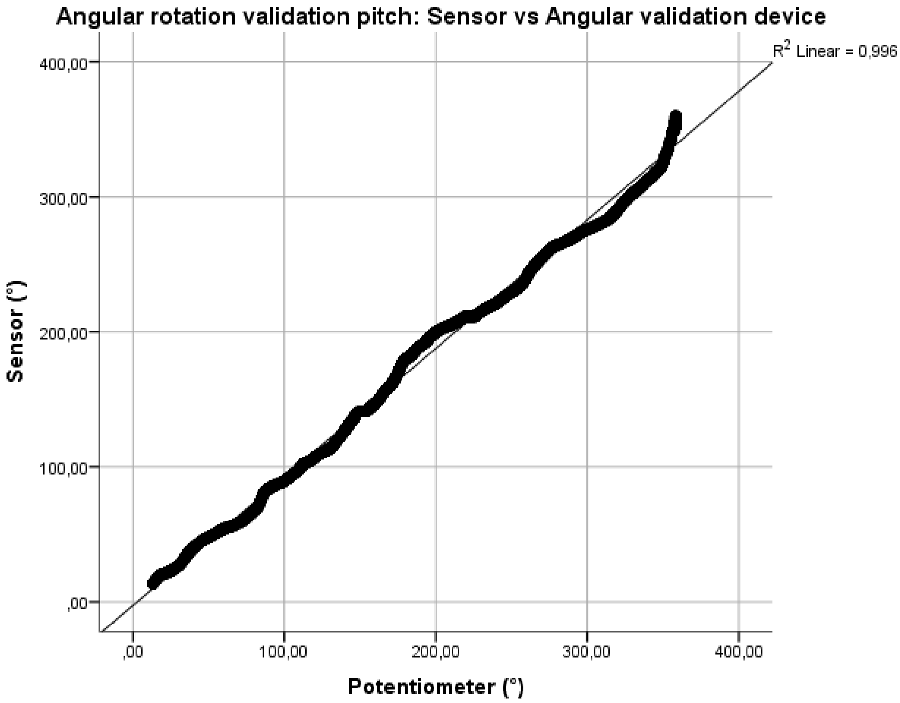


Figure 80: Angular rotation validation pitch

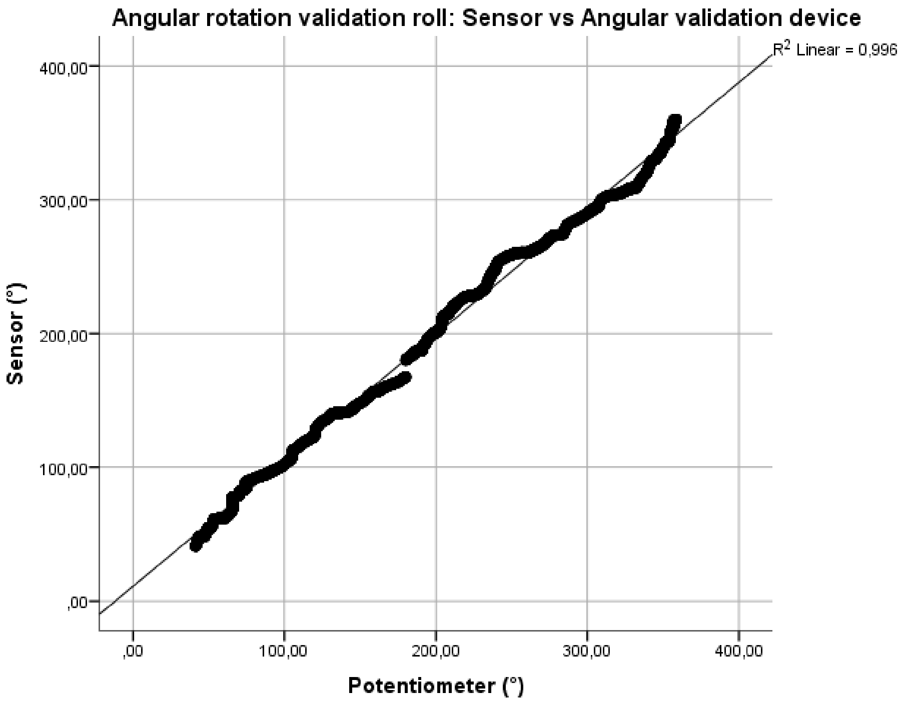


Figure 81: Angular rotation validation roll

Figure 82 to Figure 87 represent the analysis of homoscedasticity and normal distribution of the angular residuals of the yaw, pitch and roll rotational validation testing.

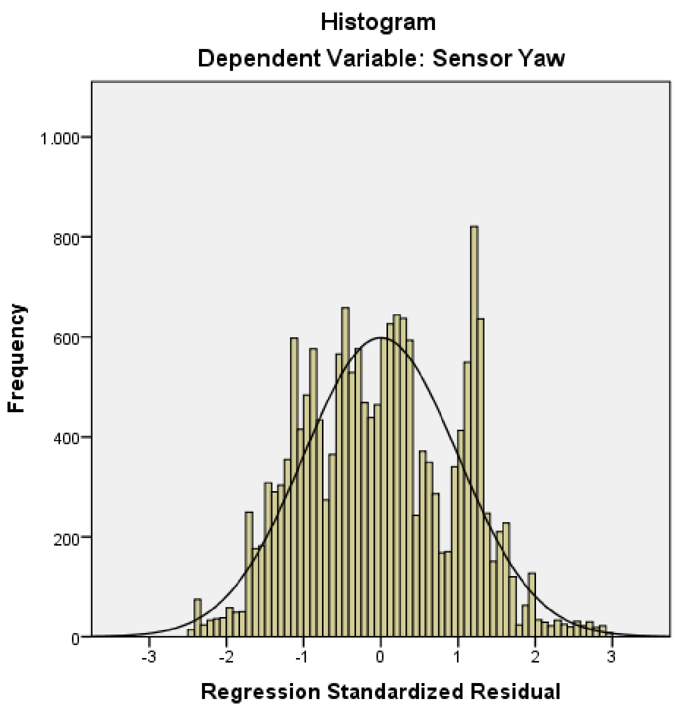


Figure 82: Histogram of angular rotation sensor yaw

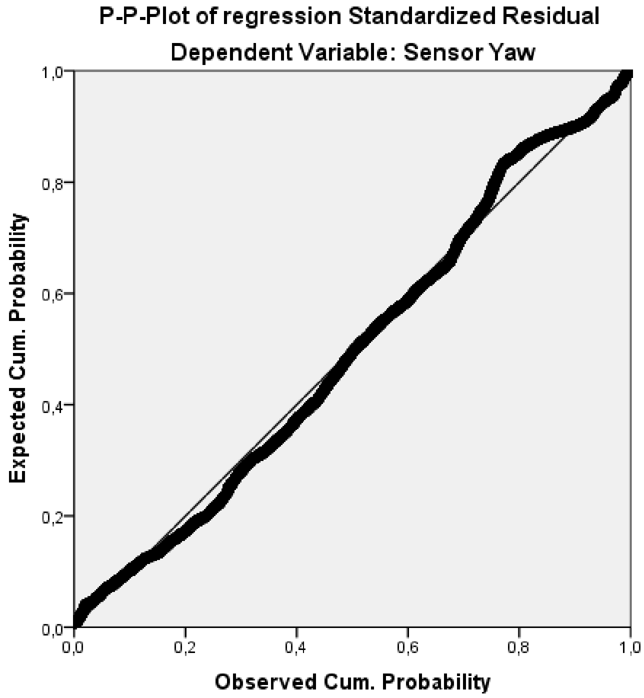


Figure 83: Regression plot of the homoscedasticity of angular rotation sensor yaw

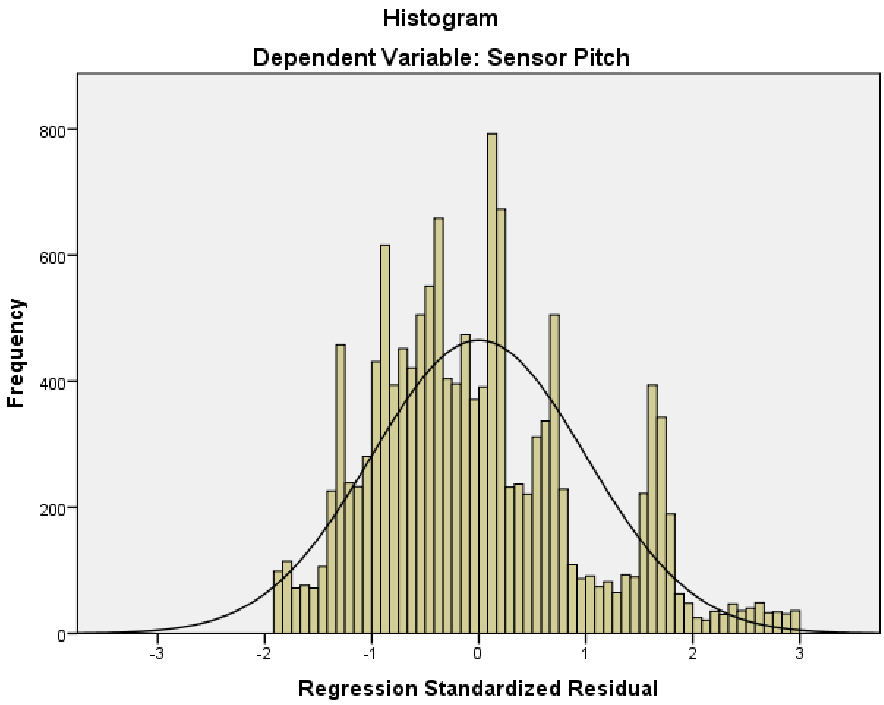


Figure 84: Histogram of angular rotation sensor pitch

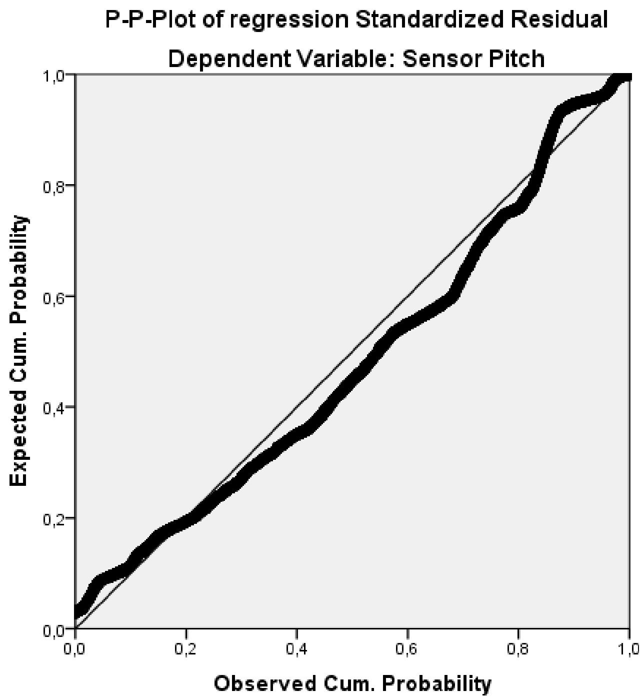


Figure 85: Regression plot of the homoscedasticity of angular rotation sensor pitch

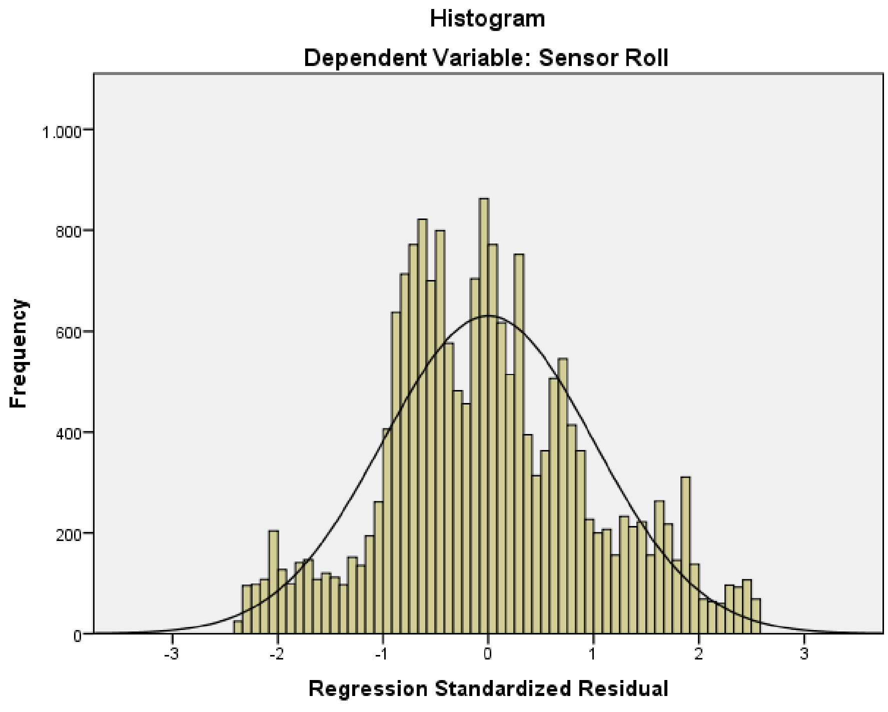


Figure 86: Histogram of angular rotation sensor roll

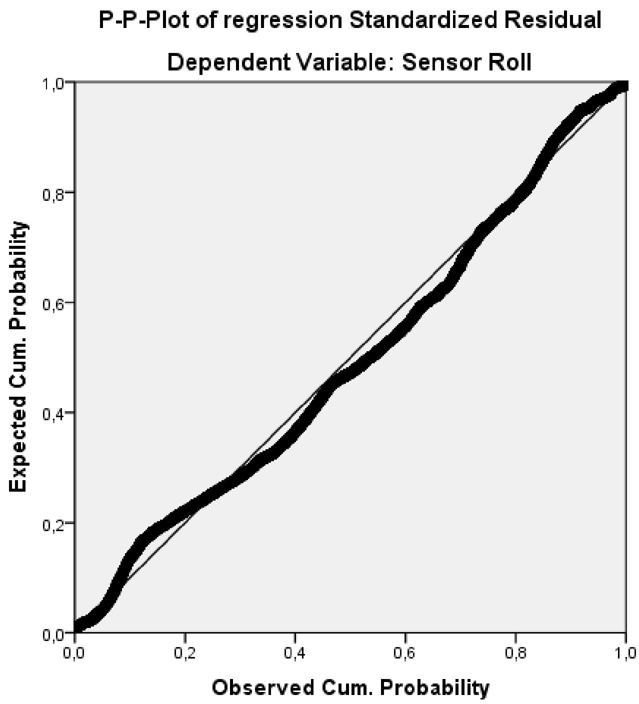


Figure 87: Regression plot of the homoscedasticity of angular rotation sensor roll

The measurement accuracies achieved using the developed validation devices could be confirmed in a further validation examination of the sensor output data in comparison to the Vicon motion capture system. The validation of the sensor data was obtained during a test subject survey with a correlation to the Vicon measurement system with a Pearson R = 0.98 ($p < 0.001$) of the measured sensor accelerations and an R of 0.98 ($p < 0.001$) of the measured angular rotation for the three examined axes of rotation and accelerations with an alpha of 5%.

The system-derived velocity determination based on the developed zero-velocity-update was also validated using a marker-based Vicon motion capture system. The validation of the system-derived punch velocity showed a high significant correlation compared to the Vicon motion capture-derived punch velocity with R = 0.97 ($p < 0.001$) with a level of significance of 5%. The validation of the automatic determination of punch-time showed a significant correlation with the Vicon motion capture system of R = 0.95 ($p < 0.001$).

The conducted angular drift test in the five-minute drift trial (Figure 88) shows the greatest drift in the roll angle between 1.32° to -1.06°. The lowest drift was observed in the yaw axis between 0.15° and -0.35° followed by a drift between 0.5° and -0.13° in the pitch axis of rotation. Analysing the drift in acceleration shows a minor drift between 0.00g and -0.01g for the y-axis, 0.00g and -0.005g of the x-axis and the lowest drift measured with 0.00g in the z-plane. Extending the trial time by a factor of three to 15 minutes (Figure 89) shows no major deterioration of the drift. Entirely the roll angle drift was increased by 0.01° between 1.33° to -1.07°. Observing the drift in acceleration no increase occurred. Same behaviour is observed for the acceleration in the third trial when increasing the time by a factor of three to 45 minutes (Figure 90). Whereas the roll angular drift is increased by 0.5° in negative as well as positive direction. No increase in drift can be observed for the yaw and pitch axis.

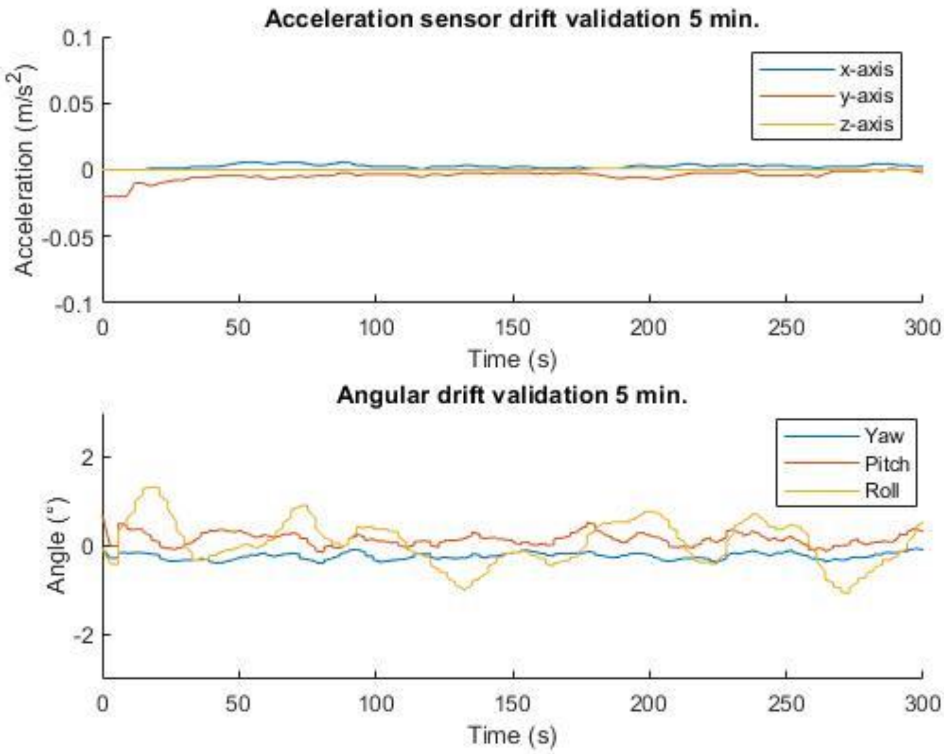


Figure 88: Validation of sensor output drift 5 min. a) drift in acceleration b) drift in angular rotation

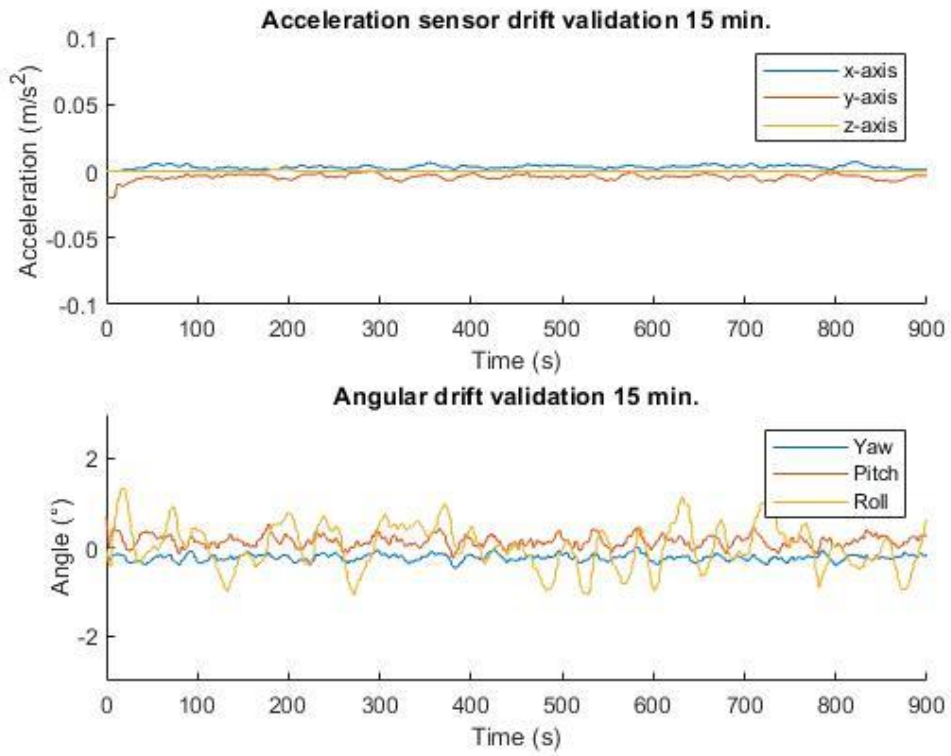


Figure 89: Validation of sensor output drift 15 min. a) drift in acceleration b) drift in angular rotation

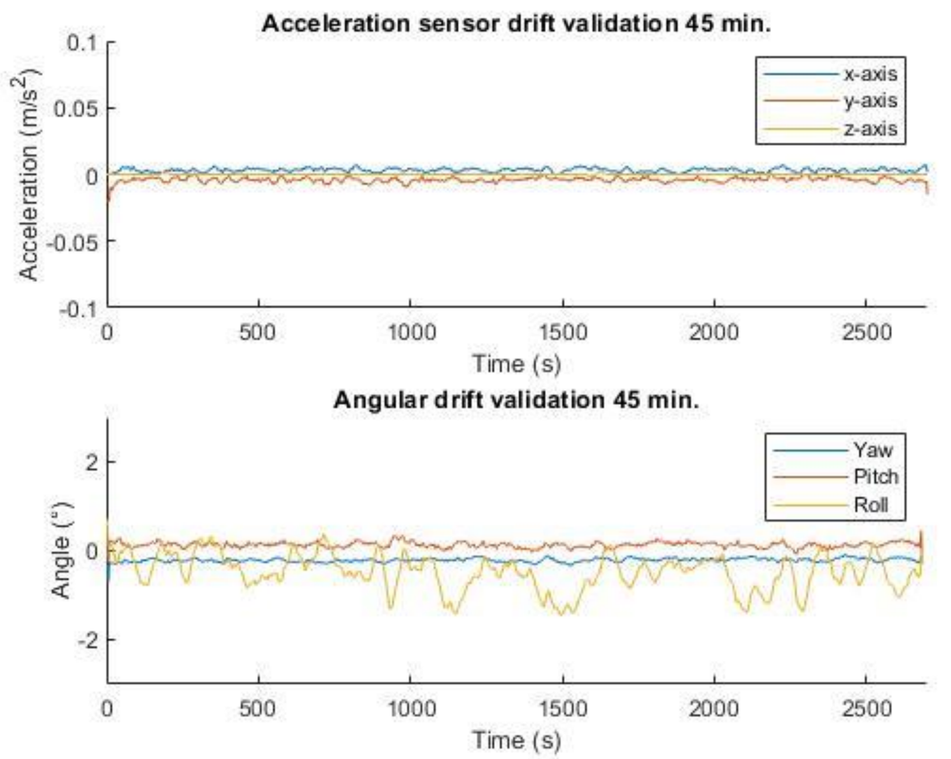


Figure 90: Validation of sensor output drift 45 min. a) drift in acceleration b) drift in angular rotation

4.1.4 Discussion

The developed sensor system will be used in the applied field of boxing training, sparring and competition for athlete performance monitoring purposes. The knowledge gained from experimental data can offer coaches and athletes themselves a tool for analyzing the requirements of a specific punching movement pattern when compared to the movement pattern of an experienced athlete, with the help of the developed boxing monitoring system. The findings can further be used to apply technology analysis for talent identification and promotion in combat sports by the system as it is presented in this paper. Coaches and performance centers can, thus, benefit from this measurement system, as the technical performance of boxing strokes can be measured, and technique correction can be made in the interests of the athlete by objective data. Therefore, this experimental study was conducted to perform a quantitative analysis to validate the novel developed measurement system. Therefore, this experimental study was conducted to perform a quantitative analysis in order to validate the developed innovative measurement system.

In consideration of the literature presented on the validation of wearable devices, it is evident that there are no standardized and generally valid validation methods and parameters, so-called "state of the art methods & parameters" for novel measurement systems such as the system presented by this thesis existent. Therefore, the study consists of different validation methods to validate the measurement system developed comprehensively. The impact force validation refers solely to the gold standard of a Kistler force plate, whereas the inertial measurement unit validation is based on generally accepted but non-standardized methods, such as the specially developed centrifugal device for acceleration validation, potentiometer instrumented gimbal device for angular rotation and an overall Vicon motion capture analysis for the validation of fist rotation, trajectory and punch velocity.

The first part of the study validates the newly developed pressure measurement system with a force measurement platform. As the system is validated in respect to applied forces, the developed measurement system is using the in chapter 3.2.2 presented developed calibration algorithms for force conversion and multiplies the individual measurement signals of the cells to a combined impact force output.

Each system was sampled at different frequencies. Therefore, a data interpolation was conducted with the developed sensor system at 1000 Hz and the Kistler force plate with a frequency of 10,000 Hz. This is due to the processing limitations of the microcontroller used to control the boxing monitoring system. Furthermore, the developed monitoring system has an inbuild threshold of 200 N. This inbuilt threshold is programmed to extract noise from so-called pit pat punches from the data analyses.

The designed, calibrated and incorporated pressure sensor results demonstrate its great applicability for boxing bouts. The presented statistical analysis of the punch force determination validation shows that with an R^2 of 0.99 the developed sensor system enables a significant determination of the impact force while punching compared to the gold standard of a Kistler force plate. The sensor system revealed even greater accuracy for punch forces above 1000 N. Whereas the punch force determination accuracy was reduced to a R^2 of 0.94 for forces below 1000 N. The observed accuracy of $R^2 = 0.94$ was nevertheless within the acceptable accuracy range defined at the beginning of the research work for the dynamic testing.

The analyses of the force–time curve of the monitoring system shows an identical pattern in comparison to the Kistler force plate-derived force–time curve (Figure 68).

During the validation study, the developed sensor system allowed for detecting every punch that was applied to the force plate, and thus, to identify and count all the applied blows from 242 N to 2310 N with a 100% detection accuracy without sensor interferences.

The experimental validation has shown that individual calibration functions for the pressure cells is resulting in a better accuracy outcome than using an overall calibration function for the entire sensor matrix.

The accuracy for all three axes of the accelerometer, gyroscope and magnetometer of the inertial measurement system is also of significant importance. These parameters are used to distinguish between punching technique for subsequent biomechanical analyses experiments on different punching techniques and their effects. Therefore, the validation was conducted in consecutive steps.

The validation of the acceleration was carried out in a first test by means of drop testing. Although these tests showed a high accuracy of $R^2 = 0.99$, this type of validation method is limited. First, the accuracy cannot be correlated with a reference input value and second, the validation range is limited to ±1 g of the Earth's gravitational acceleration. For the validation of the entire sensory measuring range of ±200 g, a special validation centrifuge with sensor mount was subsequently developed and manufactured (Acar & Shkel, 2003; Dong et al., 2018; Sporn, 1961). To simplify the validation of the acceleration, a sensor mount with a 45° inclination was mounted on the rotation platform in order to measure the linearity over two axes simultaneously. During the stepwise testing, it became apparent, that due to the higher rotational speeds of the centrifuge required for this method, that the driving motor, at a simulated rotational acceleration of 180 g did not allow any further acceleration as an internal over-load control led to the motor being switched off. To validate the entire measuring range of the sensor, the three axes were then individually aligned and validated in a flat position on the rotation platform perpendicular to the center of rotation to avoid the problem of internal overload control of the driving motor. With the help of this change of the sensor positioning, the simulated measuring range could be extended up to 200 g. The problem of the internal emergency stop was registered again after a constant acceleration for approximately two seconds at an acceleration of ±200 g. Due to this problem, the acceleration of 200 g could only be measured for a limited instant, unlike the previous measuring stages. Since the ideal measuring range of the sensor is within a range of 10% to 90% of the sensor and accelerations of ±200 g are unlikely, this limitation can be disregarded and was, therefore, neglected in the further validation process. A stronger motor would eliminate this problem, but a new drive shaft mount would need to be designed and manufactured for this purpose. Due to the negligible limitation and the possibility of measuring an acceleration of ±200 g for at least two seconds, this limitation has finally been ignored. For the complete measurement of the acceleration range of +/- 200g of the centrifuge, the centrifuge had to be stopped once during the experiment in order to change the sensor position for negative acceleration and thus validate the complete positive and negative 200g linearity acceleration range.

Another point of discussion is the sensor mounting on the rotation platform. Due to the modification of the sensor mount for separate measurement of the three acceleration axes, the sensor position varied to the axis of rotation with an average deviation of two millimetre during all modifications of the sensor for the different axis tested in x, y and z direction. This displacement is due to the mounting of the sensor mount and its bolt attachments. For the exact determination of the sensor radius from the axis of rotation, the distance was determined after each conversion and taken into account in the calculation of the revolutions per minute (RPM) that had to be accessed.

The analysis of the acceleration data showed a high linearity between sensor-derived acceleration and centrifugal-derived acceleration with an average standard deviation of +/- 0.45 g (min. 0.03g and max. 1.51g) and an average root mean square error of 0.74.

For further analysis, the sensor-derived acceleration was validated through long-term tests. For the validation period, a maximum period of 45 min was chosen to cover the maximum fight duration that can be achieved in a 12-round fight, as is common in the sport of boxing. No anomalies were found compared to the centrifugal validation. A maximum deviation of 0.02 g was measured over a test interval of 5, 15 and 45 min. This small deviation was neglected in the further course of the experimental studies.

The final comprehensive validation of the angular rotation and velocity during the execution of boxing punches showed a high significance compared to the Vicon motion capture system, and thus, demonstrates the developed sensor system's accuracy and reliability for the use in further experimental studies in laboratory as well as non-laboratory experimental settings.

4.1.5 Conclusion

The results of the experimental study presented in this chapter are in accordance with the eights hypotheses, to analyse the validity of the calibration methods used for the calibration of the instrumented sensors in the developed boxing monitoring system. With the objective of an accurate data acquisition in the field of boxing performance analyses.

Given the results of the punch force determination, as well as the measurement of acceleration and movement determination in three-dimensional space, the outcome of the validation experiments conducted demonstrate the significant accuracy of the measurements in predicting boxing-specific biomechanical movement parameters while punching (Table 12).

Table 12: Sensor validation results.

Validation Method (Sensor System vs. …)	Variable	R	*p*
Gimbal device	Angular rotation (°)	0.99	<0.001
Centrifugal device	Acceleration (g)	1.0	<0.001
Kistler Force Plate	Punch Force (N)	0.99	<0.001
	Force-time progression	0.98	<0.001
Vicon Motion Capture System	Angular rotation (°)	0.98	<0.001
	Acceleration (g)	0.98	<0.001
	Velocity (m/s)	0.97	<0.001
	Punch time (throw, contact and retraction phase) (ms)	0.95	<0.001

Note. A 95% Confidence Interval was applied.

According to the validation results, the use of piezoresistive pressure sensors with the application of a dedicated calibration and filter method, enables the measurement of impact forces and motion kinetics in the field of combat sports, with the aid of comparatively inexpensive sensors of significantly great accuracies compared to a Kistler force plate and Vicon motion capture system. The rotation in a three-dimensional space shows furthermore, the possibility to replace a camera system to some extent to be able to display the hand trajectory and punch acceleration in three dimensions. The sport of boxing and other combat disciplines have specific movement patterns which are not analyzed during competition. The developed monitoring system makes it possible to investigate these impact movements in the field and to determine the impact effectiveness from the obtained and analyzed information.

Furthermore, the experiment outlines the critical importance of the validation process for new and unique monitoring systems. The most important criterion for developed sensor systems from and especially for scientific applications is the accuracy of the data acquisition method. These sensor systems have a fundamental influence on scientific research results and in this respect on the derived insights of the information provided by the measurement system used.

The acquired information based on the comprehensive methods stated for the sensor validation is of fundamental importance for the application and execution of upcoming field studies presented in the following chapters, to expand the biomechanical scientific understanding of the sport of boxing.

4.2 Application of a Validated Innovative SmartWearable for Performance Analysis by Experienced and Non-Experienced Athletes in Boxing

The following chapter 4.2 serves to represent and outline the results of the first experimental study conducted in the field of boxing and martial arts. This study also represents the first application of the developed boxing monitoring system for the experimental generation of biomechanical performance data while punching.

The chapter is structured by outlining the objective of the research and presents in particular the existing research gap on which this study is focused. Based on this, a detailed description of the obtained experimental results is outlined. The chapter on the presentation of the applied methods for the analysis of punching technique in experienced versus non-experienced boxer concludes with a discussion and conclusion of the experimental results as well as a research outlook for the following research studies, based on the study presented.

The study presented in this chapter is published in the sensors journal 2021 (Menzel and Potthast, 2021b, 21, 7882).

4.2.1 Objective

An athlete's sporting performance depends to a large extent on the technical execution of the athletic motion in order to achieve maximum effectiveness in physical performance in attacking and defensive situations (McGarry et al., 2013). To this end, performance analysis provides a useful means of classifying and quantifying athletic prowess in terms of the significant performance aspects of a sport, to provide feedback to the athlete themself as well as their coaches. The gathered data can consequently be used to modify and optimize the athletes training and therefore their future performance (Baca et al., 2020; Baca & Gröber, 2020; Hughes & Bartlett, 2002; Thomson et al., 2013). Although professional performance analysis from a technical, biomechanical, physiological and psychological perspective is regularly applied in many sports, such as football, rugby, athletics or the rebound disciplines like tennis (Andreassen et al., 2019; Baca et al., 2020; Baca & Gröber, 2020; Carling et al., 2005; Cui et al., 2017; Gómez et al., 2019; Harper et al., 2014; Hughes & Bartlett, 2002; Kempton et al., 2013; Kempton & Coutts, 2015; McGarry et al., 2013; Rampinini et al., 2009; M. R. Smith et al., 2016; Torres-Luque et al., 2018), there are few studies conducted in the sport of boxing that describe a comprehensive and sport-related performance analysis in this regard as outlined in detail in chapter 2.2.

The number of studies focusing on performance analysis becomes even more limited in the field of boxing and martial arts when considering the comparison between experienced and non-experienced boxing athletes.

The investigation of sport-relevant techniques and the comparison of performance characteristics between experienced and non-experienced athletes has far-reaching potential for understanding a sport and, in particular, to highlight competition-relevant performance characteristics which differentiate athletes of different sport-specific levels of experience (del Villar et al., 2007; Furley et al., 2016). These studies enable, among other factors, the investigation of technical execution of an athletic locomotion, imagery, anticipation and muscle activity patterns during the execution of a specific athletic movement (Arvinen-Barrow et al., 2007; Favre et al., 2007; VencesBrito et al., 2011).

Within the study object of the expert–novice paradigm, numerous investigations have attempted to identify the characteristics that define an expert compared to a novice and how the expert performs different technical characteristics in specific movements (del Villar et al., 2007). Reviewing existing literature on the comparison of experts and non-experts, it becomes apparent that in some disciplines, such as soccer, tennis or rugby, it highlights useful performance criteria for experienced and high-performance athletes (Bächlin & Tröster, 2012; del Villar et al., 2007; Fontana, 2007; Franks, 1993, 1993; Millslagle, 2002; Onate et al., 2010; Reina et al., 2007; Tenenbaum et al., 1994; Vaz et al., 2012).

However, this type of scientific research has so far found only limited application in the field of boxing and martial arts. Such studies focus primarily on the number of punches or the maximum force of punches thrown during a boxing match or sparring to conduct a comparison between the two groups of experienced and non-experienced athletes (Favre et al., 2007; Lenetsky et al., 2013b, 2018; M. S. Smith et al., 2000; Turner et al., 2011b). Analysis of the technical implementation and trajectory of the fist during a boxing punch in order to differentiate between the technical execution of experienced and non-experienced athletes is yet to be studied.

Predominantly in existing studies in the field of boxing sciences, the focus is on experienced athletes without discussion of athletes with less or no experience in the type of sport (Ashker, 2011; Davis et al., 2015; Lenetsky et al., 2019; Piorkowski et al., 2011; Stanley et al., 2018; Thomson & Lamb, 2016a; Walilko, 2005; Whiting et al., 1988c).

Based on this research gap, the study presented in chapter 4.2 concentrates on the expert–novice paradigm with the goal of analyzing punching technique in experienced versus non-experienced boxers to identify characteristics of an expert athlete. Therefore, a specific focus is laid on the kinematic characteristics of the fist in three-dimensional space, starting from the defensive position, until the point of contact with the target and return, back to the defensive position. The objective of the study is to highlight the distinctive movement patterns performed by athletes with different levels of experience for the four main punching techniques: the straight cross, straight jab, the semi-circular uppercut and the hook punch (Thomson & Lamb, 2016b). The motion pattern is an important variable to analyze incorrect punch trajectories and the deviation from the ideal path of the fist for the individual punching techniques (Saponara, 2017, p. 2546). The experimental research investigates, in addition to the trajectory and orientation of the movement in three-dimensional space, the resulting punch force, punch speed and punch time separated into the three phases of the throw, contact and retraction period, between the two tested groups of experienced and non-experienced boxing participants.

The information obtained through this study offers further insights into the technical execution of experienced boxers and may provide specific technique training recommendations. As stated by McGarry et al. (2013), technique effectiveness and efficiency are developed and established in comparison with the athlete’s performance by identifying an optimal technical model or reference criteria (McGarry et al., 2013, p. 215). Furthermore, this study illustrates the potential benefits of the use of advanced sport equipment to provide reliable augmented feedback necessary for athletes to improve (Maslovat & Franks, 2008; McGarry et al., 2013) and overcome limitations on the accuracy with which coaches and trainers can retrieve and improve critical events within the scope of performance (McGarry et al., 2013).

4.2.2 Methodology

The following chapter is used to present the applied methodologies for the analysis of punching technique in experienced versus non-experienced boxer. Therefore, the experimental setup and protocol, data analysis and statistical analysis is outlined in detail.

a) Ethics statement

The scientific study presented in this chapter was examined by the Ethics Committee of the German Sport University Cologne (Cologne, Germany) for its ethically correct applicability. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021). Each participant received a written description of the experimental procedure before the tests were started. The collection of data could only be started after signing the written declaration of consent before the participants were granted permission to participate in the presented experiment.

b) Participants

Thirty-one subjects in total participated in the present study. At the beginning of the experiment, the participants were divided into two groups according to their level of experience in boxing. This was followed by the division, based on their experience in boxing in years. As in the experiment by Lenetsky et al. (2019), volunteers with at least three years of boxing experience were classified as experienced athletes and participants with less than three years of boxing experience were classified as non-experienced athletes to clearly distinguish between the two observation groups. The group of experienced athletes comprised 11 subjects (mean ± SD: age = 26.29 ± 4.54 years, height = 178.86 ± 6.57 cm, body mass 79.43 ± 9.31 kg and experience 7.43 ± 3.34 years), whereas the group of non-experienced athletes comprised 20 subjects (mean ± SD: age = 21.67 ±

2.46 years, height = 179.27 ± 9.76 cm, body mass 75.92 ± 8.15 kg and experience 0.36 ± 0.44 years) (Table 13). All participants were informed in advance of the data collection protocol as well as the risks and benefits of the experiment. The measurements were conducted in the boxing gym of the German Sport University Cologne, Germany, following and thus in a known training environment of the participants. Prior to the experimental testing, each participant was instructed with a boxing specific warm up for muscle activation as well as to become familiar with the setting and the equipment to be used for data acquisition.

Table 13: Subject characteristics of the experienced and non-experienced groups of boxing athletes.

	Experienced (n = 11)	Non-experienced (n = 20)
Age (years)[1]	26.29 ± 4.54	21.67 ± 2.46
Height (cm) [1]	178.86 ± 6.57	179.27 ± 9.76
Bodymass (kg) [1]	79.43 ± 9.31	75.92 ± 8.15
Experience (years) [1]	7.43 ± 3.34	0.36 ± 0.44

[1]Values are means ± SD

c) Experimental setup and protocol

To analyze punching technique in experienced versus non-experienced boxers, the subjects were instructed at the beginning of the study on the course of the experiment and the punching techniques to be thrown. This was to avoid misinterpretation of the punching techniques by the group of the inexperienced boxing participants.

The kinetic and kinematic data collection by means of the monitoring system included the measurement of punch force, punch acceleration, punch speed, fist trajectory and orientation in three-dimensional space as well as the punch time, separated into the throw, contact and retraction time.

The data acquisition was conducted using the developed and instrumented boxing glove monitoring system. The boxing monitoring system was instrumented into a 12-ounce (340.2 gram) AIBA certified, 2017 model, boxing glove from Adidas (Adidas AG, Herzogenaurach, Germany) for each subject for data collection purposes. A 40 kg punching bag made out of leather from Paffen Sport (Paffen Sport GmbH & Co. KG, Cologne, Germany) was used on a wall-mounted suspension to perform the punches against a defined and stationary target.

The data acquisition of the boxing monitoring system was conducted with a data acquisition frequency of 1000 Hz and stored in a buffer to allow a comprehensive post processing and analysis. The high measuring frequency of 1000 Hz was selected to ensure that the entire punch course, including the throw, impact and retraction, is recorded for all kinetic and kinematic stroke parameters to be collected.

The experimental protocol consists of four punching techniques to be executed by all participants. These four punching techniques are the most used techniques in boxing competition consisting of the two straight techniques of the jab and cross punch as well as the semi-circular uppercut and hook punching technique (Thomson & Lamb, 2016b). To carry out the impact tests, the test subjects were instructed to perform the impacts with two different strike intensities with the help of a defined survey protocol. Each intensity was thrown five times. The study focused on the kinetics and kinematics of the punches thrown on the suspended boxing bag. The punches were accomplished by all participants starting in a static defense positioning facing the boxing bag as the target to be hit. At the beginning of each punching technique, the test subjects were encouraged to determine and test their own punch distance. Initially, the first intensity of each type of stroke was performed slowly with a special focus on technique performance. Subsequently, the subjects were instructed to perform the test with full effort, i.e., a maximum of 100% punch intensity. During the execution of the maximum punching intensity, the test persons were actively motivated to perform the strokes with their utmost intensity. The punch still must be executed with a technique close to competition in respect to time, as a decisive criterion of a successful punch is the duration of the punching time.

This criterion is especially important in sparring or real competition situations, as strokes that take a long time to execute allow the opponent more time to react to the attack. The opponent may have a reduced reaction time for a quickly executed punch and therefore a lower chance to block the punch or even to execute a counterattack. This was to avoid strokes executed beyond the realistic punching technique used in sparring or competition.

After performing the punch, the test participants were instructed to return immediately to the defensive position, as in a sparring or competition scenario, to protect themselves against counterpunches. The subjects were instructed to remain in their defensive position for at least two seconds before the consecutive punch had to be performed.

The coordinate system for the three-dimensional measurement in space was defined as illustrated in Figure 91. The acceleration in x-axis is pointing in punch direction (anterior positive, posterior negative), the y-axis to the medial and lateral side (medial positive, lateral negative) and the z-axis in the direction of the palm (dorsal positive, palmar, negative).

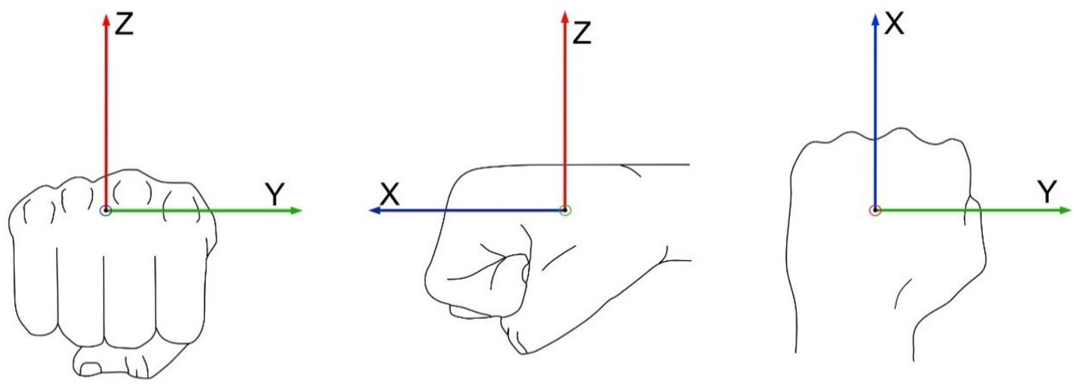


Figure 91: Direction of acceleration. The acceleration in x-axis is pointing in punch direction (anterior positive, posterior negative), the y-axis to the medial and lateral side (medial positive, lateral negative) and the z-axis in the direction of the palm (dorsal positive, palmar, negative).

d) **Data acquisition**

The biomechanical performance data collected and buffered during the experimental execution of the punching tests were processed for further data handling and advanced data analysis using custom-built MATLAB (2018b) (The MathWorks, Natick, USA) routines.

For the analysis of the biomechanical data of punch force, velocity and acceleration, the maximum values achieved for the individual impacts were determined and used for the further data analysis.

The data analysis of the defensive position was normalized for each subject individually. Therefore, the trajectory and orientation in three-dimensional space of the stroke was determined from the defensive position taken at the start of the first punch thrown. On this basis, the deviations of the defensive position for the following performed strikes were analyzed. This procedure was executed for all of the tested punching techniques. Rotations and movements in three-dimensional space were analyzed in terms of absolute angular rotations in degrees and motion trajectories in centimeters, starting from the subject's prior determined defensive position.

The punch time was normalized in order to analyze the strike pattern of the thrown punching techniques to each other as well as among all participated subjects, based on the standardized sampling frequency of 1000Hz. The absolute punch time was divided into the three phases of ‘attack’, ‘contact’ and ‘retraction’ back to the defensive position. The attacking time was determined from the initial movement of the fist in the direction of the striking object in the x-axis and finished by the first contact with the target to be hit. The contact phase was defined as the time period in which the glove is in contact with the target to be hit. This phase was further divided into the exposure time until maximum compression at the targeting object, up to the maximum achieved impact force was achieved and the pre-release phase until the hand is released from the target. The retraction time was measured starting with the release of the fist from the object to be hit until the return to the defensive position and a reduced acceleration of the fist was finalized. Furthermore, the fist velocity, peak force, punch impulse and punch trajectory were measured and analyzed in three-dimensional space to compare the punching techniques of experienced and non-experienced athletes.

e) **Statistical Analysis**

The statistical analysis is conducted using the analysis software, IBM SPSS Statistics for Windows, Version 23.0 (IBM Corporation, New York, USA).

The technical movement profiles between experienced and inexperienced boxers were calculated and compared as mean and standard deviation (SD) for each of the four punching techniques performed.

At the beginning of the statistical analysis of the experimental data, the data sets of the tested subjects were tested on outliers and anomalies. Outliers were declared to be measurements that are more than one and a half times the standard deviation of the mean value. Data points with a value more than three times the standard deviation of the mean value were defined as strong outliers. All outliers are represented by circles (light outlier) and asterisk´s (strong outlier) within the presented box-whisker plots.

Due to the greater power of expression, the Shapiro–Wilk test was used in preference to the Kolmogorov–Smirnov test for the analysis of normal distribution. A three-way ANOVA was used to evaluate group differences. The individual differences between the two groups of participants as well as punching techniques were analyzed by means of a Tukey or Games–Howell post hoc test if the homogeneity of variances was not fulfilled. The check of homogeneity of the error variances was performed by the Levene Test ($p > 0.05$). The 95% confidence intervals were calculated with an alpha level set of $p < 0.05$ to verify statistical significance.

4.2.3 Results

The following chapter serves to present the results of the punching techniques performed to investigate the technical performance analysis between experienced and inexperienced boxing athletes, using the developed sensor system. Figure 92 presents the trajectory of the fist from the defensive stance to the punching object of the punching bag and return to the defensive stance of the four punching techniques performed throughout the experimental study. The figure shows a clear distinction between the punching techniques tested with regard to displacement in three-dimensional space. The straight punching techniques of the jab and cross punch are executed in a straight line along the anterior–posterior sagittal plane (*x-axis*). The hook punching technique, on the other hand, shows a semicircular striking movement in a lateral direction on the transverse plane around the sagittal axes (*z-axis*). Whereas the second semicircular punching technique of the uppercut is performed in a semicircular movement around the horizontal axes (*y-axis*) from anterior to posterior (Figure 92).

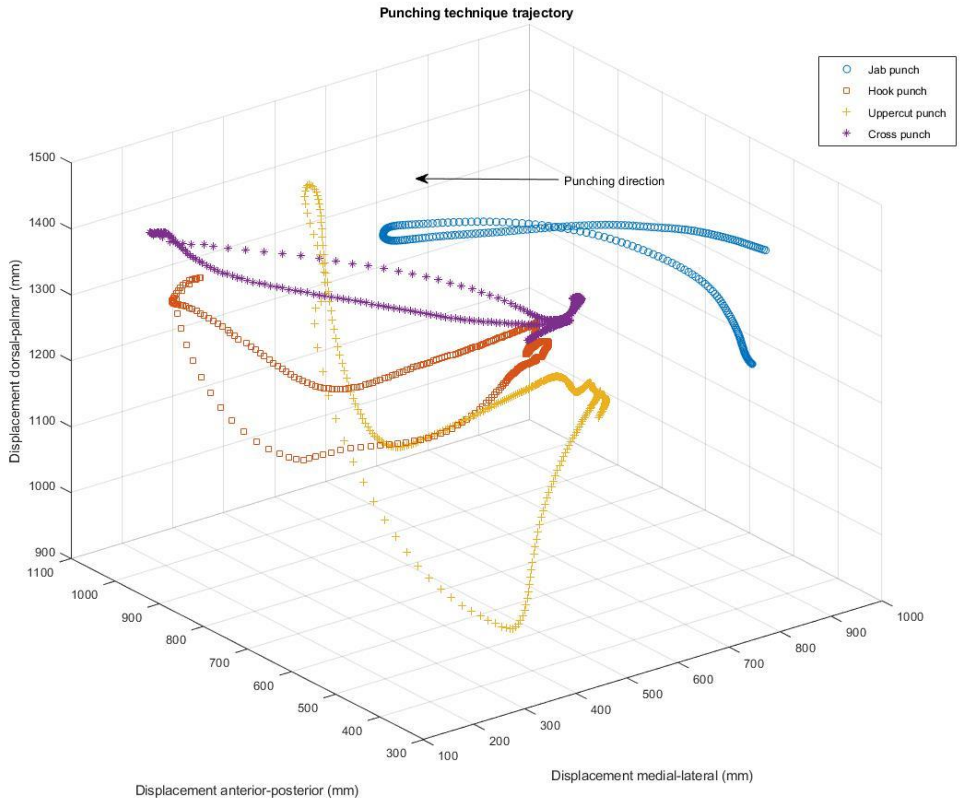


Figure 92: 3D displacement graph of single punches performed against a boxing bag

The conducted three-way ANOVA showed a statistically significant difference for the overall analysis between the two groups of experience level $F(21.00, 51.00) = 3.221$, $p < 0.001$, partial $\eta^2 = 0.570$, Wilk's $\Lambda = 0.430$; the punching techniques performed $F(63.00, 153.076) = 11.725$, $p < 0.001$, partial $\eta^2 = 0.827$, Wilk's $\Lambda = 0.005$; and for the interaction between the expert level and punching techniques thrown $F(63.00, 153.076) = 1.550$, $p = 0.016$, partial $\eta^2 = 0.388$, Wilk's $\Lambda = 0.229$.

A detailed presentation of the results for the different stroke types of the two subject groups is presented in the subsequent sections.

Cross punch results

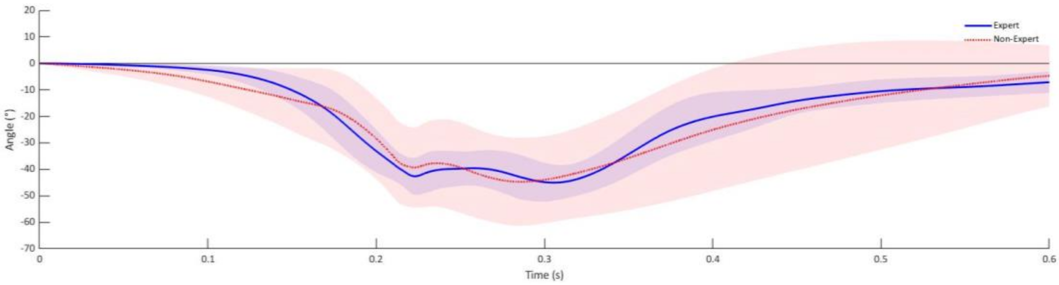
The first punching technique tested, using the developed boxing monitoring system, was the cross. Similar to the jab, the cross is a straight punch. In contrast to the jab (leading hand), the cross is performed by means of the strong striking hand.

The data sets of the tested experienced and non-experienced subject groups were analysed for normal distribution at the start of the statistical analysis of the cross punches using the Shapiro-Wilk test. The data sets of both groups of subjects showed a normal distribution of the data with $p > .05$.

The comparison of the initial fist position shows that the defensive position of the subjects of the experienced testing group take their fist in an average rotation of 62.68° (SD = 5.23°) around the transverse axis with a supination of 108.32° (SD = 16.57°) in the sagittal axis towards the target. The initial defensive position of the group of non-experienced subjects differed in comparison with a rotation of 5.81° in the transverse axis (95% - CI [-3.02°, 14.64°]) and -4.88° in the sagittal rotation (95% - CI [-25.54°, 15.77°]). This represents a mean defensive position of the inexperienced athletes with a rotation of 56.87° (SD = 16.11°) in the transverse axis, as well as a supination of 113.2° (SD = 22.46°) in the sagittal axis. No statistically significant difference in the defensive position between experienced and inexperienced subjects was detected for the rotation of the fist.

As demonstrated in Figure 93, it becomes apparent that the orientation of the fist to the object to be punched is initiated with a rotation around the longitudinal axis before the fist is orientated in the direction of the object to be hit in the transverse and sagittal axis. During the contact of the fist with the object to be struck, a mean rotation of 0.15° (SD = 13.27°) in the longitudinal axis is seen, compared to the initial defensive position of the experienced athletes. The rotation in the longitudinal axis at the time of the fist impact was higher for the group of inexperienced athletes with −7.81° than for the group of experienced athletes (95% CI [−13.61°, 29.23°]). Following the start of the rotation in the longitudinal axis, the fist of the experienced group of subjects is rotated by an average of −42.97° (SD =

3.1°) in the transversal axis and −86.21° (SD = 4.7°) in the sagittal axis up to the moment of contact with the object of impact (Figure 93 to Figure 96). In comparison, the group of inexperienced athletes performed a rotation around the transverse axis of −39.75° (Figure 93 and Figure 95) (SD = 10.41°) and a pronation of 59.41° (SD = 21.49°) in the sagittal plane until a first contact with the target (Figure 93 and Figure 96). This corresponds to a mean difference of −3.22° (95% CI [−8.81°, 2.37°]) in the transversal axis and 26.81° (95% CI [15.84°, 37.78°]) in the sagittal axis between the inexperienced and experienced group of test subjects. The results of the rotations around the longitudinal and transverse axis from the initial defensive position to the impact of the fist on the striking object showed no statistically significant differences between the experienced and non-experienced group of test subjects, rotation around the longitudinal axis (p = 0.45) or rotation around the transverse axis (p = 0.24). A significant difference between experienced and non-experienced subjects was detected in the rotation around the sagittal axis from the defensive position to the initial contact (p < 0.001).



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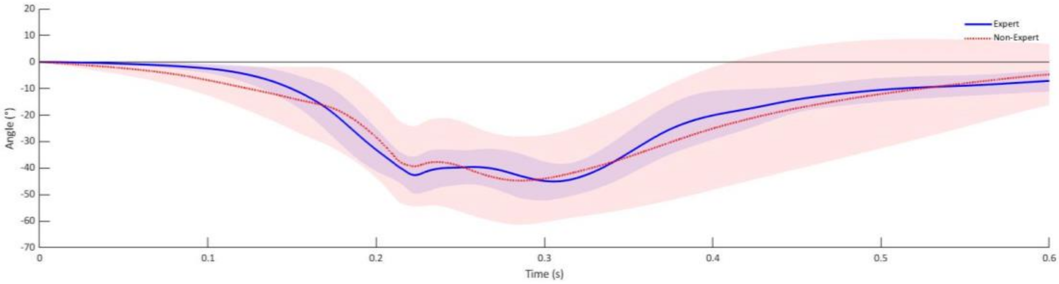

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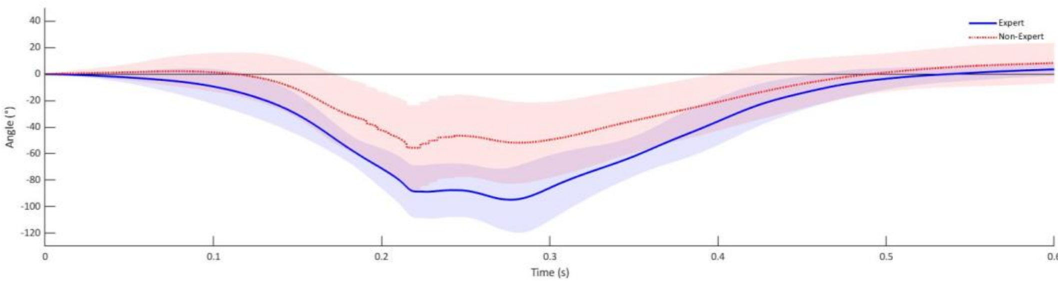

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Figure 93: Fist rotation experienced athletes cross punch: (a) longitudinal, (b) transversal and (c) sagittal axis.

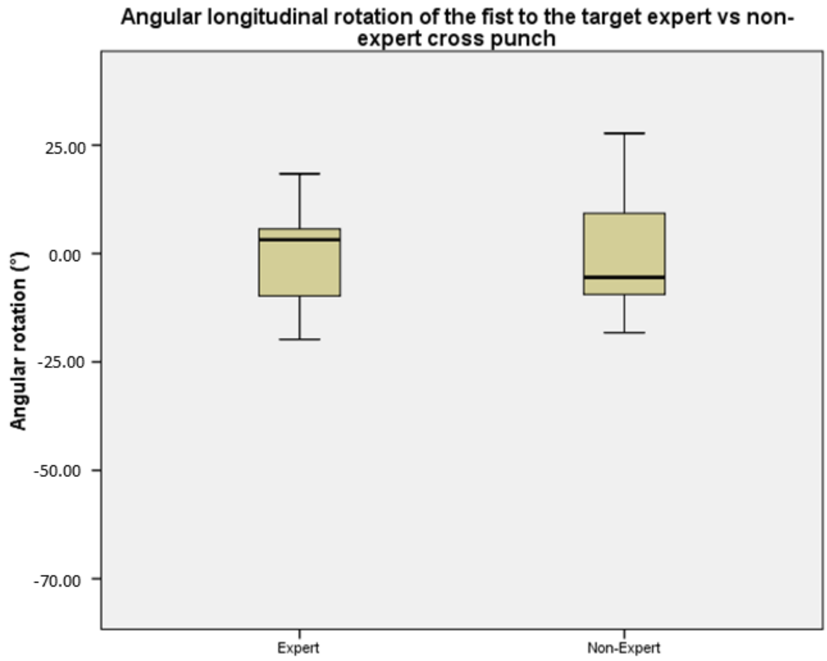


Figure 94: Angular longitudinal rotation of the fist to the target expert vs non-expert cross punch

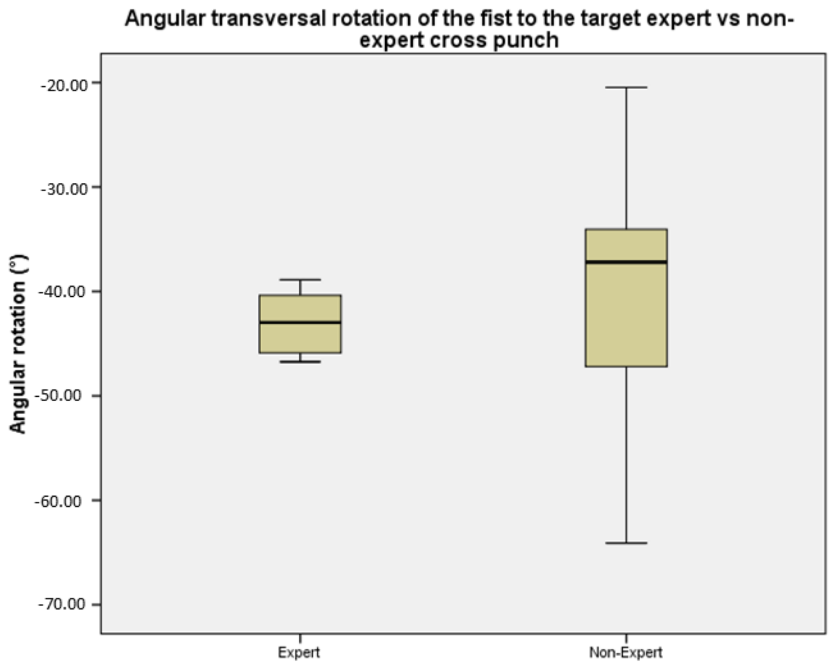


Figure 95: Angular transversal rotation of the fist to the target expert vs non-expert cross punch

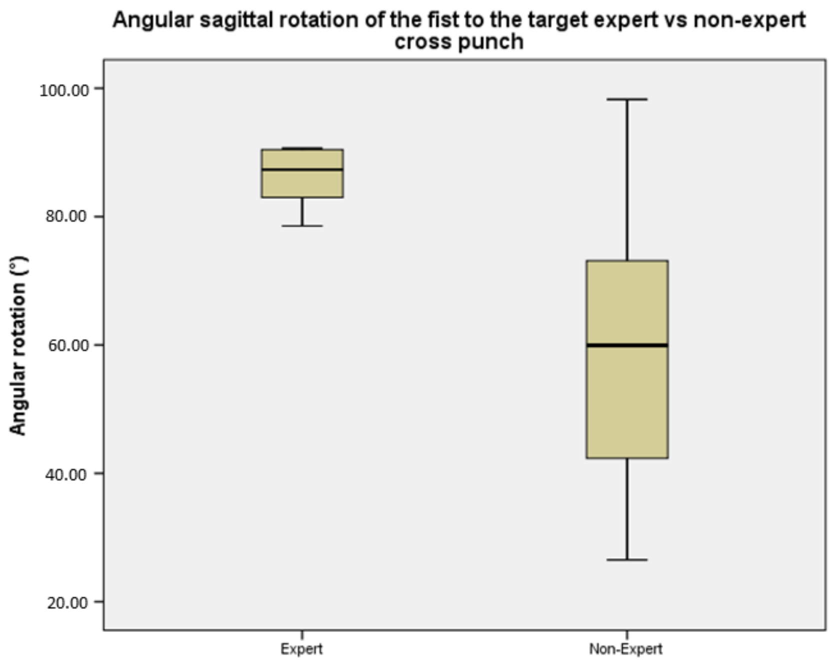


Figure 96: Angular sagittal rotation of the fist to the target expert vs non-expert cross punch

After impact, the fist is immediately returned to the defensive position. Table 14 shows a mean deviation of the orientation of the fist in three-dimensional space from the initial to the retracted position of -4.24° (SD = 3.85°) in the longitudinal axis, -1.92° (SD = 4.33°) in the transverse axis and -0.17° (SD = 6.42°) in the sagittal axis of the experienced group of participants. In the comparison of the experienced athletes, the group of non-experienced subjects presented a deviation of rotation in the longitudinal axis between the initial and retracted position of −4.95° (SD = 17.36°), a deviation of −2.51° (SD = 7.79°) in the transverse rotation and a deviation of 6.1° (SD = 14.93°) in the sagittal rotation. No statistically significant differences were tested between the initial and retracted positions of experienced and non-experienced athletes with respect to fist orientation in three-dimensional space.

Table 14: Difference in angular orientation between the initial and retracted defensive position cross punch.

	Experienced	Non-experienced
Longitudinal rotation[1]	-4.24° ± 3.85°	-4.95° ± 17.36°
Transversal rotation[1]	-1.92° ± 4.33°	-2.51° ± 7.79°
Sagittal rotation[1]	-0.17° ± 6.42°	6.1° ± 14.93°

[1] Values are means ± SD.

The absolute punching time was defined as the time from the initial fist movement from the defensive position to the object to be punched and back to the defensive position. As forementioned, the entire punch was separated into the three phases of fist movement. The first phase was defined as the throwing phase. The throwing phase was defined as the time from the initial defensive position to the first contact with the target object. The second phase was defined as the contact phase. The contact phase is defined from the first contact of the fist with the punching object until the point of time, the glove is released from the punching bag. The third and, therefore, final phase started with the beginning of the release of the glove from the punching object back into the defensive position and was defined as the retraction phase.

The absolute punch time of the cross-punch technique was on average 402 milliseconds (SD = 65 ms) for the group of experienced athletes. With an average difference of −47 milliseconds (95% CI [−150.87, 55.55]), the total cross punch time for the inexperienced group was 450 milliseconds (SD = 104 ms) (Table 18). The first of the three defined movement phases of the fist, from the defensive position to the object to be punched, took 111 milliseconds (SD = 41 ms) in the experienced group of test persons, compared to 102 milliseconds (SD = 37 ms) in the inexperienced group of subjects. This resulted in a mean difference of 9 ms (95% CI [−31.04, 48.96]) (Table 18). From the first contact of the boxing glove with the object to be hit until the fist is released, the fist remains for 122 milliseconds (SD =

18 ms) in contact with the boxing bag for the expert group and 118 milliseconds (SD = 25 ms) in the group of non-experts (Table 18). The punch is completed with the third phase of the fist movement back into the defensive position. This action phase averages 169 milliseconds (SD = 41 ms) in the expert group and 235 milliseconds (SD = 79 ms) in the non-experienced group of subjects (Table 18). The statistical investigation revealed no statistically significant differences between the experienced and non-experienced group of subjects in the absolute impact time (p = 0.35) as well as the three temporal action phases of the throw (p = 0.65), contact (p = 0.72) and the retraction phase (p = 0.09) for the cross.

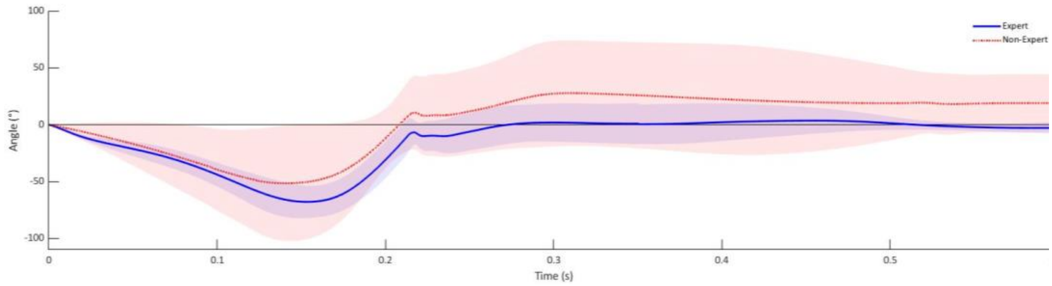
Hook punch results

After testing the cross, the hook technique was performed as the first semicircular punch. The detailed examination of the normal distribution using the Shapiro–Wilk test showed a normal distribution for the datasets of the experienced and inexperienced test groups with $p > 0.05$.

The defensive position of the experienced group of test persons measured at the beginning of each stroke showed an average rotation around the transversal axis of 58.03° (SD = 6.23°) and a pronation of 113.86° (SD = 30.47°) of the orientation of the fist in three-dimensional space. With an average difference of 15.83° in the transverse axis (95% CI [5.84°, 25.82°]) and 13.82° in the sagittal axis (95% CI [−23.35°, 51°]) the average defensive position of the inexperienced group of subjects was measured with a rotation of 42.2° (SD = 17.35°) in the transverse axis and 100.04° (SD = 17.8°) in the sagittal axis. This result showed a statistically significant difference in the defensive position of the transverse axis ($p = 0.004$), but no statistically significant difference in the orientation of the sagittal axis between experienced and inexperienced boxing subjects.

The rotation of the fist orientation in three-dimensional space shown in Figure 97 shows that the fist moves towards the target object with an average rotation of −70.94° (SD = 14.06°) around the longitudinal axis. At the time the fist reaches the target object, the longitudinal axis is rotated with an average of −11.54° (SD = 8.59) in the group of experienced subjects (Figure 97 and Figure 98). A similar movement pattern is shown by the group of inexperienced participants in the rotation around the longitudinal axis from the defensive position to the point the fist makes contact to the target. The non-experienced group of participants performed the rotation in the longitudinal axis, with a laterally directed rotation of −51.58° to the target. This corresponds to a mean difference of 19.36° (95% CI [−10.95°, 23.65°]). At the target, the fist shows a −13.89° (SD = 17.98°) rotation compared to the defensive position in the longitudinal plane (Figure 97 and Figure 99). In the transversal axis, the experienced group of test subjects tilted the fist by an average of −48.99° (SD = 8.21°), as well as a pronation in the sagittal axis of −79.38° (SD = 1.66°) at the point where the fist arrives at the target

(Figure 97 and Figure 100). In contrast, the group of inexperienced test subjects showed an inclination of the fist in the transverse axis of −35.88° (SD = 17.73°), as well as a rotation in the sagittal axis of −34.95° (SD = 22.14°) from the defensive position to the target (Figure 97). This corresponds to a mean difference of −13.11° in the transverse axis (95% CI [−24.66°, −1.57°]) and −44.29° in the sagittal axis (95% CI [−54.88°, −33.98°]). The rotation of the fist from the defensive position to the punching object around the longitudinal axis shows no statistically significant group difference between experienced and inexperienced boxers (p = 0.45). A statistically significant difference was analyzed between the experienced and non-experienced group of subjects in the rotation around the transverse axis (p = 0.02) as well as the sagittal axis (p < 0.001).



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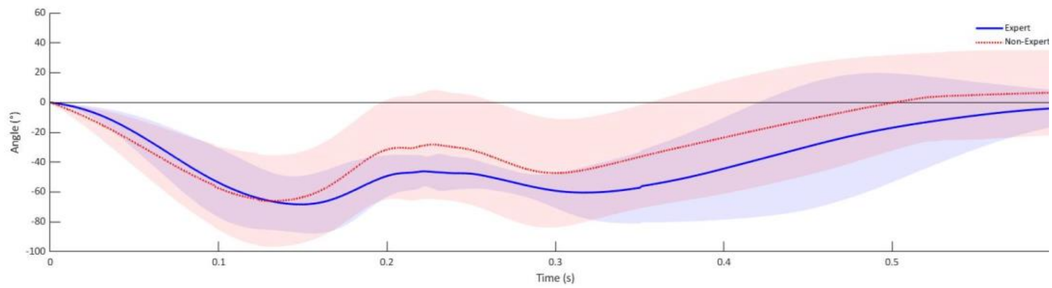

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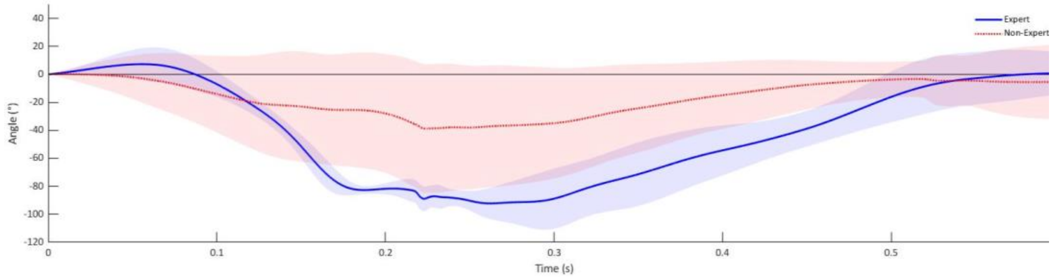

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Figure 97: Fist rotation experienced athletes hook punch: (a) longitudinal, (b) transversal and (c) sagittal axis.

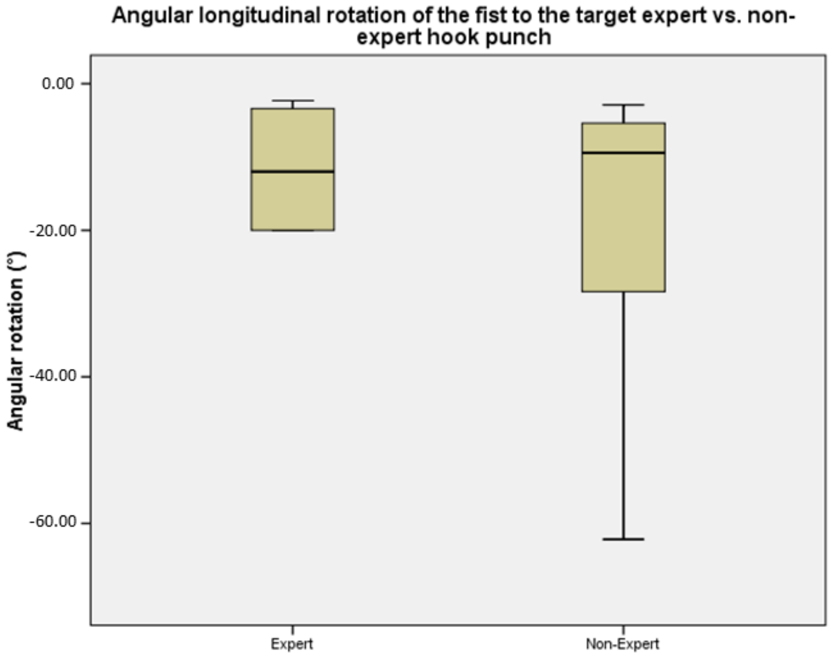


Figure 98: Angular longitudinal rotation of the fist to the target expert vs non-expert hook punch

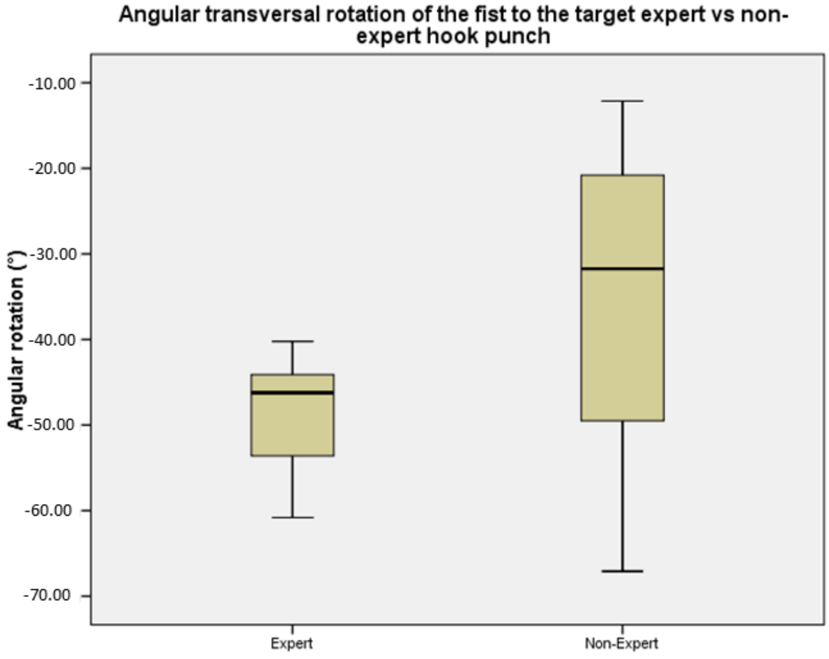


Figure 99: Angular transversal rotation of the fist to the target expert vs non-expert hook punch

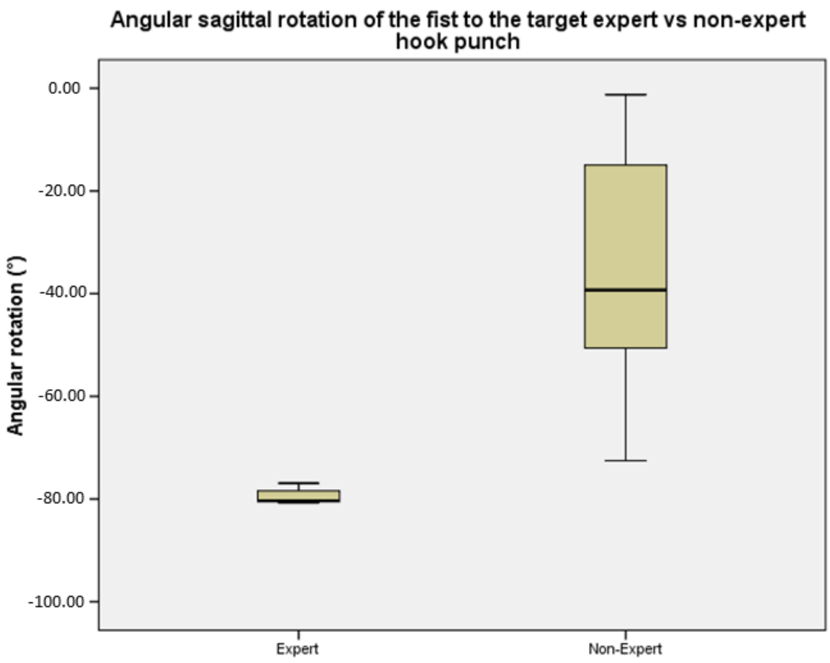


Figure 100: Angular sagittal rotation of the fist to the target expert vs non-expert hook punch

After the target was hit, the fist is immediately returned to the defensive position for defensive purposes. The group of experienced boxing participants showed a mean deviation of the orientation of the fist in the three-dimensional space between the defense position before and after the impact of −9.78° (SD = 7.16°) in the longitudinal axis, −0.26° (SD = 2.45°) in the transverse axis and −4.56° (SD = 12.38°) in the sagittal axis (Table 15). The non-experienced group of subjects returned the fist to the defensive position following the executed punch with a mean deviation of −25.2° (SD = 30.94°) in the longitudinal axis, 7.10° (SD = 19.62°) in the transverse axis and −2.26° (SD = 23.1°) in the sagittal plane for the executed punches (Table 15). The deviation in the defensive position before and after the executed stroke showed no statistically significant differences in the defensive positions within a group of subjects, nor in the deviation between the experienced and inexperienced group of participants.

Table 15: Difference in angular orientation between the initial and retracted defensive position hook punch.

	Experienced	Non-experienced
Longitudinal rotation[1]	-9.78° ± 7.16°	-25.19° ± 30.94°
Transversal rotation[1]	-0.26° ± 2.45°	7.10° ± 19.62°
Sagittal rotation[1]	-4.56° ± 12.38°	-2.26° ± 23.1°

[1] Values are means ± SD

The analysis of the three defined impact phases for the hook punch shows that the absolute impact time was performed faster in the group of experienced subjects with an average duration of 441 milliseconds (SD = 104 ms) as compared with the group of non-experienced subjects whose average duration was 479 milliseconds (SD = 117 ms), with an average difference of 38 ms (95% CI [−169.07, 93.4]) (Table 18). The throw phase took an average of 91 ms (SD = 50 ms) in the experienced group of subjects and 72 ms (SD = 233 ms) in the inexperienced group (Table 18). This corresponds to a mean difference of 18 ms (95% CI 119.01, −228.63]). In the second phase, the experienced group of test persons had 141 ms (SD = 29 ms) of contact with the object to be punched, from the first impact of the fist to the release of the punching bag. With an average difference of 71 ms (95% CI [−280.01, 138.07]), the fist of the inexperienced test persons was in contact with the object to be punched with a mean time of 212 ms (SD = 198 ms) (Table 18). The retraction phase of the fist from the target to the defensive position lasted on average 168 ms (SD = 97 ms) in the experienced group compared to the inexperienced group with 186 ms (SD = 83 ms) (Table 18). This corresponds to a mean group deviation of 18 ms. The investigation of group differences regarding the temporal movement phases of the fist shows no statistically significant differences in the absolute punch time (p = 0.55) nor in the three temporal action phases of the throw (p = 0.88), contact (p = 0.49) and the retraction phase (p = 0.68).

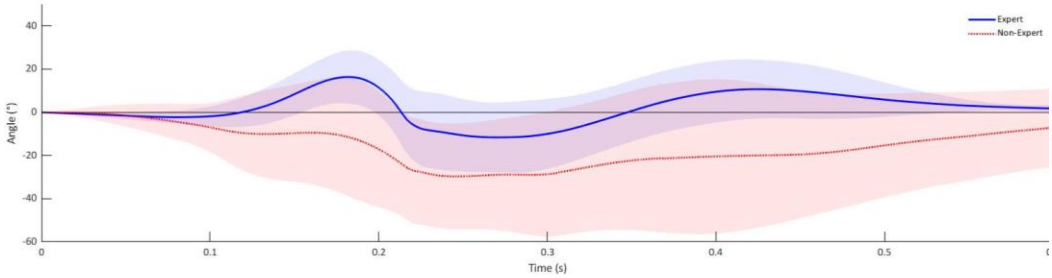
Jab punch results

As the third punch technique, the jab was performed. Similar to the cross, the jab is a straight punching technique. In contrast to the cross, the jab punch technique is performed with the leading hand and serves primarily as a punch to keep the opponent at a distance and prepare for a following effective punch.

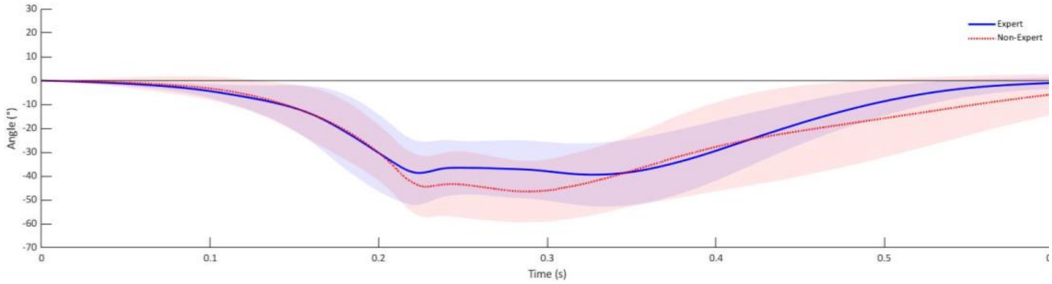
As already practiced for the first two striking techniques, the data sets for the technical analysis of the experienced and non-experienced subjects were tested on normal distribution initially of the analysis. In this context, the Shapiro-Wilk test performed, verified the normal distribution of the collected data sets with $p > .05$.

The experienced group of participants showed a mean rotation of 58.25° (SD = 2.54°) in the transverse axis and a supination of 111.19° (SD = 27.84°) of the fist at the start of the test series as well as prior to each test cycle in the assumed defensive position. With an average difference of −4.55° in the transverse axis (95% CI [−10.39°, 1.29°]) and −8.9° in the sagittal axis (95% CI [−36.2°, 18.72°]) the inexperienced subjects took up the defensive position with a rotation of 62.81° (SD = 11.2°) in the transverse axis and a supination of 120.18° (SD = 30.12°). The orientation of the fist in three-dimensional space in the defensive position of experienced and non-experienced athletes showed no statistically significant differences.

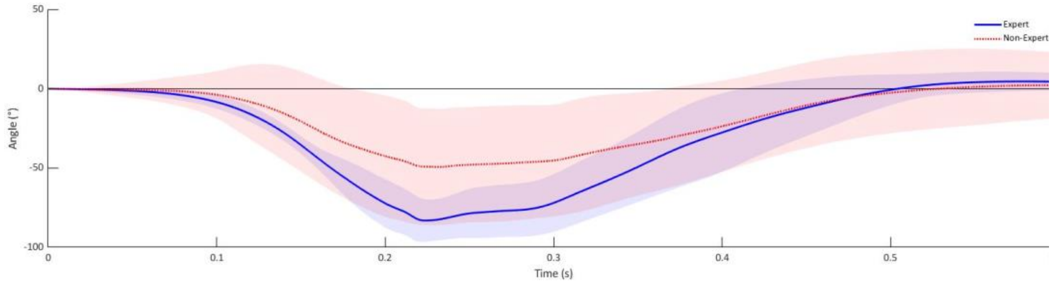
The movement of the fist towards the target object begins with a rotation in the longitudinal axis (Figure 101). This movement is followed by a temporally offset alignment of the fist around the transversal and sagittal axis (Figure 101 to Figure 104). At the moment of the fist hitting the targeting object, the fist was rotated from the defensive position by an average of -11.75° (SD = 11.17°) in the longitudinal axis in the experienced group of test persons (Figure 101 and Figure 102). With an average difference of 12.97° (95% - CI [-10.31°, 28.26°]) the non-experienced group of subjects shows an average rotation of -24.72° (SD = 23.42°) in the longitudinal axis (Figure 101 and Figure 102). The transversal rotation, which starts after the initial rotation in the longitudinal axis, had an average of −41.59° (SD = 3.12°) for the experienced group of test persons and −43.38° (SD = 13.92°) for the non-expert group until the fist hits the punching bag (Figure 101). This corresponds to a mean deviation of -2.21° (95% - CI [-7.47°, 7.04°]) between the two tested groups. The third rotation in the sagittal axis shows a mean difference in pronation of the fist from the defensive position to the target of -36.16° (95% - CI [-51.75°, -20.56°]) between the experienced test group (-82.2° (SD = 8.48°)) and the non-experienced test subjects (-46.04° (SD = 28.87)) (Figure 101 and Figure 103). The rotation around the longitudinal and transverse axis from the defensive position to the object showed no statistically significant differences between the two tested groups' rotation around the longitudinal axis (p = 0.35) and rotation around the transverse axis (p = 0.97). In contrast to the first two rotations, the rotation around the sagittal axis showed a statistically significant difference between the two groups in the rotation from the defensive position to the first contact with the target ($p < 0.001$) (Figure 101 to Figure 104).



(**a**)



(**b**)



(c)

Figure 101: Fist rotation experienced athletes jab punch: (a) longitudinal, (b) transversal and (c) sagittal axis.

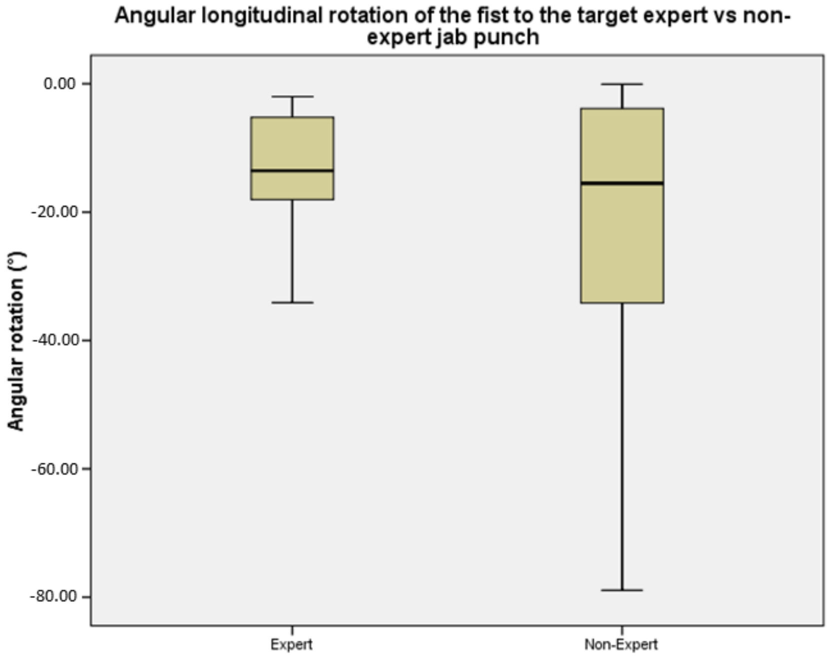


Figure 102: Angular longitudinal rotation of the fist to the target expert vs non-expert jab punch

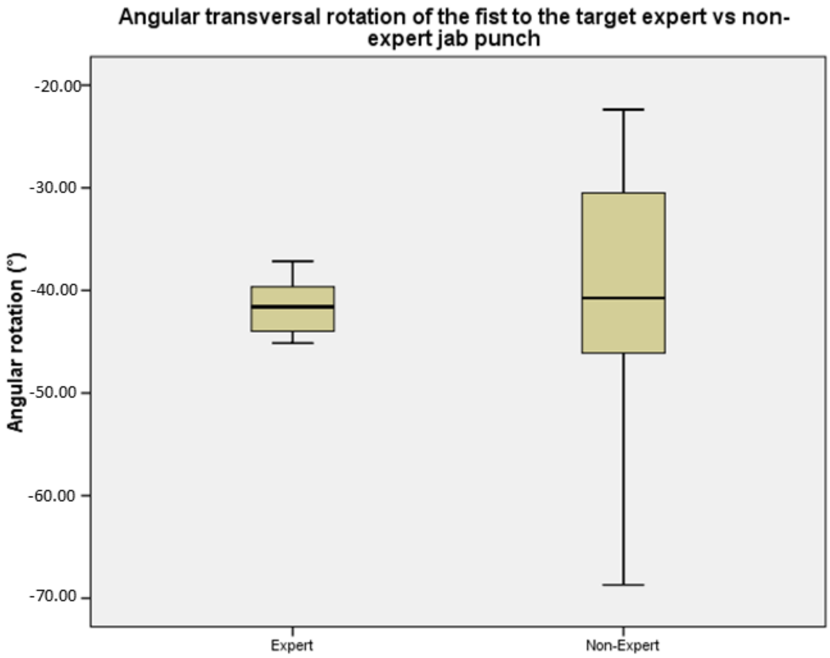


Figure 103: Angular transversal rotation of the fist to the target expert vs non-expert jab punch

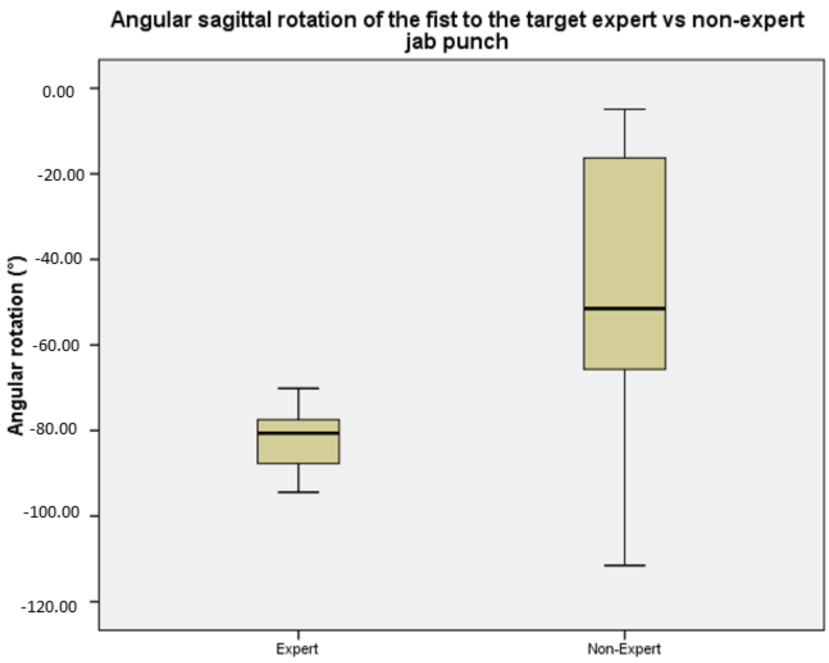


Figure 104: Angular sagittal rotation of the fist to the target expert vs non-expert jab punch

As shown in Table 16, a deviation of the fist orientation in three-dimensional space of 6.14° (SD = 8.47°) in the longitudinal axis, -6.16° (SD = 4.3°) in the transverse axis and 1.4° (SD = 2.8°) in the sagittal axis is shown between the first defensive position before the punch is executed to the defensive position after the impact was executed for the group of experienced participants. With an average difference of 8.34° to the experienced group, the retracted defensive position of the non-experienced group of subjects is set with a deviation of -2.2° (SD = 15.43°) from the initial defensive position (Table 16). In addition, the retracted defensive position deviates from the initial position by -9.63° (SD = 11.47°) in the transverse axis and -7.24° (SD = 18.34°) in the sagittal axis (Table 16). This corresponds to a mean difference from the experienced group by 3.47° in the transverse axis and 8.64° in the sagittal axis. The results presented do not show statistically significant differences between the two groups of subjects.

Table 16: Difference in angular orientation between the initial and retracted defensive position jab punch

	Experienced	Non-experienced
Longitudinal rotation[1]	6.14° ± 8.47°	-2.2° ± 15.43°
Transversal rotation[1]	-6.16° ± 4.31°	-9.63° ± 11.47°
Sagittal rotation[1]	1.4° ± 2.8°	-7.24° ± 18.34°

[1] Values are means ± SD

The investigation of the duration of the three defined impact phases for the jab punch technique shows a mean difference between the experienced and inexperienced group of test persons of 39 ms (95% CI [−44.71, 122.02]). The group of non-experienced subjects exhibits a shorter average duration of 485 ms (SD = 98 ms) than the experienced group, with an average duration of 524 ms (SD = 63 ms) (Table 18). In contrast to the total punch time, the phase of the throw was performed with a duration of 117 ms (SD = 25 ms). This shows a mean difference of −18ms (95% CI [−53.2, 17.67]) for the experienced group of test subjects compared to the inexperienced group with a duration of 135 ms for the throw (Table 18). The fist of the inexperienced test persons exerts pressure on the punching bag with a mean contact time of 138 ms (SD = 28 ms). The retraction phase was measured with a duration of 212 ms (SD = 75 ms). With a difference of 6 ms (95% CI [−19.11, 31.8]), the third punching phase in the experienced group of test persons measured a duration of 144 ms (SD = 27 ms), while the retraction phase for the return to a defensive position took a mean 262 ms (SD = 42 ms) (Table 18). This corresponds to a mean difference of 50 ms in the third stroke phase between the two tested groups of participants. The investigation for significance shows that no statistically significant difference was measured for the total punch time (p = 0.35) as well as the first two defined movement phases of the throw (p = 0.31) and contact period (p = 0.61). In contrast, a statistically significant difference between the two tested groups was measured for the retraction phase with (p = 0.04).

Uppercut punch results

The fourth and last performed punching technique was the uppercut. The uppercut is the second semicircular punching technique following the thrown hook. The detailed examination of the data sets of both groups of boxing subjects, the inexperienced and the experienced athletes, showed a normal distribution of the data using the Shapiro–Wilk test ($p > 0.05$).

The defensive position at the beginning of the test series, as well as before the individual test cycles, of the experienced group of test subjects was measured with an average rotation around the transverse axis of 46.71° (SD = 18.02°) and a supination of the fist of 86.36° (SD = 65.73°). In comparison to the experienced group, the defensive position of the non-experienced participants was taken with a rotation of 24.51° (SD = 11.29°) in the transverse axis and a supination of 98.09° in the sagittal axis. This corresponds to a mean difference of 22.2° between the two tested groups in the transverse axis (95% CI [−4.18°, 48.59°]) and −11.72° in the sagittal axis (95% CI [−69.79°, 46.35°]). The performed statistical analysis of the defensive position showed no statistically significant differences ($p > 0.05$).

The rotation in three-dimensional space shown in Figure 105 shows that the rotation of the fist from the defensive position to the object to be hit is initiated by a simultaneous rotation around the longitudinal and transverse axis before a supination of the fist to the target is executed. At the point of time the fist makes contact with the object to be struck, the fist is displaced by −16.49° (SD = 7.43°) in the longitudinal axis from the defensive position. Likewise, the fist is tilted by 1.51° (SD = 9.15°) in the transverse axis and supinated by 59.53° from the defensive position in the experienced group of subjects (Figure 105). The rotation of the fist at the target in the non-expert group is rotated by −3.9° (SD = 6.95°) in the longitudinal axis, 1.53° (SD = 7.08°) in the transverse axis and supinated by 57.12° (SD = 12.75°) (Figure 105).

The investigation shows no statistically significant difference between the experienced and inexperienced test group in the rotation from the defensive position to the targeting object, around the longitudinal axis ($p = 0.24$) and the transverse axis (p = 0.9) as well as in the rotation around the sagittal plane of the fist between the two tested groups with (p = 0.94).

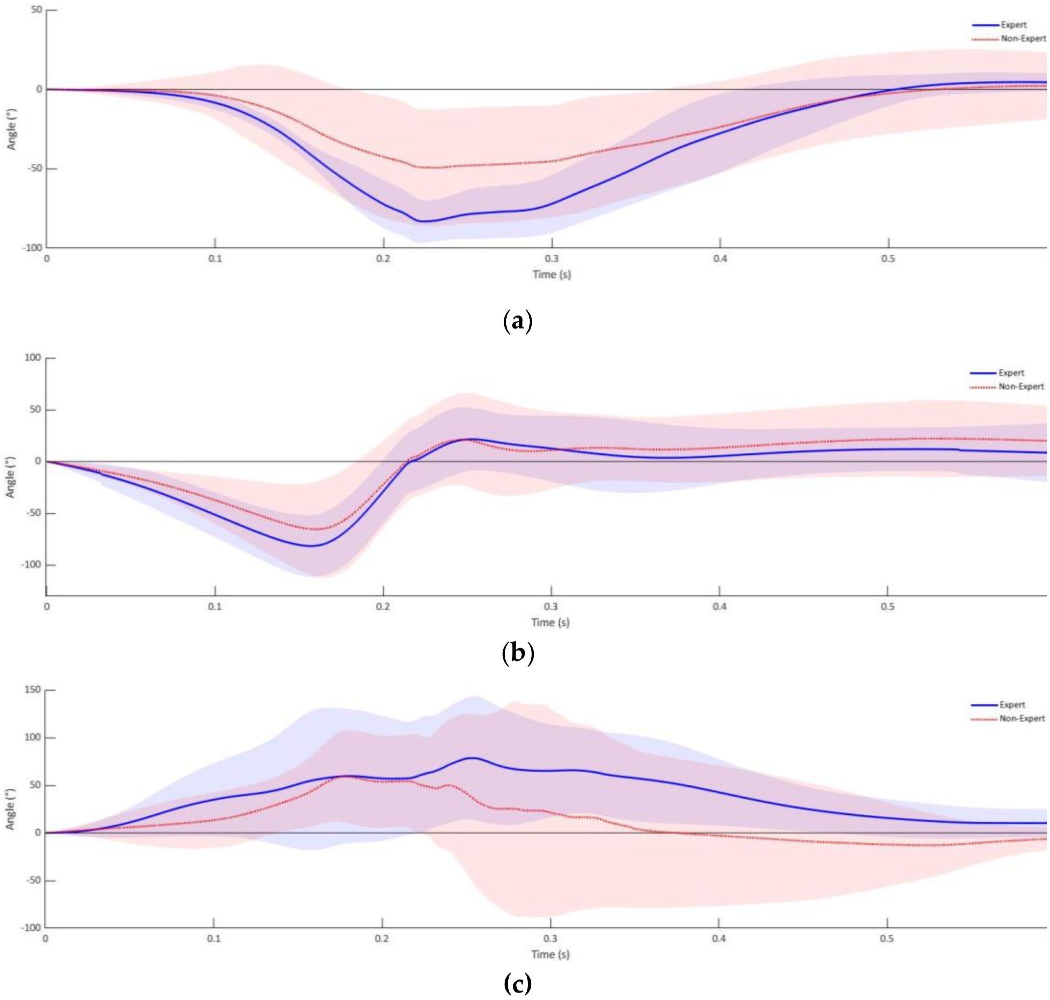


Figure 105: Fist rotation experienced athlete's uppercut punch: (a) longitudinal, (b) transversal and (c) sagittal axis.

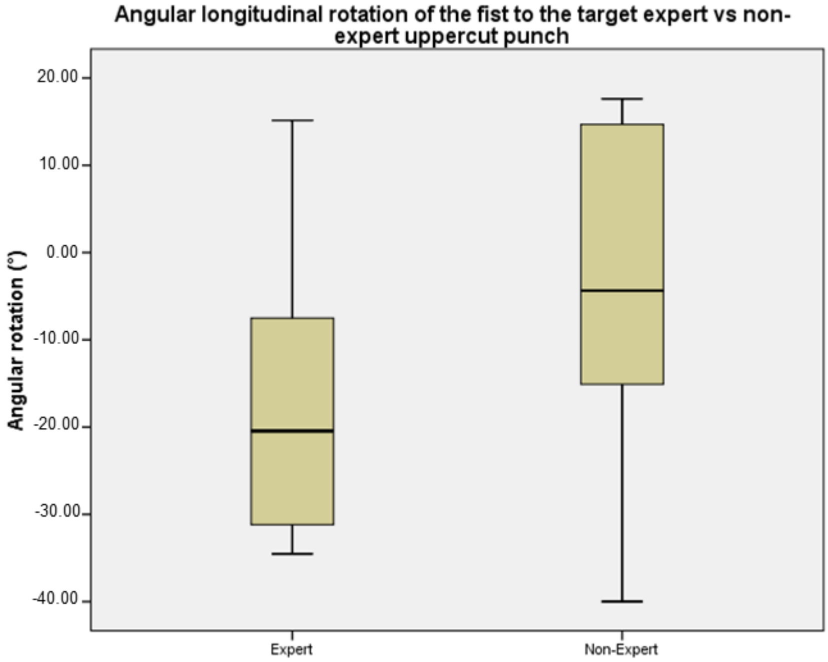


Figure 106: Angular longitudinal rotation of the fist to the target expert vs non-expert uppercut punch

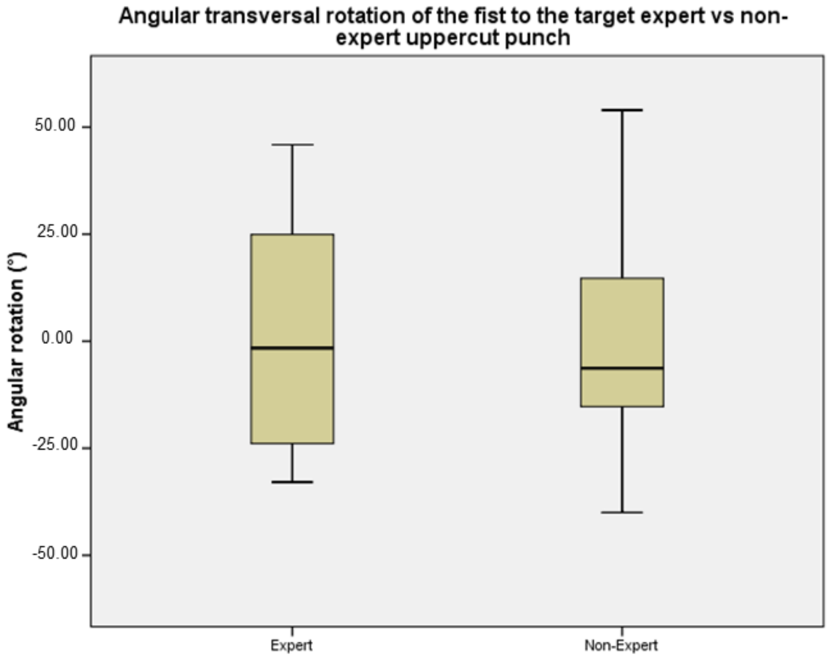


Figure 107: Angular transversal rotation of the fist to the target expert vs non-expert uppercut punch

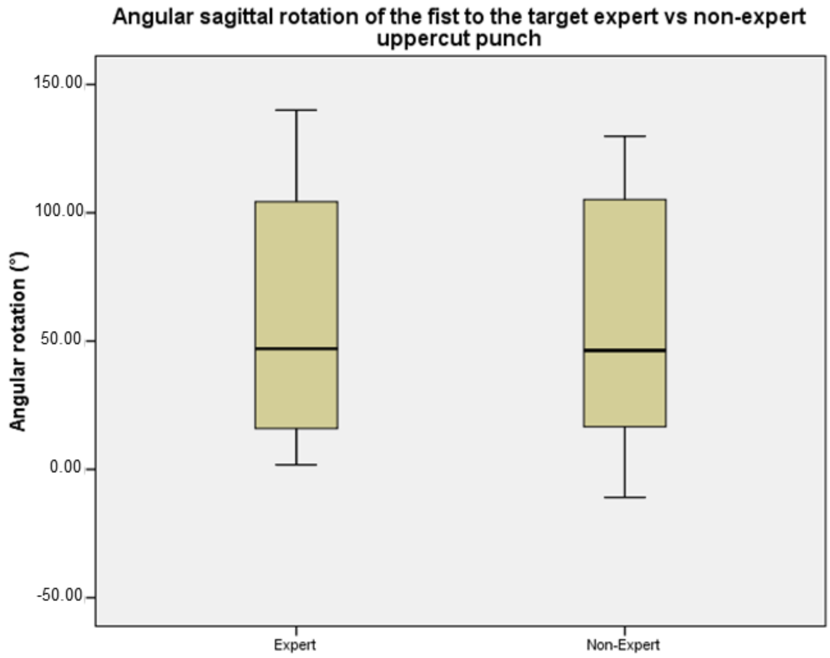


Figure 108: Angular sagittal rotation of the fist to the target expert vs non-expert uppercut punch

Analysis of the fist rotation for the retracted defensive position shows a mean deviation of 4.18° (SD = 10.28°) in the longitudinal axis, 5.18° (SD = 9.12°) in the transverse axis and 2.94° (SD = 5.05°) in the sagittal axis of the experienced group of subjects (Table 17). In comparison, the inexperienced group showed a larger mean difference. The assumed defensive position after the executed stroke showed a deviation from the first defense positioning prior to impact of −26.85° (SD = 27.4°) in the longitudinal axis, 34.89° (SD = 37.48°) in the transverse axis and −11.24° (SD = 20.53°) in the sagittal axis (Table 17). The results presented show a statistically significant difference between the two groups of subjects in terms of the deviation between the defensive position before and after the blow, in the longitudinal axis (p = 0.001), transverse axis (p = 0.009) as well as the sagittal axis (p = 0.02).

Table 17: Difference in angular orientation between the initial and retracted defensive position uppercut punch.

	Experienced	Non-experienced
Longitudinal rotation[1]	4.18° ± 10.28°	-26.85° ± 27.4°
Transversal rotation[1]	5.18° ± 9.12°	-34.89° ± 37.48°
Sagittal rotation[1]	2.94° ± 5.05°	-11.24° ± 20.53°

[1] Values are means ± SD

The total duration of the uppercut stroke was on average 385 ms (SD = 65 ms) in the experienced group of subjects (Table 18). In comparison, the time of execution in the inexperienced group of subjects was measured with a mean difference of 68 ms and a total duration of 453 ms (SD = 60 ms) (Table 18). In a detailed analysis of the three defined impact phases, the experienced test subjects' impact required an average of 71 ms (SD = 36 ms) from the defensive position to impact. The fist was in contact with the targeting object for a total of 143 ms (SD = 34 ms) (Table 18). The retraction phase back into the defense position was measured with 171 ms (SD = 33 ms) (Table 18). For the non-experienced group, the average time required for the throw phase was 83 ms (SD = 29 ms), for the contact period 163 ms (SD = 23 ms) and for the retraction phase 204 ms (SD = 41 ms) (Table 18). The investigation on significant effects (Table 19) shows a significant difference in both the absolute impact time (p = 0.01) and the duration of the retraction phase (p = 0.04) between the experienced and non-experienced group. No statistically significant differences were detected for the first and second stroke phase of the throw (p = 0.39) and the contact period (p = 0.10).

In addition to the investigation of the technical orientation variables of the fist in three-dimensional space, further punch variables between experienced and non-experienced subject groups were collected. The results displayed in Table 18 show the mean punch forces and punch velocities achieved of the four tested punching techniques for the experienced and non-experienced group of test participants. Significant differences in the maximum achieved punch force for the hook, jab and uppercut technique were observed for the experienced group of subjects compared to the non-experienced group of participants. For the three punch types, the experienced group of test persons performed a mean of 1322.66 N (SD = 561.66 N) greater maximum punch force than the test persons with lesser boxing experience. No significant differences were observed when comparing the maximum punch velocities between experienced and non-experienced participants.

Table 18: Punch variables of the four tested punching techniques.

	Cross	Rear Hand Hook	Jab	Uppercut
Experienced				
Total mean punch time (ms)	402 ± 65	441 ± 104	523 ± 63	385 ± 65
Mean throw time (ms)	111 ± 41	91 ± 50	117 ± 25	71 ± 36
Mean contact time (ms)	122 ± 18	141 ± 29	144 ± 27	143 ± 34
Mean retraction time (ms)	169 ± 41	168 ± 97	262 ± 42	171 ± 33
Peak fist velocity (m/s)	7.88 ± 1.0	6.93 ± 0.9	7.9 ± 0.9	6.8 ± 0.9
Mean fist velocity (m/s)	6.6 ± 0.9	5.87 ± 0.9	6.3 ± 0.9	5.40 ± 0.8
Peak force (N)	3149.1 ± 741.3	4177.5 ± 1155	3167.8 ± 676.2	3851.0 ± 768.9
Mean force (N)	1918.8 ± 787.5	1946.2 ± 720.6	1383 ± 234.8	1949.1 ± 395.3
Punch impulse (N·s)	223.2 ± 62.4	277.3 ± 79.2	189.4 ± 22.5	236.5 ± 83.8
Non-experienced				
Total mean punch time (ms)	450 ± 104	479 ± 117	485 ± 98	453 ± 60
Mean throw time (ms)	102 ± 37	72 ± 233	135 ± 42	83 ± 29
Mean contact time (ms)	118 ± 25	212 ± 198	138 ± 28	163 ± 23
Mean retraction time (ms)	235 ± 79	186 ± 83	212 ± 75	204 ± 41
Peak fist velocity (m/s)	7.6 ± 1.4	6.6 ± 1.2	6.9 ± 1.1	6.34 ± 0.8
Mean fist velocity (m/s)	5.7 ± 0.9	5.8 ± 1.0	6.0 ± 1.1	5.03 ± 0.9
Peak force (N)	2936.4 ± 662.1	2206.9 ± 646.7	2154.6 ± 503.9	2867.16 ± 540.1

Mean force (N)	1756.9 ± 752.8	1722.0 ± 405.2	1372.4 ± 415.2	1791.9 ± 607.6
Punch impulse (N·s)	215.3 ± 64.7	387.7 ± 46.4	186.5 ± 47.9	295.8 ± 86.3

Values are means ± SD.

Table 19: Presentation of the significant punch type results.

Punch Technique (Expert vs. Novice)	Significant Variable	*p*
Cross	Rotation around the sagittal axis from the defensive position to target	<0.001
Hook	Defensive position of the transverse axis	=0.004
Jab	Rotation around the transverse axis to target	=0.02
	Rotation around the sagittal axis to target	<0.001
	Absolute impact time	=0.01
	Duration of the retraction phase	=0.04
Uppercut	Deviation between the defensive position before and after the blow longitudinal axis	=0.001
	Deviation between the defensive position before and after the blow transverse axis	=0.009
	Deviation between the defensive position before and after the blow sagittal axis	=0.02
	Absolute impact time	=0.01
	Retraction time	=0.04

Note. A 95% Confidence Interval was applied.

4.2.4 Discussion

As described in detail in the objective of this experiment, based on the existing scientific literature, the athletes sporting performance depends to a large extent on the technical execution of the athletic motion to achieve maximum effectiveness of the physical performance in attacking as well as defensive situations as described by McGarry and colleagues in 2013. The purpose of the conducted experimental research, outlined in this chapter 4.2, was to present a first field investigation by use of the developed sensor system and to highlight the possibilities of the measurement parameters generated by the sensor system to be compared with the existing scientific literature. Furthermore, the study served to extend the existing scientific insights in the field of the technical execution of boxing and martial arts striking techniques. For this purpose, a technical comparison of athletes with different levels of experience regarding punch execution and fist rotation in three-dimensional space for the four main punching techniques of the jab, cross, hook and uppercut was conducted. Thus, it was the expectation prior to the presented work, to find significant differences in the technical execution of experienced and non-experienced athletes.

To the authors' knowledge, this is the first experimental study that analyses the technical aspects of the four main punching techniques, with a specific observation of the fist orientation in three-dimensional space from the defence orientation to the impact rotation and return of the fist, by use of a wearable boxing sensor system.

The statistical results of the ANOVA data analysis demonstrated significant performance differences between the experience level, the performed stroke technique, as well as the interaction between experience level and stroke technique.

The results of the technical analysis of fist orientation in three-dimensional space have shown that the fist orientation taken at the beginning of each punch in the defensive position differs between the two groups of test persons of experienced and non-experienced athletes. The results show that the defensive position of the group of subjects, classified as experts, is taken with an average rotation of 56.42° (SD = 6.82°) in the transverse axis and 104.94° (SD = 12.59°) in the sagittal axis. The uppercut stroke technique showed the greatest deviation (9.71°) from the mean defensive position with 46.71° (SD = 18.02°) compared to the cross, hook and jab. The average defensive position of the non-experienced athletes was shown with a deviation of −4.42° from the experienced group of subjects. The examination revealed no significant but tendential deviations between the two subject groups regarding their fist orientation in the defensive position of the cross, jab and uppercut punch. A statistically significant difference of 15.83° was observed on average in the transverse axis of the hook punch defensive position.

Greater statistically significant results were shown in the differences in the rotation from the defensive position to the targeting object. The results demonstrated a statistically significant difference in the rotation of the fist in the sagittal axis of 35.01° (SD = 7.34°) on average between experienced and non-experienced athletes in each of the four striking techniques performed. The pronation of the fist in the direction of the object to be hit is of particular importance for the optimal impact area of the fist, as described by Arus (2018a), that the palm is facing downwards to hit the target with the second to fourth heads of the metacarpals and the metacarpophalangeal (MCP) joints.

The analysis of fist orientation in three-dimensional space has furthermore demonstrated that the rotation of the fist is initiated prior to the acceleration of the fist towards the target object. The initial rotation starts on average 0.1 to 0.2 s before the actual throw phase is initiated.

In the third phase of action, following the executed impact, returning the fist to the defensive position, it is shown that the group of test persons of the experienced athletes demonstrated an average deviation from the initial defensive position of 2.03° (SD = 5.1°) in the longitudinal axis, −0.79° (SD = 4.69°) in the transverse axis and −0.09° (SD = 3.24°) in the sagittal axis. With a significant larger deviation, the defensive position of the non-experienced group of subjects was taken with −11.33° (SD = 13.51°) in the longitudinal axis, 7.46° (SD = 19.52°) in the transverse axis and −3.67° (SD = 7.46°) in the sagittal axis. A maximum average deviation of −26.85° (SD

= 27.4°) up to 34.89° (SD = 37.48°) was observed in the uppercut punching technique. The retracted orientation of the defensive position revealed a significantly higher technical reproducibility for the experienced group of subjects compared to the non-experienced group.

Beyond this, the present study sought to evaluate the punch speed and punch force and compare experienced and non-experienced boxers. Furthermore, the time period of the three defined punching phases was examined. The analysis of sport-specific time-motion variations is a non-invasive method of performance diagnostics for the examination of performance characteristics and movement patterns (Slimani et al., 2017).

The investigation of the mean and the maximum punching speeds achieved before impact has shown that no significant differences emerged between the groups of experienced and non-experienced participants or between the punching techniques within a subject group. A detailed examination of the results reveals that the group of experienced participants showed a greater tendency of punching speed in all measurements of maximum and mean punching results for the four punching techniques executed. These results are consistent with the findings of Whiting et al. (1988) that more experienced athletes exhibit a greater overall punch speed than athletes with less experience.

The punching techniques of the jab and cross showed an equal maximum speed of 7.88 m/s in the group of experienced test persons. In addition, the mean fist velocity of 6.6 m/s in the cross punch technique showed consistency with the published measurement results of Whiting (1988) as well as with the results published by Baitel and Deliu (2014). Furthermore, the cross has shown the shortest mean contact time of both groups of subjects for all punching techniques performed.

In the comparison of the two semicircular punching techniques of the rear hand hook and the uppercut, the rear hand hook revealed a 0.12 m/s moderately greater maximum punch speed of 6.93 m/s (SD = 0.93 m/s), than the uppercut with 6.81 m/s (SD = 0.89 m/s). These measurement results show a considerable deviation from results of previous studies (Piorkowski et al., 2011; Whiting et al., 1988). According to the literature, the hook punching technique has achieved a higher stroke speed than the jab or cross. The greater punch speed is based on the fact that the hook stroke generates a greater range of movement due to shoulder flexion and adduction than it can be achieved with the jab or cross, that is mainly executed via the elbow extension (Piorkowski et al., 2011).

The extended acceleration distance is, moreover, the main factor in the significantly longer mean throw time of the hook. The two tested groups demonstrated a threefold higher duration of the throw phase compared to the straight punching techniques of the cross and jab. Whiting et al. (1988) and Piorkowski et al. (2011) have also demonstrated a greater punch execution time before impact for the hook compared to jab and cross, albeit with less significance.

Despite a lower striking speed, the two semicircular striking techniques of the rear hand hook with 4177.47 N (SD = 1155.04 N) and the uppercut with 3851.03 N (SD = 768.92 N) show significantly higher striking forces compared to the straight punches of the cross and jab. This result leads to the assumption that the experienced athletes transferred a higher effective mass into the punch. The investigation of the effective mass used, provides a further point of investigation for follow-up studies to extend the range of investigation in martial arts between experienced and non-experienced athletes. The mean punch forces achieved with the jab (1383 N, SD = 234.81 N), the cross (1918.82 N, SD = 787.49 N) and rear hand hook (1949.08 N, SD = 395.27 N) for the experienced subject group displayed similar results to the study by Lenetsky and colleagues (2018).

The longest total mean punch time from the initial fist movement to target and return to the defensive position was measured in the jab for both groups of non-experienced 485 ms (SD = 98 ms) and experienced subjects at 523 ms (SD = 63 ms). In contrast, the shortest duration of the mean throw time was measured in the uppercut technique with 71 ms (SD = 36 ms) in the experienced group and 83 ms (SD = 29 ms) in the non-experienced group of subjects. The short mean throw time can be explained mainly by the shorter distance to the object of impact. Both groups of subjects performed the uppercut technique with the shortest distance to the object compared to the cross, jab and rear hand hook technique.

Furthermore, the punch impact was determined to further evaluate the punch effectiveness. The results show no statistically significant differences between the experience levels. The results also indicate that, due to the longer contact time of the inexperienced subjects, a higher impact was measured for the two semicircular punching techniques. These punching techniques are considered more demanding punching techniques, making the use of the punch impulse an unreliable variable for determining punching effectiveness.

Although the scientific experiment was primarily conducted to represent the first field test with the developed boxing monitoring system, further scientific results in the sport of boxing and martial arts were obtained by comparing experienced and non-experienced test subjects regarding their technical execution of the four punching techniques tested. The experiment undertook data collection during a normal training session on a punching bag. At no point in time in this study were data collected in a competition-specific situation as it is presented by a sparring training or a regular boxing match. This type of competition situation does not allow the athletes to focus on a single maximum stroke, but rather is carried out purely on the basis of the context, resulting in a deviation in maximum stroke forces, speed and technical-temporal movement sequences. In addition, only single maximal strokes were performed in the current study. The comparison to punching combinations would provide further insights, as the study by Piorkowski et al. (2011) has shown that a significant difference between punching combinations and single maximal punches could be measured in terms of contact speed.

Based on the results of Piorkowski et al. (2011) follow-up studies to examine punch combinations, with regard to the temporal sequence of the individual punch phases as well as the retraction orientation of the fist, would be extremely useful.

For further investigation, a third group of subjects should be considered in a follow-up study. For this purpose, the level of experience should be extended and athletes with international experience should be added. Furthermore, another potential follow-up could examine the technical execution of the tested strokes in different situations, such as competition, in order to be able to compare the performance outcome with the two previous groups of experience and to highlight potential movement patterns executed. Finally, with regard to the selection of participants regarding their level of experience, it is suggested that a more homogeneous group of subjects could be selected for the individual experience groups to help identify a clear distinction between movement patterns of subjects according to ability and level of experience. In order to obtain further information in the current field of investigation, further studies are planned in a competitive situation, at the time of the writing of the thesis.

4.2.5 Conclusion

According to the results, the research shows statistically significant differences in the technical execution between experienced and non-experienced subjects in the four main punching techniques of the jab, cross, rear hand hook and uppercut (Table 19). The significant results can be used as a starting point for obtaining objective data to create a technical model and reference criteria to enable athletes to optimize punch effectiveness and efficiency by the help of data-based punch models. The possibility of three-dimensional analysis of the stroke trajectory demonstrates the possibility of conducting in field investigations for motion analysis, detached from laboratory requirements. The analysis of the trajectory in three-dimensional space shows the possibility to replace a camera system to a certain extent in order to display the hand trajectory and punch acceleration in three dimensions. Boxing and martial arts are defined by specific movement patterns that are not analyzed in competition. The developed monitoring system makes it possible to investigate these punching movements in the field and to determine the punching effect from the obtained and analyzed information.

Furthermore, the presented results show a concordance with the results of previous publications in the areas of punch force, punch speed and punch duration assessment.

The developed system has been able to demonstrate its applicability in the conducted field study and thus enables further research in the field of boxing and martial arts to expand the current biomechanical information available. The knowledge gained from the experimental data can offer coaches and athletes a tool for analyzing the requirements of a specific punching movement pattern with the help of a novel boxing monitoring system. The results of this study can be used to apply technological data-based analysis for talent identification and promotion in martial arts, by a system as it is demonstrated in this work. Coaches and performance support centers in particular can thus benefit from such a measurement system, with which the technical performance of boxing strokes can be measured and potential technique correction can be made in the interests of the athlete by objective data.

4.3 Analysing Self-Assessment of Punching Intensity in Amateur Boxing between Experienced and Non-Experienced Athletes

Chapter 4.3 serves to present and outline the results of the second experimental study carried out in the field of boxing biomechanics and the analysis of punching techniques. The study also represents the second investigation in the analysis and comparison of experienced and non-experienced athletes in the technical execution of boxing punches by the application of the unique developed sensor system. The research is conducted in particular for the accuracy analyses of self-assessment of punching intensity based, on punch force (N). The study represents the second follow-up experiment based on the research results obtained with the developed boxing monitoring system for the experimental generation of biomechanical performance data in the sport of boxing.

The chapter is structured by starting to present the objective of the research, in particular by outlining the existing research gap for which scientifically profound data has to be generated. Based on this, a detailed description of the research methodology applied is presented and the experimental results obtained are outlined. The chapter for analysing self-assessment of punching intensity in amateur boxing between experienced and non-experienced athletes concludes with a discussion and conclusion of the experimental results and a research outlook based on the results achieved.

4.3.1 Objective

The sporting performance of the participants involved in a sporting event is a situation that is determined by self-assessment and evaluation by third parties (Blecharz et al., 2014). The self-assessment is influenced and regulated by situation-dependent emotional and cognitive factors (Hook et al., 2013; Howle & Eklund, 2013). By taking a more detailed examination of the individual self-perception in martial arts training and competition, research in psychology and pedagogy describe the individual ability of self-assessment in this scenario in close connection with the aggressive reactions to the environment and the ability to control aggressive impulses, or to manifest the resulting energy in a socially acceptable way (Cynarski & Litwiniuk, 2006; Ivaskiene et al., 2017; Stanger et al., 2017). Due to the direct confrontation with a training or competition partner, boxing and other martial arts represent a unique situation and importance of accurate self-assessment, in which an incorrect self-assessment can lead to possible injuries of the participant himself or the training partner (Kontos, 2004; Saw et al., 2017; Verhagen et al., 2010). Johnson and Levine (2009) state that the overestimation of self-assessment is a common human psychological phenomenon. Furthermore, the literature argues that a realistic and accurate self-evaluation is only possible from a higher experience level in the respective sport, that is close to excellence (Ivaskiene et al., 2017; MacNamara, 2011). This raises certain questions for the application of boxing and training competition with inexperienced participants, as boxing is becoming increasingly popular among the population as outlined in chapter 1. Among other things, this leads to its application in fitness boxing or its interdisciplinary implementation in social areas such as school sports, clinical therapy or therapeutic youth facilities for the prevention of violence (Blöcher, 2018; Joswig, 2013; Käser, 2012; Marquardt, 2013; Mösch, 2015). There are not many techniques associated that involve the self-assessment of athletes. The primary part of studies that is dealing with self-assessment of athletes comes from the field of psychology and pedagogics. The primary techniques used in these fields are questionnaires, especially the athlete self-report measure (ASRM) as a subjective tool (Saw et al., 2017).

In order to reduce the intensity and possible injuries, boxing has been modified in recent years, resulting in new forms of competition and exercise. One of these forms is the modification of light contact boxing (Käser, 2012; Marquardt, 2013). The modification of light contact boxing was invented by Jean Letessier as early as the 1970s and aims to allow participating athletes to perform the sport only, with a self-determined reduced punch intensity, without directly specifying the magnitude of punches been executed (Blöcher, 2018; Marquardt, 2013). This form of boxing is widely used in school sports, as well as in social institutions where it is used inter alia for the prevention of violence.

The conducted literature research has shown that there are few studies and publications in the field of self-assessment in sport, especially in the disciplines of martial arts. In addition, observations made in the first studies have shown that athletes with a lower level of experience encounter difficulties in implementing instructions directly. In contrast, the group of subjects with a longer boxing experience showed a faster implementation of instructions due to the internalized cognitive abilities for the sport of boxing.

Based on the findings of the literature research as well as the first studies presented, it is therefore questionable to what extent participants of a boxing event are able to objectively and accurately assess their own punch intensity in order not to injure a training partner or unintentionally violate the rules of an event, as it is for example presented by school sports or a therapeutic group for the prevention of violence. On this occasion, the possibilities of the developed boxing monitoring system will be considered in a broader context, to what extent participants should be provided with an additional tool to support the limitation of punch intensities with the help of a direct biofeedback.

Based on the research gap illustrated, the study presented in chapter 4.3 was focussing on the investigation of the self-assessment of punch force, measured in Newtons, for different punching intensities and punching techniques. The experiment is conducted in order to investigate the application of the regulation of punching intensities during training or sparring in different forms of boxing, as required for light contact boxing, boxing in schools or for violence prevention in social institutions. For this purpose, punches of different punch intensities were performed by experienced and non-experienced test participants to investigate the accuracy of the self-estimated punch intensity during training.

Hypothesis 1 H1: There is a significant difference between experienced and non-experienced boxers in terms of the accuracy in self-assessed punching intensities of 50% and 70%.

Hypothesis 2 H1: There is a significant difference between experienced and non-experienced boxers in terms of the repeatability of the maximal punch intensity.

4.3.2 Methodology

The following chapter serves to present and illustrate the methodology used to analyse the self-assessment of punching intensity between experienced and non-experienced athletes. The chapter contains a detailed description of the experimental setup, the applied experimental protocol, the data analysis and the applied methods for the statistical analysis of the experimental results.

a) Ethics statement

The third scientific study in the field of boxing biomechanics and the research presented in this chapter was examined by the Ethics Committee of the German Sport University Cologne (Cologne, Germany) for its ethically correct design and execution. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021). Each participant received a written description of the experimental procedure before the tests were started. The collection of data could only be started after signing the written declaration of consent before the participants were granted permission to participate in the presented experiment.

b) Participants

A total of 31 subjects took part in the study to analyse the self-assessment of punching intensity in amateur boxing between experienced and non-experienced athletes. At the beginning of the experimental study, the participants were divided into two groups. Similar to the study presented in chapter 4.2, the test persons were divided into the groups according to their level of experience in boxing. The division was made by years of boxing experience. Similar to the study presented previously and the experimental study published by Lenetsky et al. (2013), participants with at least three years of boxing experience were classified as experienced athletes, whereas participants with less than three years of boxing experience were classified as non-experienced athletes in order to allow a clear differentiation between the two subject groups. The experienced athlete group consisted of 11 subjects (mean ± SD: age = 26.29 ± 4.54 years, height = 178.9 ± 6.6 cm, body mass 79.4 ± 9.3 kg and experience 7.43 ± 3.34 years), while the non-experienced athlete group consisted of 20 subjects (mean ± SD: age = 21.67 ± 2.46 years, height = 179.3 ± 9.8 cm, body mass 75.9 ± 8.2 kg and experience 0.36 ± 0.44 years) (Table 20). All participants were informed in advance about the data collection protocol as well as the risks and benefits of the experiment. The experimental data acquisition was performed in the boxing gym of the German Sport University Cologne and thus in a familiar training environment of the participating subjects. Prior to the experimental testing, each participant was instructed with a boxing specific warm up that allowed the participants to get used to the experimental setting and the equipment to be used for the experimental data acquisition.

Table 20: Characteristics of the experienced and non-experienced groups of boxing athletes

	Experienced (n = 11)	Non-experienced (n = 20)
Age (years) [1]	26.29 ± 4.54	21.67 ± 2.46
Height (cm) [1]	178.9 ± 6.6	179.3 ± 9.8
Bodymass (kg) [1]	79.4 ± 9.3	75.9 ± 8.2
Experience (years) [1]	7.43 ± 3.34	0.36 ± 0.44

[1]Values are means ± SD

c) Experimental setup and protocol

For the analysis of the self-assessment of punch intensity in amateur boxing between experienced and non-experienced athletes, the participating test subjects were informed at the beginning of the study about the course of the experiment and the punch intensities as well as the punch techniques to be carried out. The instructions served in particular to avoid misinterpretations of the understanding of the self-assessed punch intensities and the different punching techniques to be performed for both groups of subjects to be tested.

The kinetic and kinematic data acquisition was carried out with the application of the boxing monitoring system, developed and presented in the previous course of the thesis, as in the previous experimental studies about the analysis of punching technique in experienced compared to non-experienced boxers. The data collection for the analysis of self-assessment of striking intensities focused on the measurement of the participants executed maximum punch force. Additionally, the punch acceleration, punch speed, punch trajectory and the orientation of the fist in three-dimensional space as well as the punch time, separated into the throw, contact and retraction time, were measured. The boxing monitoring system was incorporated into an AIBA-certified boxing glove weighing 340 grams (12 ounces) from Adidas (Adidas AG, Herzogenaurach, Germany) for data measurement. A 40 kg leather punching bag from Paffen Sport (Paffen Sport GmbH & Co. KG, Cologne, Germany) was mounted on a wall attachment and served as a target for the punches to be executed against a predefined stationary target.

The recording of the measurement parameters were carried out with a data acquisition frequency of 1,000 Hz. The measured parameters were stored on the receiver device using a buffer for subsequent post-processing and comprehensive data analysis using MATLAB (The MathWorks, Natick, USA). The 1,000 Hz measurement frequency was used to ensure that the entire biomechanical data is fully recorded during the impact, including the throw, impact and retraction phase. As in the previous study, that was presented in chapter 4.2 for the analysis of boxing biomechanics, the experimental protocol used in this study consists of the four main punching techniques to be tested (jab, cross, uppercut and hook), according to Thomson and Lamb (2016). This separation was made repeatedly in order to reduce the existing punching technique variations in the sport of boxing, that had to be performed by all participants in a sequence. The selection was made as the four applied punching techniques are the most commonly used techniques in the sport of boxing. The two straight techniques of the jab and cross punch as well as the semi-circular uppercut and hook punch were therefore executed. To perform the impact tests, the participating subjects were instructed to perform the impacts with four different impact intensities according to a defined survey protocol that was instructed by the investigator for each impact intensity to the participants.

The study addressed the self-assessment accuracy of default punching intensities in amateur boxing by experienced and inexperienced athletes and the resulting kinetics and kinematics of the thrown punches. In this study the achieved punching force was of particular importance for the statistical analyses of the testing. The punches were performed by all participants from a static defensive position with the punching bag as a target in front of the subjects. At the beginning of each punching technique the subjects were instructed to determine their own punch distance and to test the distance in order to avoid unnecessary variations during the experimental data acquisition.

The study commenced with a slow technique focussed execution at the beginning of each punching technique. Thereafter, the subjects were instructed to increase their impact intensity in predefined punch intensities. The defined impact intensities were 50%, 70% and consequently 100% of the self-assessed punch intensity. During the execution of the maximum punching intensity the test persons were actively encouraged to execute the impacts with their highest intensity. Furthermore, the subjects were instructed to immediately return to their defensive position after the execution of a punch, as it would be the case in a sparring match or competition. This execution sequence was chosen in order to execute the punch realistically in its full range of motion and to determine differences in the time required to execute the different punching intensities. The participants were instructed to remain in their defensive position for at least two seconds before the subsequent punch was allowed to be executed.

d) Data analysis

The data analysis to determine the self-estimated punching intensity in boxing was carried out in an identical approach as in the study presented in chapter 4.2 about the analysis of the punching technique in experienced versus non-experienced subjects. The buffered biomechanical performance data collected during the experimental performance of the punching tests were processed for data processing and data analysis using MATLAB (2018b) routines. For the data analysis of the self-assessment of the punching intensity in amateur boxing between experienced and non-experienced athletes, the theoretical punching intensity was calculated as a percentage of the maximum punching intensity of 50% and 70%. The maximum punching intensity was determined at the beginning of the study for each individual subject and was used for further data analysis.

A special focus for the determination of the self-assessment was the analysis of the punch force. In addition, the punch acceleration and punch velocity were determined and used for data analysis. The maximum values achieved for the individual impacts were determined and used for further data analysis.

In addition to the punch force, the stroke duration was detected. As in the previously presented study on the analysis of punching techniques between experienced and non-experienced athletes, the punch time was normalized in order to analyse the pattern of thrown punching techniques among each other and between all participating subjects. The absolute impact time was divided into the three phases of the attack, contact and retraction phase. The attack time was determined from the initial movement of the fist in the direction of the striking object in the x-axis and ended by the first contact with the striking target. The contact phase was defined as the time during which the glove is in contact with the target. This phase was further subdivided into the exposure time up to the maximum impact peak reached, i.e. up to the maximum achieved impact force (N), and the pre-release phase until the hand is released from the target. The retraction time was measured, starting with the release of the fist from the targeting object until the hand returns to the defensive position and the reduced acceleration of the fist.

e) Statistical Analysis

Building up on the preliminary presented data processing, the statistical analysis of the experimental performance data is conducted for the analyses of self-assessment accuracy of punching intensity in amateur boxing between experienced and non-experienced athletes. The statistical analysis is performed using the analysis software, IBM SPSS Statistics for Windows, Version 23.0 (IBM Corporation, New York, USA).

The analysed descriptive data of the self-assessment of punch intensity in amateur boxing are presented as mean values and standard deviations. The data was tested for anomalies and outliers at the beginning of the statistical data evaluation. To classify outliers, measurement data with a standard deviation of more than one and a half times the mean value were classified as minor outliers. Data points with more than three times the standard deviation from the mean value were declared as strong outliers. The graphical representation of outliers is presented using box-whisker plots. Within the box whisker plot, light outliers are marked as circles and strong outliers as asterisks. In order to analyse the normal distribution, the Shapiro-Wilk test was preferred in preference to the Kolmogorov-Smirnov test. The test selection is justified by the greater significance of the Shapiro-Wilk test for the prediction of normal distribution. The Levene test was performed to check for homogeneity in variance of the experimental data. In order to evaluate the group differences between experienced and non-experienced athletes, a three-way ANOVA was calculated. Group differences as well as differences between the technical punching techniques were analysed by means of a Tukey or Games-Howell post hoc analysis, if the homogeneity of variances was not fulfilled. For all statistics, a 95% confidence interval was calculated with an alpha level set as $p < 0.05$ for the detection of significant differences in all statistical tests applied.

Subsequently, the effect size was calculated in a first attempt using Cohen's *d* (Cohen, 1988). Since the effect size is not limited according to Cohen's *d* in positive and negative direction, the Pearson product-moment coefficient *r* was calculated on the basis of Cohen's *d* for a uniform standardization (Aaron et al., 1998). The correlation coefficient has the advantage that it is limited from -1.0 to +1.0 and thus shows a clear distinction. An effect size from 0.1 represents a small effect, an effect size from 0.3 a medium effect and an effect size from 0.5 a strong effect (equation 86).

$$r = \frac{d}{\sqrt{d^2 + 4}}$$

Equation 86: Calculation of the effect size *r* (Cohen, 1988, p. 23)

Due to the unequal sample size of experienced and non-experienced subjects, the effect size is calculated according to Aaron, Kromney and Ferron (1998) using the pooled standard deviation (equation 87).

$$r = \frac{d}{\sqrt{d^2 + (N^2 - 2 \cdot N) / (n_1 \cdot n_2)}}$$

Equation 87: Calculation of the effect size *r*

4.3.3 Results

The statistical data analysis for the verification of accuracy in self-assessed punch intensities for the four main punching techniques of the jab, cross, hook and uppercut showed statistically significant differences. The differences identified were assessed between the tested groups of experienced and non-experienced boxing athletes. The results of the three-way ANOVA showed statistically significant differences for the overall analysis between the two assessed experience level F (4.00, 194.00) = 8.973, $p < 0.001$, partial η^2 = .156, Wilk's Λ = .712 and the punching techniques performed F (4.00, 194.00) = 7.140, $p < 0.001$, partial η^2 = .128, Wilk's Λ = .760.

The following subsequent sections present a detailed representation of the statistical results for each of the four punching techniques tested with the self-assessed intensities.

Cross punch results

Figure 109 presents the box-whisker plot for the display in variation of self-assessed punching intensity of experienced and non-experienced boxing athletes. The plot presents the subject data for a 50% intensity of the performed cross-punch technique. The experimental data obtained for this experiment has shown normal distribution for both subject groups with *p* > .05 as assessed by the Shapiro-Wilk test.

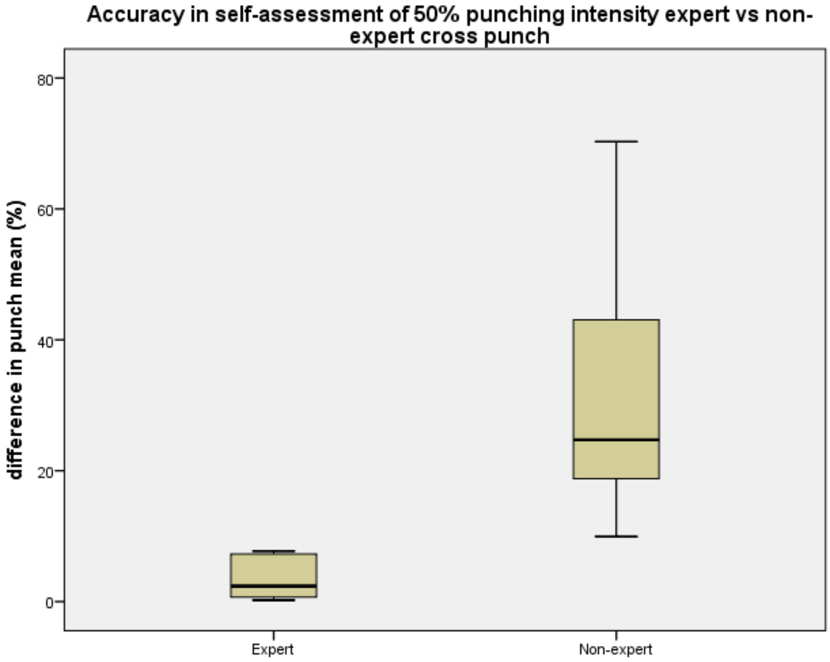


Figure 109: Accuracy in self-assessment of 50% punching intensity expert vs non-expert cross punch

The evaluation of the experimental data on the self-estimated impact intensity shows that the group of experienced test persons performed the cross punches with a mean deviation of 3.57% (SD = 3.38%) based on the test instructions. The results of the non-experienced group of subjects shows a greater deviation of 29.9% with a standard deviation of 16.39% of their self-estimated executed impact force measured in Newtons (Figure 112). The mean difference between the experienced and inexperienced group of subjects with respect to their self-estimated punch intensity shows a difference of -26.32% (95% - CI [-34.76, -17.89]). This result indicated a statistically significant difference in the accuracy of self-assessment between the two groups of subjects tested with a significance of $p < .001$. The calculated effect size indicates a strong effect, based on Pearson's product-moment coefficient r between the experienced and non-experienced subject groups (0.8).

The second punching intensity tested was the accuracy in self-assessment for punches thrown with 70% of the self-assessed maximal punch intensity (Figure 111 and Figure 112). The experimental data revealed no outliers within the data set of experienced and non-experienced athletes tested as seen in Figure 110. Furthermore, as analysed for the first intensity level of 50%, normal distribution was assessed by the Shapiro-Wilk test with $p >$ .05.

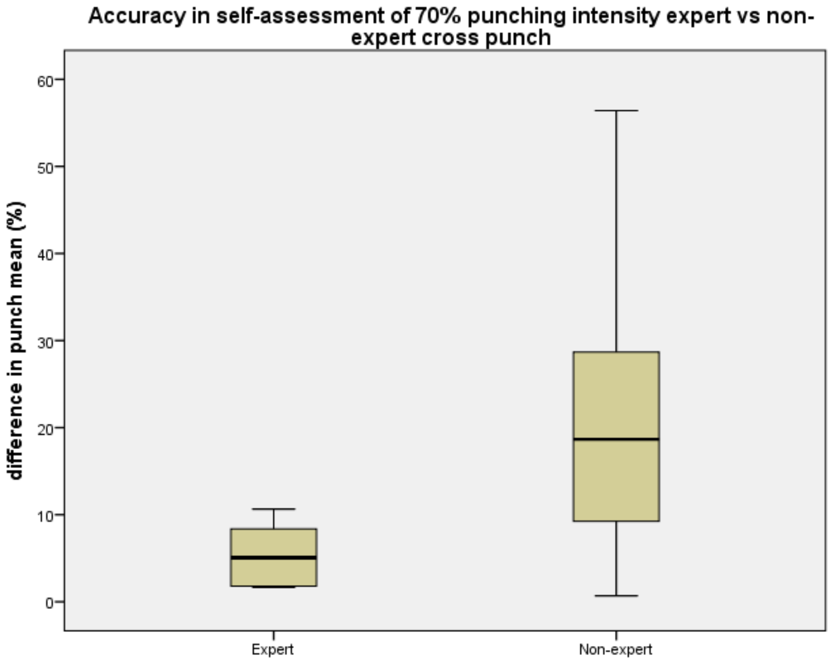


Figure 110: Accuracy in self-assessment of 70% punching intensity expert vs non-expert cross punch

The analysis of the impact intensity revealed that the group of non-experienced athletes showed an average deviation of 21.76% (SD = 17.58%) from the specified and individually determined impact force for the subjects tested. In comparison, the test group of the experienced test persons performed the requested intensity level with a mean deviation of

5.35% (SD = 3.9%), as presented by Figure 110. The mean accuracy of the self-assessed punching intensities was 16.41% more accurate by the expert group (95% - CI [-25.51, -7.31]). This leads to a statistically significant difference between the two groups of experience with p = .001.

The effect size of 0.61, determined with the help of the Pearson product-moment coefficient r, shows a large effect between the two groups of test persons regarding the accuracy of the self-estimated impact intensity (Table 21).

Table 21: Accuracy of self-assessed punch intensity experienced vs non-experienced subject's cross punch

	Experienced	**Non-experienced**	**p-value**	**ES (rating)**
Cross punch 50% self-assessed intensity*	3.57%. ± 3.38%	29.9% ± 16.39%	p < .001	0.8 (large)
Cross punch 70% self-assessed intensity*	5.35%. ± 3.9%	21.76% ± 17.58%	p = .001	0.61 (large)

* All values presented are means ± standard deviation; ES = Effect size;

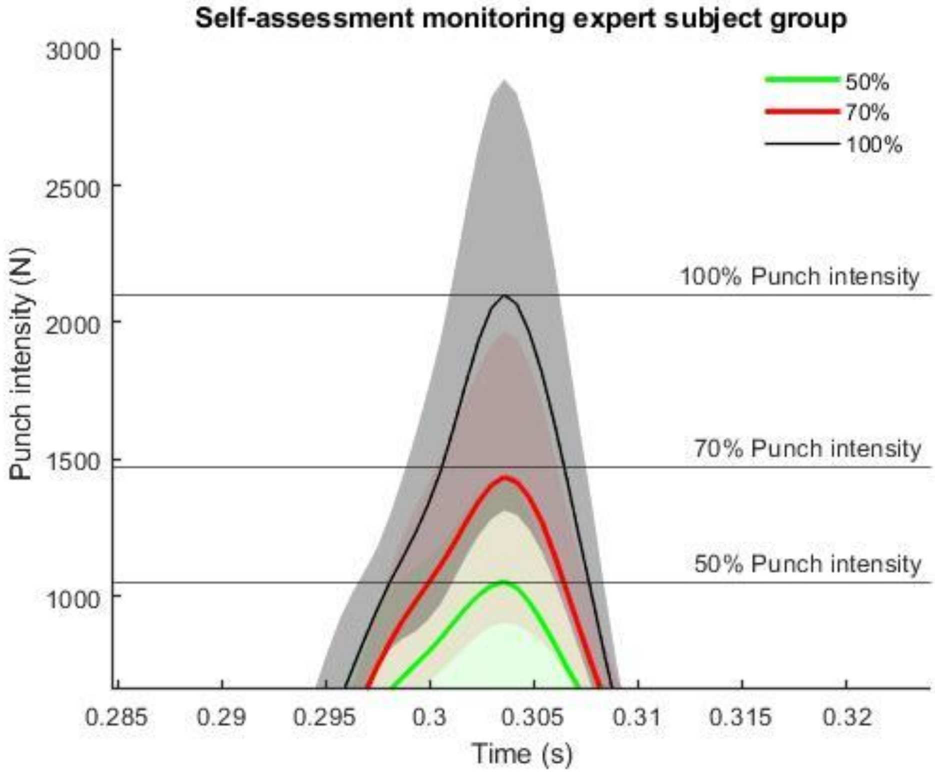


Figure 111: Self-assessment monitoring experienced subject group cross-punch

*All values presented are means ± standard deviation

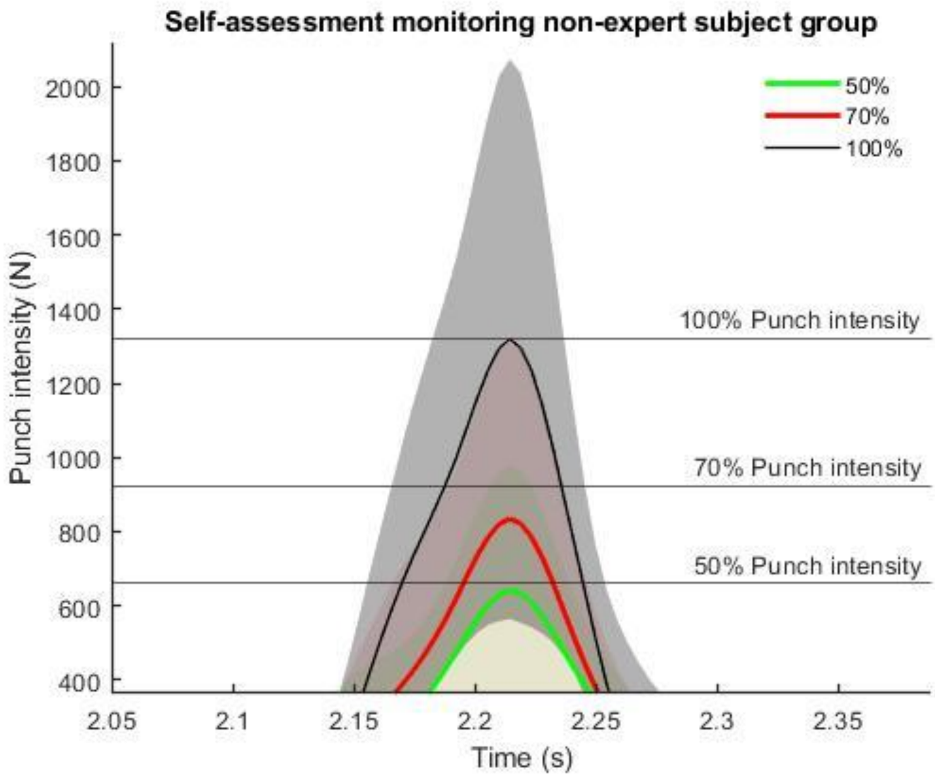


Figure 112: Self-assessment monitoring non-expert subject group cross-punch

*All values presented are means ± standard deviation

Hook punch results

The second punch technique executed to examine the self-assessment accuracy was the hook punch. By analysing the 50% punch level, no outliers of the data sets were detected for the group of non-experienced as well as experienced subjects (Figure 113). The data sets of both groups of subjects, tested positive for normal distribution using the Shapiro-Wilk test (p > .05).

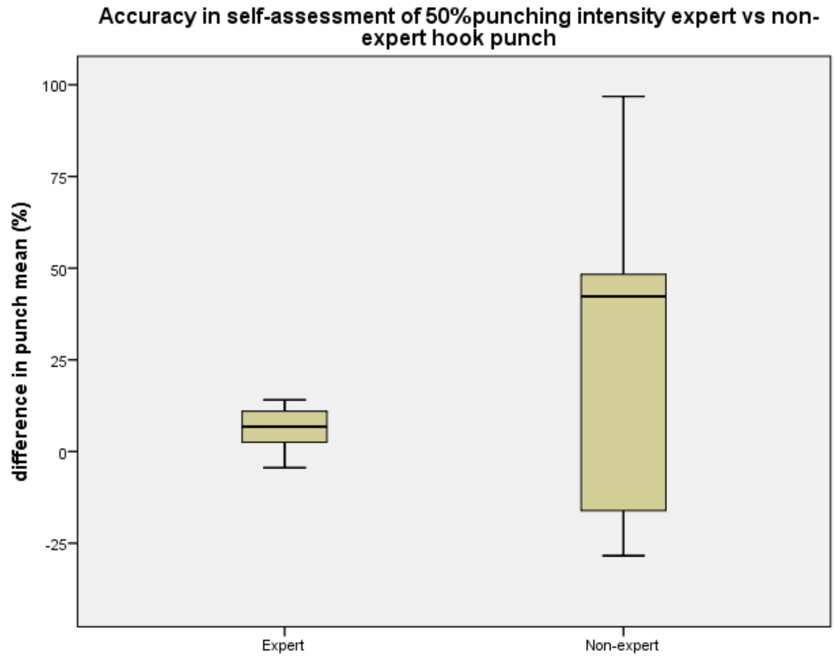


Figure 113: Accuracy in self-assessment of 50% punching intensity expert vs non-expert hook punch

The participant group of non-experienced subjects executed the self-assessed hook punch with a mean of 26.93% (SD = 43.28) above the default punch intensity. In contrast, the group of experienced test persons showed a self-estimated impact intensity with a deviation of 6.28% (SD = 6.23) from the default intensity of 50%. This represents a group-specific deviation of the self-estimated accuracy with an average of -20.65% (95% -CI [-41.89, 0.58]). No statistical significance was assessed for the group difference (p = .056). However, the data shows a strong trend that the group of experienced test persons achieved a higher accuracy regarding the self-estimated impact intensity. The verification of the effect size using the Pearson product-moment coefficient *r* showed a low effect size of 0.16 (Table 22).

The analysis for outliers for the intensity level of 70% showed no anomalies in the data sets for the experienced and inexperienced group of subjects (Figure 114).

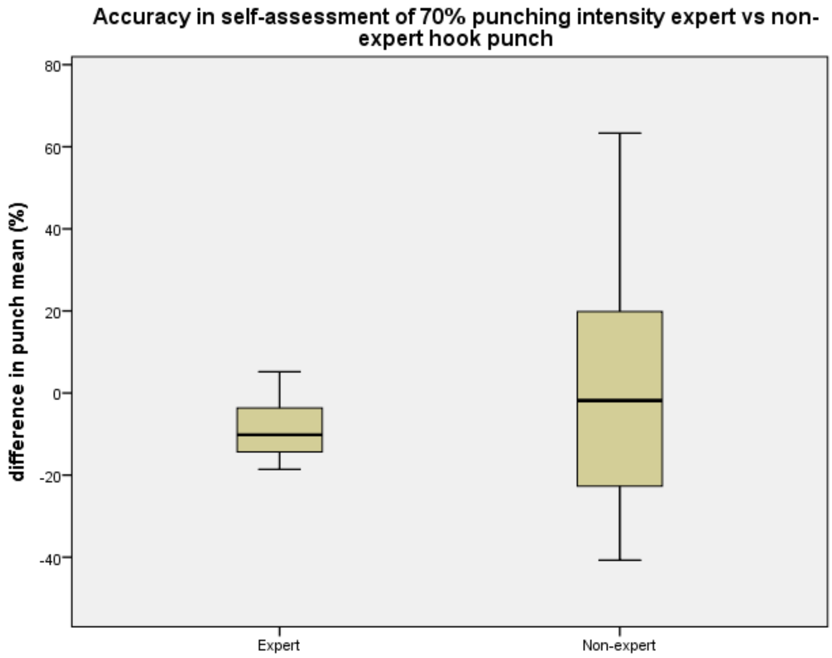


Figure 114: Accuracy in self-assessment of 70% punching intensity expert vs non-expert hook punch

The test for normal distribution confirmed a normal distribution of the collected data sets using the Shapiro-Wilk test (p > .05), for both groups of test persons in respect of the self-estimated impact intensity of 70% for the hook punch technique. The group of experienced subjects showed an average deviation of accuracy with respect to the punching intensity of -8.71% and a standard deviation of 7.76% (Figure 114).

In contrast, the group of inexperienced subjects performed the hook punching technique with a mean deviation of -0.71% (SD = 28.12) of the 70 % desired intensity. This corresponds to a mean difference of -8% (95% -CI [-22.50, -6.5]). The statistical examination of significance shows a tendency of group differences as illustrated in Figure 115 to Figure 116. Although no significant difference between experienced and inexperienced boxers p = .27 was observed.

The effect size of 0.08 outlines a low effect size based on Pearson´s product-moment coefficient r between the two tested groups of subjects (Table 22).

Table 22: Accuracy of self-assessed punch intensity experienced vs non-experienced subjects hook punch

	Experienced	Non-experienced	p-value	ES (rating)
Hook punch 50% self-assessed intensity*	6.28%. ± 6.23%	26.93% ± 43.28%	$p = .056$	0.16 (small)
Hook punch 70% self-assessed intensity*	-8.71%. ± 7.76%	-0.71% ± 28.12%	$p = .27$	0.08 (small)

* All values presented are means ± standard deviation; ES = Effect size;

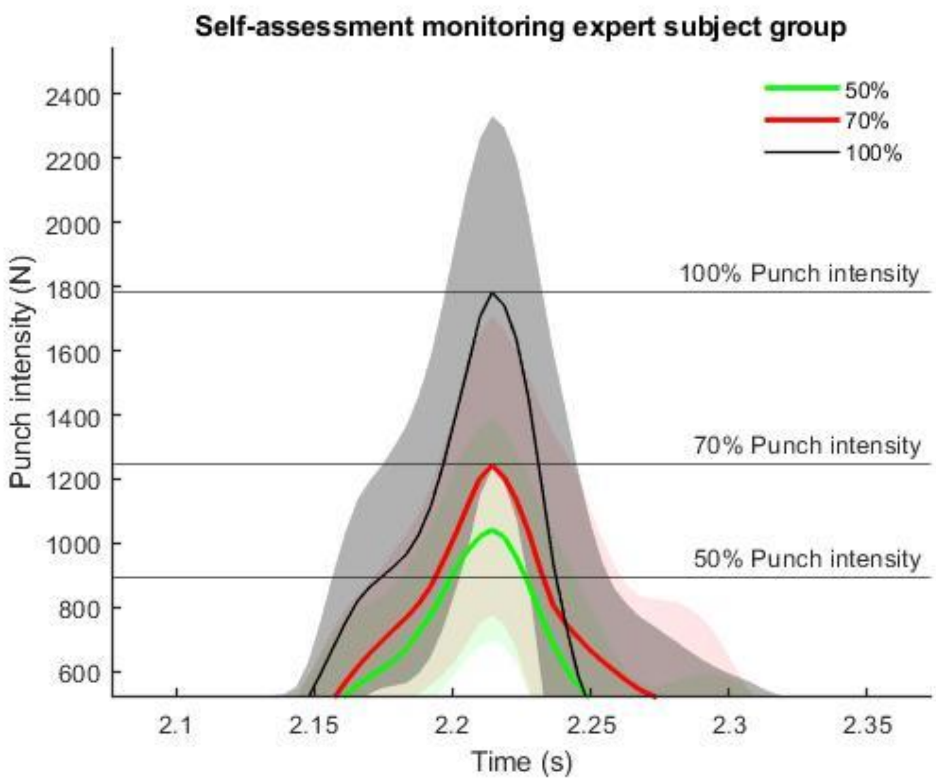


Figure 115: Self-assessment monitoring expert subject group hook punch

*All values presented are means ± standard deviation

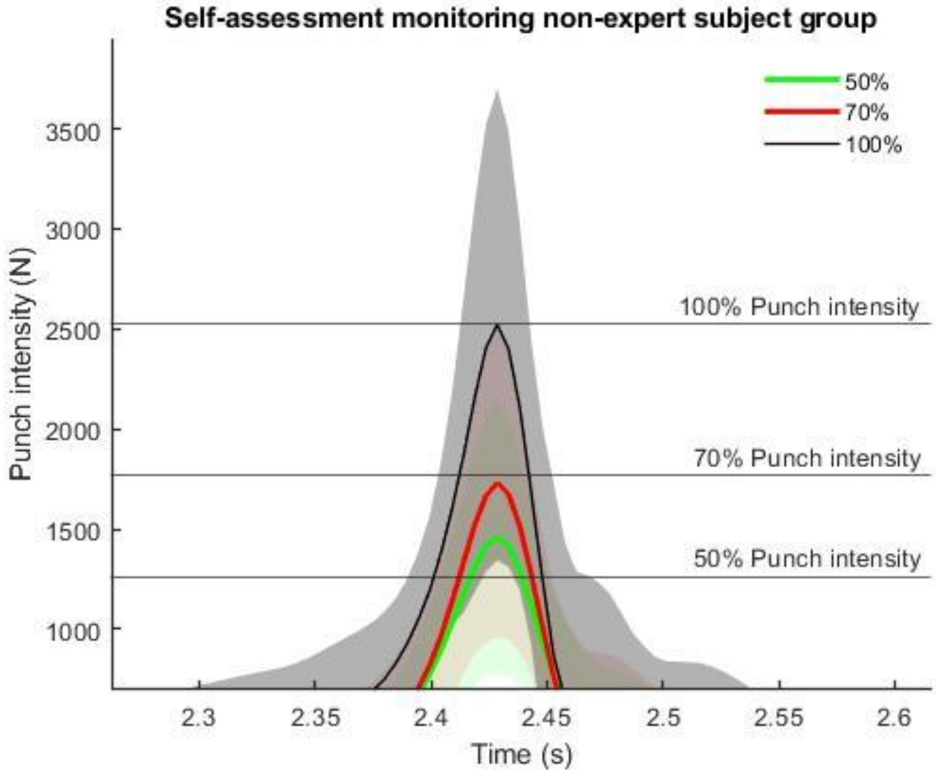


Figure 116: Self-assessment monitoring non-expert subject group hook punch

*All values presented are means ± standard deviation

Jab punch results

The analysis of the third punch technique of the jab punch, shows no outliers in the data sets of the experienced and inexperienced participants for the determination of the self-estimated mean accuracy of the 50% punch level as illustrated in Figure 117. The results of the conducted Shapiro-Wilk test show a normal distribution of the datasets for both groups of participants, experienced and non-experienced (p > .05).

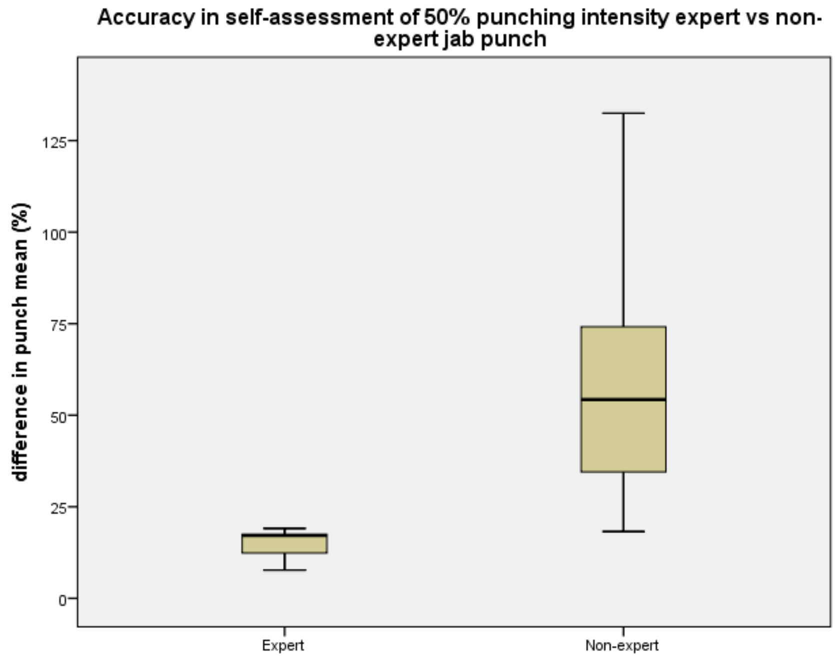


Figure 117: Accuracy in self-assessment of 50% punching intensity expert vs non-expert jab punch

The results of the experienced participants show a mean difference of 15.11% (SD = 3.96%) from the default punch force of 50% (Figure 117). The results of the inexperienced group of participants show a mean deviation of 58.35% from the specified impact intensity of 50% with a standard deviation of 29.91% (Figure 117). This result corresponds to a group difference of -43.24% (95% - C [-57.88, -28.6]). The analysis of significance has shown a statistically significant difference between the self-assessed accuracy of the experienced and non-experienced subject groups of p < .001. With an effect size of 0.94, based on Pearson's product-moment coefficient *r*, the results indicate a strong effect between the two tested groups (Table 23).

In common with the data analysis of the first impact intensity of 50%, the data analysis of the second intensity level of 70% showed no outliers within the data sets for both, experienced and non-experienced subjects (p > .05). For the analysis of the second self-estimated punch intensity of 70% in this study, it is found that the group of test subjects with a lower boxing experience performed the punches with a mean deviation of 26.74% (SD = 22.86%) from the default punch level (Figure 118). Contrary to this, the group of test persons with a more extensive boxing experience showed a mean deviation of 5.42% (SD = 3.56%) of the required punch intensity (Figure 118). This result corresponds to a mean deviation of -21.32% (95% - C [-32.57, -10.06]). The results show a significant difference between the two experience levels tested, of p = .001, with a strong effect size of 0.61 (Table 23).

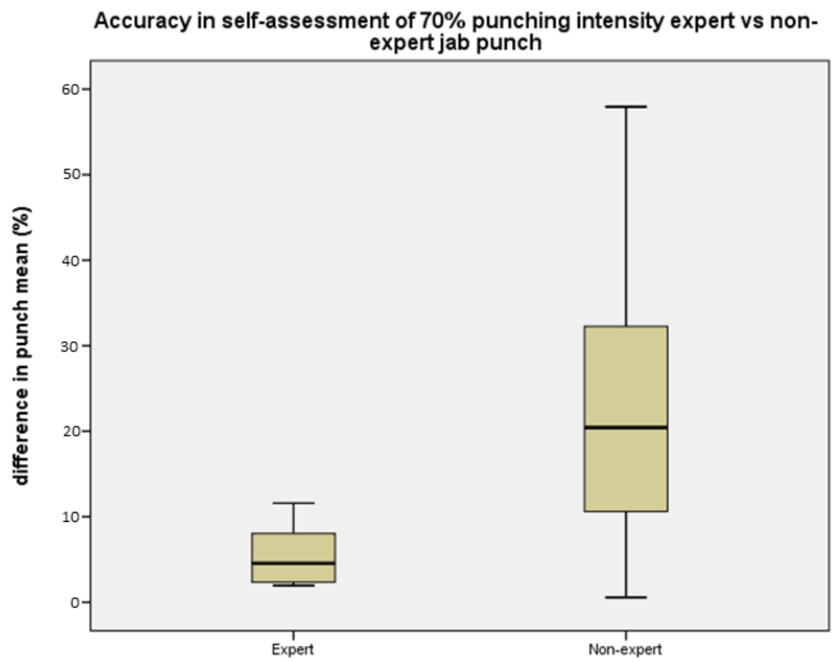


Figure 118: Accuracy in self-assessment of 70% punching intensity expert vs non-expert jab punch

Table 23: Accuracy of self-assessed punch intensity experienced vs non-experienced subjects jab punch

	Experienced	Non-experienced	p-value	ES (rating)
Jab punch 50% self-assessed intensity*	15.11%. ± 3.96%	58.35% ± 29.91%	$p < .001$	0.94 (strong)
Jab punch 70% self-assessed intensity*	5.42%. ± 3.56%	26.74% ± 22.86%	$p = .001$	0.61 (strong)

* All values presented are means ± standard deviation; ES = Effect size;

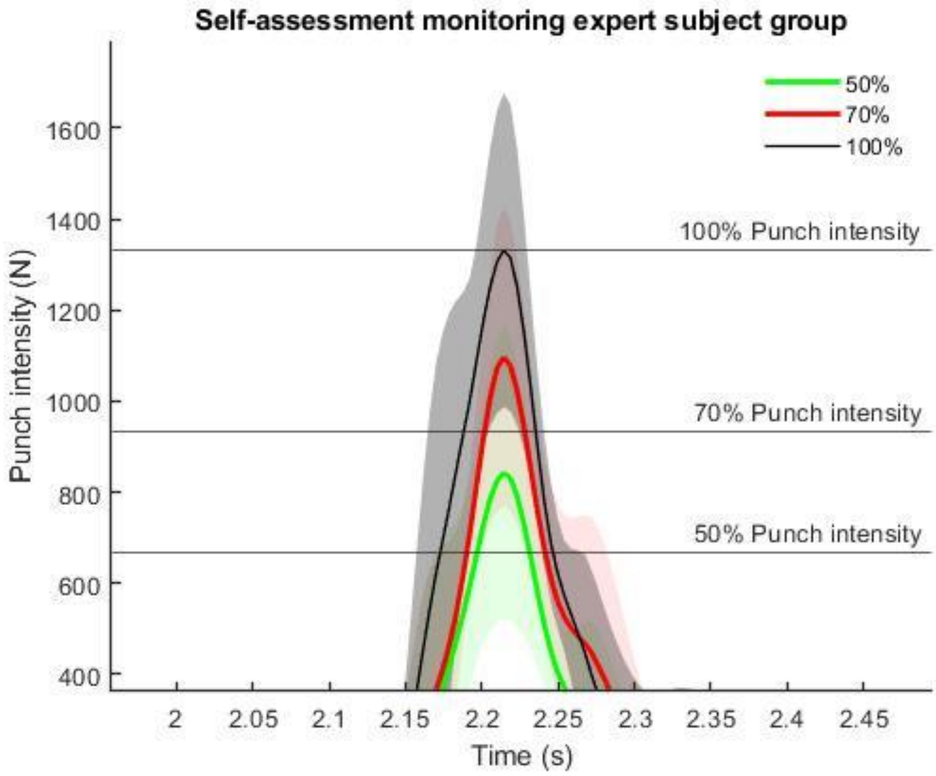


Figure 119: Self-assessment monitoring expert subject group jab-punch

*All values presented are means ± standard deviation

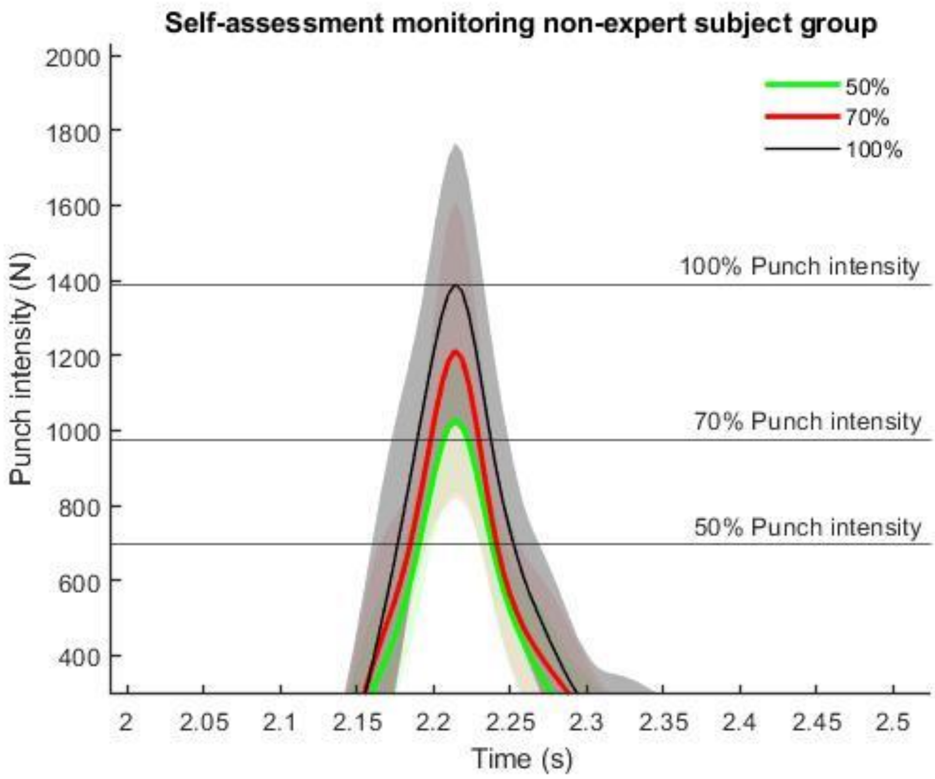


Figure 120: Self-assessment monitoring non-expert subject group jab-punch

*All values presented are means ± standard deviation

Uppercut punch results

The uppercut punching technique was the final punch tested. The analysis of anomalies for the data sets of the experienced and non-experienced subjects revealed no outliers (Figure 121). Normal distribution was assessed for both groups of datasets using the Shapiro-Wilk test (p > .05).

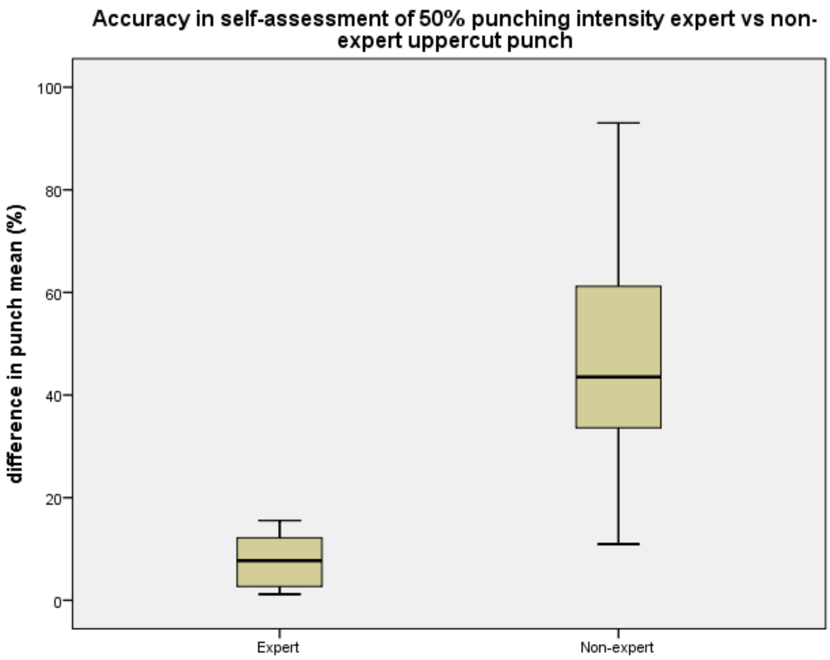


Figure 121: Accuracy in self-assessment of 50% punching intensity expert vs non-expert uppercut punch

To perform the self-estimated punch intensity of 50%, the test persons with a non-experienced boxing level showed an average deviation of 48.51% (SD = 22.35) of the individually targeted punch intensity range (Figure 121). In comparison, the group of experienced subjects performed the tests with a mean of -40.98% more accurate compared to the inexperienced group. This corresponds to a mean deviation of the experienced group of participants of 7.52% and a standard deviation of 5.32% from the impact intensity to be achieved (95% - C [-52.91, -29.05]) (Figure 121). The comparison of the two groups shows a significant difference with a p value < .001 (

Table 24).

The second intensity of 70% self-assessed punching level for the uppercut punching technique showed one outlier in the group of the experienced subjects at 14% (Figure 122). No outlier was detected for the group of non-experts. The datasets for both levels of boxing experience revealed a normal distribution as assessed by the Shapiro-Wilk test (p > .05). The accuracy of the 70% self-estimated impact intensity was shown in the group of inexperienced subjects with a mean deviation of 24.15% (SD = 16.19%) (Figure 122). In contrast, the test subjects with a greater boxing experience showed a mean deviation from the defined impact intensity of 70%, with a deviation of 7.63% (SD = 3.46%) (Figure 122). The results of the 70% uppercut stroke intensity shows that the strokes of the experienced subjects were performed with a mean difference of -16.51% (95% - C [-25.1, -7.93]) more accurate compared to the non-experienced group of subjects. This corresponds to a significant difference in the accuracy of the group's impact assessment with a strong effect size of 0.73 (p = .001) (Table 24).

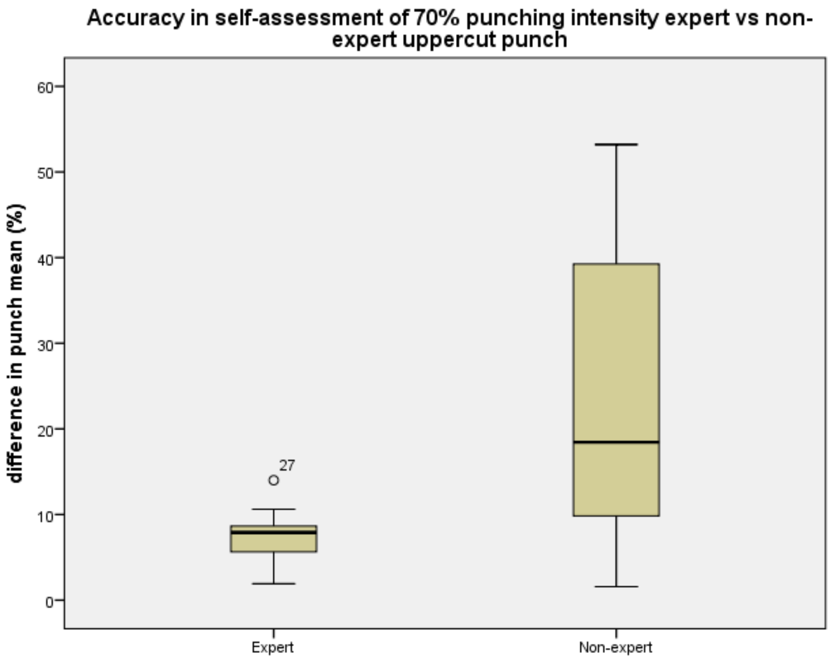


Figure 122: Accuracy in self-assessment of 50% punching intensity expert vs non-expert uppercut punch

Table 24: Accuracy of self-assessed punch intensity experienced vs non-experienced subjects uppercut punch

	Experienced	Non-experienced	p-value	ES (rating)
Uppercut punch 50% self-assessed intensity*	7.52%. ± 5.32%	48.51% ± 22.35%	*p* = .001	1.0 (strong)
Uppercut punch 70% self-assessed intensity*	7.63%. ± 3.46%	24.15% ± 16.2%	*p* = .001	0.73 (strong)

* All values presented are means ± standard deviation; ES = Effect size;

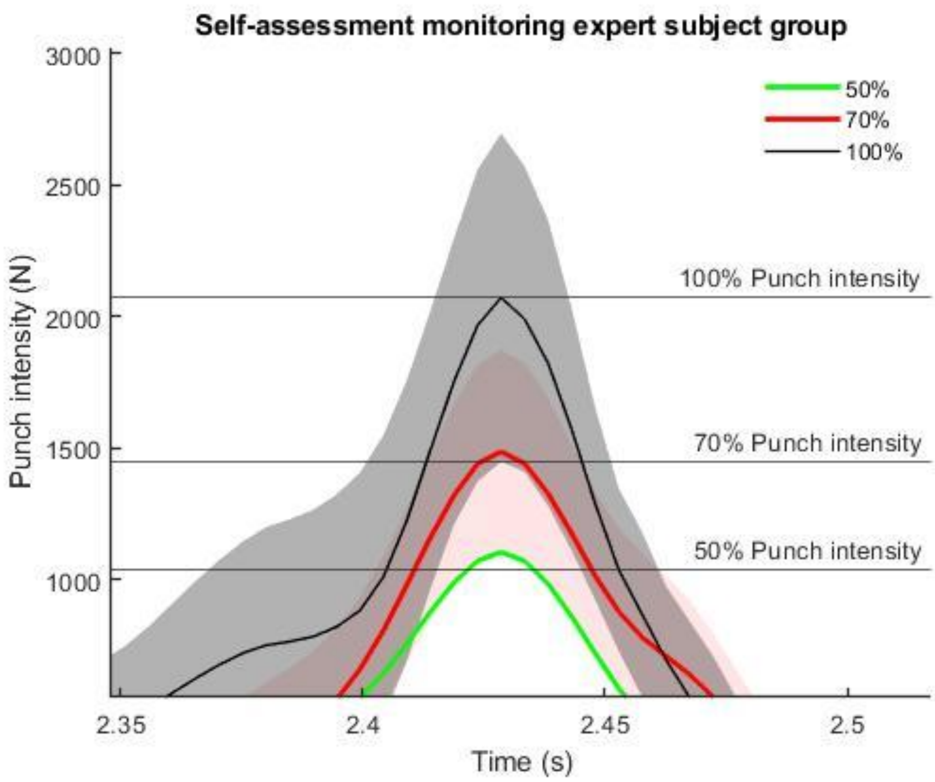


Figure 123:Self-assessment monitoring expert subject group

*All values presented are means ± standard deviation

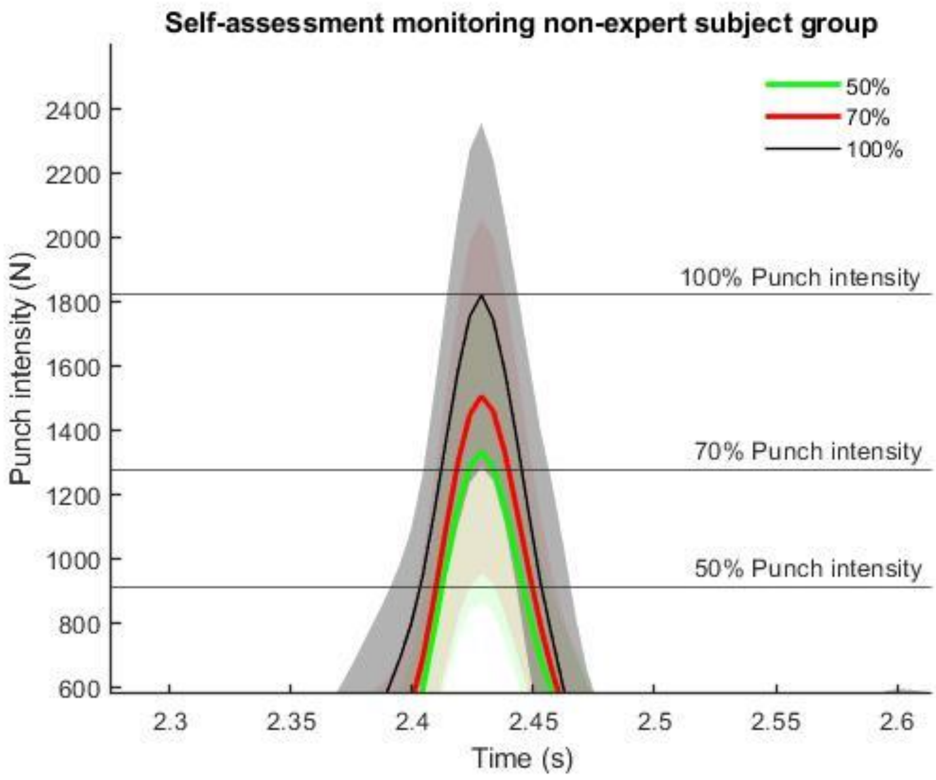


Figure 124: Self-assessment monitoring non-expert subject group

*All values presented are means ± standard deviation

4.3.4 Discussion

The examination of self-assessment of the individual's physical performance in the field of sports is an important criterion in the adaptation to existing guidelines and regulations as well as for the optimization of motion and technical processes (Hofseth et al., 2017; Johnson & Fowler, 2011; Saw et al., 2017). The skill of adequate self-assessment is of great importance in the high-performance sector as well as in recreational and amateur sports. With the help of the conducted literature research, no study was found that examines the accuracy of the self-assessment of personal punch force in boxing and that compares this ability between experienced and non-experienced athletes. The exposed research gap shows the needs as well as the possibilities to provide valuable and unique information to sport and science practitioners, that can be collected and evaluated by use of the developed boxing monitoring system. For this reason, the field of application of the developed sensor system was extended. Hence, the presented experimental study in this chapter is the first study to the authors knowledge, with the aim to collect punch force data of different intensities and to analyse these data on accuracy and reproducibility. To investigate the self-assessment in punch intensity of the four main punching techniques (Thomson & Lamb, 2016) of the jab, cross, uppercut and hook punch, the study tested and statistically compared thirty-one subjects, divided into eleven experienced and twenty non-experienced boxers regarding their boxing experience in years. To determine the self-assessment, the punch force was selected based on the research design of the first study. The results of the study demonstrated that due to the significantly longer contact time of the inexperienced subjects with the target object, the impulse as a possible variable is significantly increased and thus represents an ineffective variable for a comparison of self-assessed punch forces.

The experimental results presented in Chapter 4.3.3 shows significant differences in the accuracy in which experienced and non-experienced athletes are able to achieve and reproduce for individual punch intensity levels and punching techniques. The statistical results of the ANOVA analysis has shown significant performance differences between the two assessed experience level as well as the techniques executed.

The group of subjects with a higher experience level of 7.43 years (SD = 3.34 years) showed an average deviation of 5.27% from the given intensities to be thrown of 50% and 70% for all four punching techniques. Investigating the accuracy of the intensities of the striking techniques, it is analysed that the striking intensity of 50% was achieved with a 5.7% higher average deviation of 8.12% (SD = 4.94%) than for the intensity level of 70%. The level of 70% punch intensity shows an average deviation of 2.42% (SD = 7.5%) for all tested punching techniques. These results were compared to the average deviation in accuracy of the inexperienced group of test subjects with 0.36 years of experience (SD = 0.44 years). The results show that the tested subjects reached an average deviation of 29.4% for all strokes to the default intensities. Likewise, to the experienced group of test subjects, it was analysed that the performed strokes of the 50% punch intensity level were performed with a 22.94% higher deviation of 40.92% (SD = 15.03%) than the 70% intensity level. The level of 70% intensity was performed with an average of 17.98% (SD = 12.62%) deviation from the default intensity to be executed.

A more detailed examination of the individual punching techniques and the comparison of the two tested experience level shows, that the cross-punch analyses revealed a significant difference in accuracy between the experienced and inexperienced group of participants for both punch intensity level. As outlined in the results of the study presented by Thomson and Lamb (2016), the cross punch is the second most frequently performed punching technique in boxing. This is also reflected by the accuracies achieved in this study for the group of experienced athletes tested. In a comparison of the four punching techniques, the cross punch shows the smallest deviation in the level of 50% punch intensity with an average deviation of 3.57% (SD = 3.38%), that is 4.55% below the average deviation of the punch accuracy of all punches thrown. In contrast to this result, the deviation of the accuracy of the 50% cross punch intensity of the non-experienced group of test persons is with 29.9% (SD = 16.39%) exactly within the average deviation of the punch intensity accuracy achieved for all techniques tested. A similar result is shown for the 70% impact intensity level. The results of the group of experienced athletes showed again the highest accuracy for this punching technique with an average deviation of 5.35% (SD = 3.9%). This result is 1.43% more accurate than the average accuracy deviation of the punching techniques performed.

An unexpected result was shown in the results of the striking technique of the hook punching technique. Although, in contrast to the cross punch, this punching technique is a technically more complex and less frequently used punch in boxing, the results of the inexperienced group of test persons demonstrated the smallest deviation in percentage from the default punch intensities tested. This result is evident for the intensity of 50% as well as for 70%. For the 70% impact intensity level, the average deviation of -0.71% (SD = 28.12%) was even tested to be below the group of experienced athletes with -8.71% (SD = 7.76%). Furthermore, the analysis of the 70% stroke intensity results shows, that the hook punch was the only stroke, for both groups of subjects, in which the stroke intensity was estimated to be on average lower than the default intensity level. Due to the good self-assessment of the non-experienced group of test persons for this punching technique, the hook punch was the only technique that showed a strong tendency but no significant difference between the two groups of experience level.

The third punching technique performed was the jab punch. The analysis of the results of this technique reveals that both groups of test participants achieved the highest deviation in accuracy percentage for the 50% impact intensity level of all tested punching techniques. Thus, for the group of experienced athletes this was a deviation of 15.11% (SD = 3.96%) and for the group of inexperienced athletes an average deviation of 58.35% (SD = 29.91%). The inexperienced group, in contrast to the experienced group, also shows the highest percentage deviation of the tested striking techniques for the level of 70% punch intensity in the jab punching technique, with a deviation of 26.74% (SD = 22.86%). Despite the large deviation of both groups, the results of both intensity level show a significant difference between the groups of test subjects and a strong effect size of >0.5.

The greatest effect size and thus the greatest difference in the accuracy of the impact intensity was shown by the impact technique of the uppercut. The greatest difference between the group of experienced and inexperienced test persons was revealed at the level of 50% impact intensity. The impact level at 50% as well as at 70% showed a significant difference in the accuracy of the self-estimated punch intensity measured in Newtons.

The experimental results of the study show a confirmation of the H1 hypothesis that states, that there is a significant difference between experienced and non-experienced boxers in terms of accuracy in self-assessed punching intensities. These results not only confirm the expert-novice paradigm, that athletes with a greater experience show a better technical execution but also, that experienced athlete show greater cognitive skills for the sport of boxing due to their years of experience (Cesari & Bertucco, 2008; Lenetsky et al., 2018). Furthermore, the results show consistency with the phenomenon described by Johnson and Levine in (2009), that overestimating self-assessment is a widespread human psychological phenomenon. The subjects only showed an underestimation of punch forces for the 70% punch intensity level of the hook punching technique. In all other test cycles, the results showed a tendency towards a stronger execution of the punch intensity in relation to the calculated self-assessment. The results demonstrate the difficulty in the accuracy with that non-experienced boxing athletes can control and assess their punching intensity and the strong deviation from the actual default punch level. According to Marquard (2013), this is however the basic requirement, as punches are classified differently from participant to participant and therefore a good self-assessment of the impact severity is of fundamental importance. Additionally, the reproducibility of the impact intensities is of importance as well, that is indispensable during a training session with a training partner. This shows that the H1 hypothesis of the second hypothesis can be assumed, since inexperienced athletes have shown a greater variance of up to 58% in punch intensities than experienced athletes with a mean maximum variance of 7% (hook punching technique) in their individual intensities executed throughout the experimental study.

Furthermore, the analysed results and applied methodology can be of great interest across the use in recreational and amateur sports, to control sparring matches or training sessions in their limit of punch intensity and furthermore, to provide injury prevention during training with the help of a biofeedback to competitive sports for both high performance as well as amateur athletes.

All punches were executed in the course of a normal boxing training session. Therefore, it would be of great interest, to measure the frequencies of the different punch intensities during a sparring match or a real competition to determine the intensity of the strokes that are performed more frequently during the competition. In the scenario of a competition, an athlete has less time to prepare for a punch as the target is moving and the athlete must expect counter-attacks and is therefore restricted in his execution that can lead to a limitation of punch intensity.

In order to carry out follow-up studies, especially the ratio of experienced to inexperienced athletes of one to two has to be criticised. The planned follow-up studies deal therefore with an expansion of the number of test subjects, especially for the experienced group of participants. For follow-up experiments, the experience level will also be expanded in order to include athletes with international experience and thus to include a third group of excellence performance in the study design, as well as to make a division between men and women.

4.3.5 Conclusion

The experimental investigation presented in this chapter had the purpose to present a novel method of measuring the accuracy of self-assessed punch force accuracy in experienced and non-experienced boxing athletes. The study outlines the versatile field of application of the developed boxing monitoring system to contribute new information in the field of boxing and martial arts research. The results show that an exact assessment of non-experienced athletes regarding their stroke intensity is not possible without a large deviation from the default intensity.

The developed measuring system outlines in this study, that it cannot only be of great use in performance diagnostics for competitive sports, but that this development can also make a decisive contribution to its application in school sports or social institutions for inter alia violence prevention classes. Therefore, the developed type of system can be an important support when it comes to contributing a direct and objective feedback to the people involved, in order to provide biofeedback to students and participants with the help of a predefined intensity limit. This kind of biofeedback allows participants to receive direct feedback and thus to adhere to the rules and regulations of the event in a consistent manner in order to immediately detect a possible exceeding of punch severities.

In addition, the possibility of recognising stroke intensities can furthermore be transferred to competitive sports, among other things for training control and load management.

4.4 Analysis of Fist Activity while Punching. A Comparison of Experienced and Non-Experienced Athletes.

The following chapter 4.4 serves to present and outline the results of the third experimental study conducted in the research field of boxing biomechanics and the analysis of striking technique. The research is conducted in particular for the analyses of fist closure while punching and to investigate the activity of the boxer´s fist as the major body part in the field of combat sports. The study represents the second follow-up experiment based on the research results obtained with the developed boxing monitoring system for the experimental generation of biomechanical performance data in boxing.

The chapter is structured by outlining the aim of the research, in particular of the existing research gap on which this study is focussed on. Based on this, a detailed description of the research methodology used is given and subsequently the experimental results obtained are presented. The chapter on the presentation of the applied methods for the analysis of fist activity in amateur boxing while punching concludes with a discussion and conclusion of the experimental results with a research outlook for follow up research studies based on the results presented.

4.4.1 Objective

The fists have without objection a superior importance in the martial arts as it is in boxing. Protected by the boxing gloves, the fists serve the athlete not only as the primary body part for attacking in the offensive but also for the defensive part to protect the athlete from blows of the opponent. Due to the primary importance of the fists in boxing, most scientific literature in the field of martial arts and combat sports focuses on the impact kinetics generated by the fists. This was presented and outlined in the literature review in chapter 2.1.1 in detail, inter alia on the basis of studies by Loturco et al., (2016), Pierce et al., (2006), Piorkowski et al, (2011) and Smith (2006), about the kinetics and kinematics of boxing punches. In the studies by Pierce et al. (2006) and Neto et al. (2007), the authors pointed out that direct punch impact measurement can be used to determine the experience level of athletes as “motor skills characteristics are the main variable to represent boxing technical performance” (Ashker, 2011, p. 357). As described by Slimani et al. (2017) the time structure of an athletic motion is “an effective way to obtain information for creation of a training prescription, as well as to quantify physical and technical patterns” (Slimani et al., 2017, p. 1137). Therefore, “time–motion analysis is a non-invasive performance analysis technique that provides broader insights into the activity pattern […] of boxing competition” (Slimani et al., 2017, p. 1137).

In addition, Filimonov et al. (1985) described that the winner or loser of a competition can solely be determined by collecting data on punch characteristics. The studies demonstrate the importance of the kinetic parameters of the fist and the tremendous forces exerted by the fist on a target during a punch. Considering the fist as the last link in a kinetic chain before the fist hits the object and the interaction of muscle contraction for optimal power transmission, it is important to investigate at what point in time the fist is closed during a punch to ensure optimal power transmission (Turner et al., 2011). In the publication by Blum in 1977 about "the physics and art of kicking and punching", the author suggests that in order to generate optimal strength and mass, the martial artist should not tense the fist and arm muscles until the moment of impact. This confirms the recommendations made by Turner (2011) that stiffening the muscular system of the arm just before contact will increase the effectiveness of the punch thrown. Other than the study by Blum (1977), no study was found that has analysed or investigated the fist closure and its timing importance.

According to a multitude of boxing and martial arts literature, the importance of closing the fist before the impact is described and uniformly emphasized as a decisive performance feature to generate the highest possible punching effectiveness (Smith, 1989; Werner, 2003; Werner & Lachica, 2000). However, a comprehensive literature research revealed the lack of scientifically profound evidence in the area of fist-closure and fist re-opening, after the impact and during the execution of boxing punches. Only one study was found that has investigated a comparison and the significance of a clenched and unclenched fist in terms of punch force. Horn, Jung and Carrier (2015) discovered, that a punch can be executed with 55%

greater punch force when the fist is clenched completely compared to an unclenched or semi clenched fist (Horns et al., 2015).

Considering the importance of the direct measurement of athletic motion, especially the fists in boxing and the information value provided by this approach to direct performance analysis, the range of scientific research on fist activity in martial arts is severely limited, as the subject of this study reveals. This research gap requires an extended analysis of the fist activity during a punch, since the hands are exposed to a high risk of injury due to the high appearing impact forces (Alton & Carayannopoulos, 2019; Javed et al., 2011; Jeanmonod et al., 2011; Jordan, 1993; Michael Loosemore et al., 2017; Lopez-Ben et al., 2003; Malik & Rosenberg, 2020; Melone et al., 2009; Shewring et al., 2015; Van Der Zee et al., 2015). Loosemore, Lightfood and Beardsley (2015) stated in their publication that up to 55% of all injuries counted in the sport of boxing occurred in the upper extremity area with the most common injury location to be the area of the hand (Michael Loosemore et al., 2015). The authors point out that the fingers and thumbs are particularly affected. These results were also previously highlighted by Noble (1987) and Prevel et al. (1995), as described in detail in Chapter 2.3 on the medical aspects of boxing. Morgan and Carrier (2013) as well as Luchetti, Pegoli and Bain (2018) state that a clinched fist while punching is supposed to reduce the risk of hand injuries to the person throwing the punch. As a result of limited information on the cause of hand and finger injuries from a blow, scientific studies indicate that for a better understanding of the aetiology of hand injuries in boxing, it is necessary to understand the characteristics and distribution of impact forces experienced during a punch. An understanding of how these impact forces differ among athletes and whether a particular punching profile in terms of fist activity is associated with an increased risk of injury will help to develop successful injury prevention interventions and increase the overall understanding of the subject.

Furthermore, the importance of the study of fist activity during a punch, that is presented in the following, is additionally supported by the competition regulations of the AIBA (International Boxing Association) and the WBF (World Boxing Foundation).

Therefore, the objectives of this study were to analyse and to describe the hand activities regarding the athlete's fist closure during the throw period (before impact) and the re-opening of the fist after the impact occurred. For this purpose, the time of fist closure and fist opening in the four main punch types as represented by the jab, cross, uppercut and hook punch are analysed. For further analysis, the data will be collected with the help of experienced and inexperienced athletes to highlight potential differences between the two groups of experience level.

Hypothesis 1 H1: There is a significant difference between experienced and non-experienced boxers in terms of the point in time when the boxing athletes clench their fist before the impact at the target occurs.

Hypothesis 2 H1: There is a significant difference between experienced and non-experienced boxers in the time the fist remains clenched after the impact of the punch on the target.

4.4.2 Methodology

The following chapter is intended to present and illustrate the applied methodology for the analysis of fist activity in amateur boxing while punching between experienced and non-experienced athletes. The test setup, the test protocol, the data analysis and the statistical analysis are presented therefore in detail.

a) Ethics statement

The scientific study presented in this chapter was examined by the ethics committee of the German Sport University Cologne (Cologne, Germany) for its ethically correct applicability. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021). Each participant was given a written description of the experiment before the tests were started.

b) Participants

Twenty-two subjects participated in total in the study for the analysis of fist activity in amateur boxing while punching. At the beginning of the experimental study, the participants were divided into two groups, similar to the previously presented studies in this thesis, according to their level of experience in boxing. This was followed by the division into years, based on their boxing experience over time. Following the study for the analysis of punching technique in experienced vs non-experienced boxer and the experimental study conducted by Lenetsky et al. (2013) the participating subjects with at least three years of boxing experience were classified as experienced athletes and participants with less than three years of boxing experience were classified as non-experienced athletes for a clear distinction between the observation groups. The group of experienced athletes comprised 10 subjects (mean ± SD: age = 25.83 ± 4.79 years, height = 178.7 ± 7.2 cm, body mass 78.5 ± 9.8 kg and experience 5.72 ±

4.37 years) whereas the group of non-experienced athletes comprised of 12 test subjects (mean ± SD: age = 20.86 ± 0.9 years, height = 178.6 ± 12.2 cm, body mass 74.9 ± 9.4 kg and 0.25 ± 0.12 years) (Table 25). All participants were informed in advance of the data collection protocol as well as the risks and benefits of the experiment. The purpose of measuring the participants fist clinch was not mentioned to the subjects in order not to manipulate the data collection in the sense that the test persons pay special attention to the clenching of the fist during the execution of the movement. The measurements were conducted in the boxing gym of the German Sport University Cologne and thus in a known training environment of the participants. Prior to the experimental testing, each participant was instructed with a boxing specific warm up and to get used to the experimental setting and the equipment to be used for the experimental data acquisition.

Table 25: Characteristics of the experienced and non-experienced groups of boxing athletes

	Experienced (n = 10)	Non-experienced (n = 12)
Age (years)[1]	25.83 ± 4.79	20.86 ± 0.9
Height (cm)[1]	178.7 ± 7.2	178.6 ± 12.2
Bodymass (kg)[1]	78.5 ± 9.8	74.9 ± 9.4
Experience (years)[1]	5.72 ± 4.37	0.25 ± 0.12

[1]Values are means ± standard deviation (SD)

c) Experimental setup and protocol

For the analysis of fist activity in terms of fist closure and reopening in amateur boxing during the performance of different punching techniques, the participating test persons were instructed at the beginning of the study on the course of the experiment and the punching techniques to be performed. This measure served in particular to avoid misinterpretation of the understanding of the punching techniques to be executed for the group of inexperienced boxing subjects as conducted in chapter 4.2.

As in the previous experimental study on the analysis of punching technique in experienced versus non-experienced boxing athletes, the kinetic and kinematic data acquisition was performed with the application of the boxing monitoring system developed and presented in the previous course of the thesis. The data acquisition included the measurement of punch force, punch acceleration, punch speed, trajectory and orientation of the fist in three-dimensional space as well as punch time, separated into the throw, contact and retraction time. In addition to the developed boxing monitoring system, the system was extended, as described in the objective 4.4.1 following the observations and findings of the study about the punching technique in experienced and non-experienced athletes from chapter 4.2. Therefore, the developed sensor system was extended with additional sensors incorporated in the metacarpal and interphalangeal joint area of the boxing glove, in order to detect the closure of the fist while punching. For this purpose, the measurement system included a special calibration routine, which was performed at the beginning of the study for all participants individually. With the help of this calibration routine, the system enables an exact detection of whether the fist of the patient is clenched or unclenched in the course of the striking motion. Therefore, the test subjects had to close and open their fist in a particular sequence to conduct the calibration method.

The data acquisition was performed as described, by the developed and instrumented boxing monitoring system and in addition by application of the sensor extension for the monitoring of the fist closure. The boxing monitoring system including the sensor extension was installed for all test subjects in to a 340.2-gram (12 ounces) AIBA-certified boxing glove for competition from Adidas (Adidas AG, Herzogenaurach, Germany) for the data acquisition. A 40 kg heavy leather punching bag from Paffen Sport (Paffen Sport GmbH & Co. KG, Cologne, Germany) was mounted on a wall suspension and served as a striking target to perform the blows against a predefined stationary target.

The data acquisition of the experimental investigation on fist activity was performed with a data acquisition frequency of 1,000 Hz. The generated data was stored in a buffer for subsequent post-processing and comprehensive data analysis using MATLAB (The MathWorks, Natick, USA). The measurement frequency of 1,000 Hz was used to ensure that the entire biomechanical data during the course of the impact, including the throw, impact and retraction movement, is recorded in its entirety.

Like the previous studies presented for the analyses of boxing biomechanics, the applied experimental protocol composed of the four main striking techniques to be investigated in order to pre-define the striking variants that had to be performed by all participants consecutively. As described previously, the four selected punching techniques are the most frequently used punching techniques in the sport of boxing in competition and training. Subsequently, the two straight techniques of the jab and cross punch as well as the semicircular uppercut and hook punch techniques were performed. To execute the punching tests, the participating subjects were instructed to conduct the punches with full effort. This method is following the approach as executed in the study of the analyses of self-assessment of punching intensity in amateur boxing between experienced and non-experienced athletes. The punches were performed against the boxing bag. The study focused on the closure of the fist during the punching exercise and on the resulting kinetics and kinematics of the punches thrown. The punches were performed by all participants from a static defensive position with the punching bag as the target in front. At the beginning of each punching technique, the test persons were instructed to determine their own punching distance and to test the distance to avoid unnecessary variations during the experimental data collection. The subjects were instructed to conduct four sets of five punches each, to generate a total of 20 punches for each technique performed.

During the execution of the punching tests, the subjects were encouraged actively to execute the impacts at their highest intensity. After the stroke was executed, the test subjects were instructed to immediately return to their defensive position, as it would be performed in a sparring or competition fight in order to protect themselves and to determine differences in the defence position prior and after the punch was thrown. The subjects were instructed to remain in their defensive position for at least two seconds before the following punch was allowed to be executed.

d) Data analysis

Using specially designed MATLAB (2018b) routines, the biomechanical performance data collected and buffered during the experimental execution of the impact tests were processed for further data processing and data analysis. For the analysis of fist activity in amateur boxing while punching, a special calibration routine was used for the new integrated sensors in the boxing gloves. The calibration routine for the analysis and determination of the fist closure and reopening is based on a binary coding of the sensor-derived data. For this purpose, the fist closure is controlled with a measuring frequency of 1,000 Hz during the execution of the punching motion to detect the exact point of time when the fist is starting to be clenched during the execution of the stroke. The binary coding was defined with "0" to represent that the fist is open and with "1" that the fist is clenched. In addition to the fist closure, the biomechanical performance data of the participants were collected. For this purpose, the performance data of the impact technique of both groups, the experienced and non-experienced subjects, were adjusted according to their calibration results.

The maximum values achieved for the individual strikes were determined for the analysis of the biomechanical performance data of punch force, speed and acceleration and then used for further data analysis.

For each subject the data analysis of the defensive position was normalized individually. Consequently, the trajectory and orientation in the three-dimensional space of the stroke was determined from the defensive position established at the beginning of the first stroke conducted of the test cycle. The deviations of the defensive position for the following executed hits were analysed on this basis. The normalization was conducted for all tested striking techniques. Three-dimensional space rotations and displacements were analysed in terms of absolute angular rotations in degrees and trajectories in centimetres, based on the test subjects prior determined defensive posture.

The punching time was normalized based on the standardized measuring frequency of 1,000 Hz. This procedure enables the analysis of the striking pattern of the performed punching techniques with each other and between all participating test subjects. The absolute punching duration was divided into the three phases of the attack, contact and retraction time, back to the defensive position, in order to investigate the time of fist closure within the defined phases. The first phase of the boxing punch was determined from the initial movement of the fist in the direction of the striking target in the x-axis and ended by the first contact with the target. The contact phase was defined as the period of time when the glove is in contact with the striking object, starting from the moment when the glove first comes into contact with the target. The second phase of the punching execution was further divided into the exposure time and pre-release phase. The exposure phase is defined until the glove is maximally compressed at the targeting object, i.e. until the maximum impact force is reached. The second part of the pre-release phase is defined until the hand is released from the impact object. The third phase, the time of retraction, was measured starting at the end of the pre-release phase until the hand returns back to the defensive position and the associated reduced acceleration of the fist.

e) Statistical analysis

The statistical analysis of the experimental performance data for the analysis of fist activity in amateur boxing while punching is based on the preliminary presented data processing conducted. The statistical analysis is performed using the analysis software, IBM SPSS Statistics for Windows, Version 23.0 (IBM Corporation, New York, USA).

The descriptive data of the fist clinch and reopening in terms of punching technique analysis are presented as mean values and standard deviations.

At the beginning of the statistical analysis, the data was tested for outliers. Measurement data that is greater than one and a half times the standard deviation from the mean value are defined as light outliers. In addition, measurement results with more than three times the standard deviation from the mean value were defined as strong outliers. If outliers were identified within the experimental results, they are displayed by means of a box-whisker plot. In this case, light outliers are marked as a circle and strong outliers as an asterisk.

Due to the greater power of expression, the Shapiro-Wilk test was used in preference to the Kolmogorov-Smirnov test for the analysis of normal distribution. The homogeneity of variance was tested by means of the Levene test. A three-way ANOVA was used to evaluate group differences and individual differences between the two groups of subjects and the four punch techniques performed. Individual differences were assessed by means of a Tukey or Games-Howell post hoc test if the homogeneity of variances was not fulfilled. For all statistics, a 95% confidence interval was calculated with an alpha level set at $p < 0.05$ for the detection of significant differences in all statistical tests applied.

In a final step, the effect size was determined by using Pearson´s product-moment coefficient *r* based on Cohen's *d* (Cohen, 1988). An effect size of 0.1 represents a small effect, an effect size of 0.3 a medium effect and an effect size greater 0.5 a strong effect (equation 86). Due to the unequal sample size of experienced and non-experienced subjects, the effect size is calculated according to Aaron, Kromney and Ferron (Aaron et al., 1998) using the pooled standard deviation (equation 87).

4.4.3 Results

The statistical data analysis for the verification of the time of fist closure before impact as well as the timing of the re-opening of the fist after the impact occurred during the execution of the four tested punching techniques of the cross, jab, uppercut and hook punch shows statistically significant differences. These differences were analysed between the tested groups of experienced and non-experienced martial artists. In the following a detailed presentation of the statistical results for each of the four punch types is presented. The conducted three-way ANOVA showed statistically significant difference for the punching techniques performed $F(6.00, 176.0) = 4.0$, $p = 0.001$, partial $\eta2 = 0.120$, Wilk's $\Lambda = 0.774$; but not for the overall analysis between the two groups of experience level $F(2.00, 88.00) = 1.361$, $p = 0.262$, partial $\eta2 = 0.03$, Wilk's $\Lambda = 0.97$.

A detailed presentation of the results for the different stroke types of the two subject groups is presented in the subsequent sections.

Cross punch results

The box-whisker plots for the display of variation in samples of the subject data for the performed cross punch technique revealed no outlier (Figure 125). As assessed by the Shapiro-Wilk test, the experimental datasets for the conducted cross punch has shown normal distribution for both groups of participants ($p > .05$).

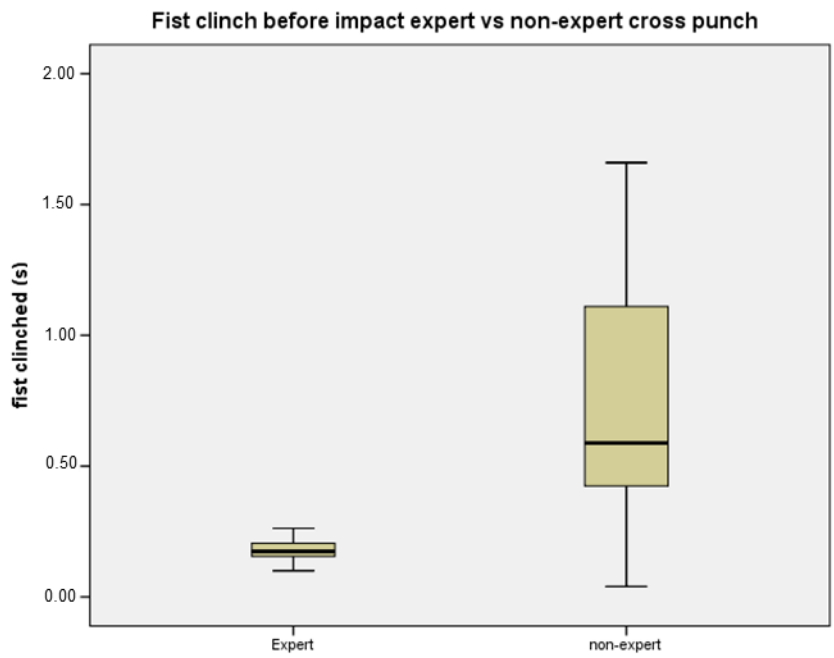


Figure 125: Fist clinch before impact expert vs non-expert cross punch

Figure 125 and the statistical data evaluation indicates that the fist closure of inexperienced boxing athletes is performed at a mean of 0.75 seconds (SD = 0.48 sec.) before the fist reaches the object being hit. The group of the tested experienced boxing athletes executed the fist closure 0.17 seconds (SD = 0.05 sec.) before the event of the impact. The fist closure was performed by the expert group 0.57 seconds (95% - CI [-0.81, -0.33]) later compared to the non-experienced group (0.75 seconds), before impact (Figure 126). This testing shows a statistically significant difference in the timing of the fist clinch between the experienced and non-experienced participants ($p < .001$). The effect size based on Pearson´s product-moment coefficient r demonstrates with a result of 0.6 a strong effect between the two tested groups (Table 26).

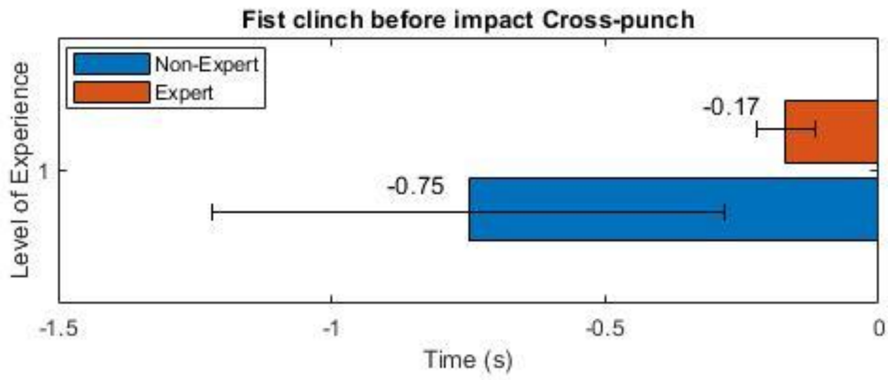


Figure 126: Fist clinch before impact: Comparison Expert vs. Non-Expert cross-punch

The examination of the fist opening after the impact of the cross-punch technique shows no outliers as it was observed in the data set for the fist closure for the group of experienced and unexperienced participants (Figure 127).

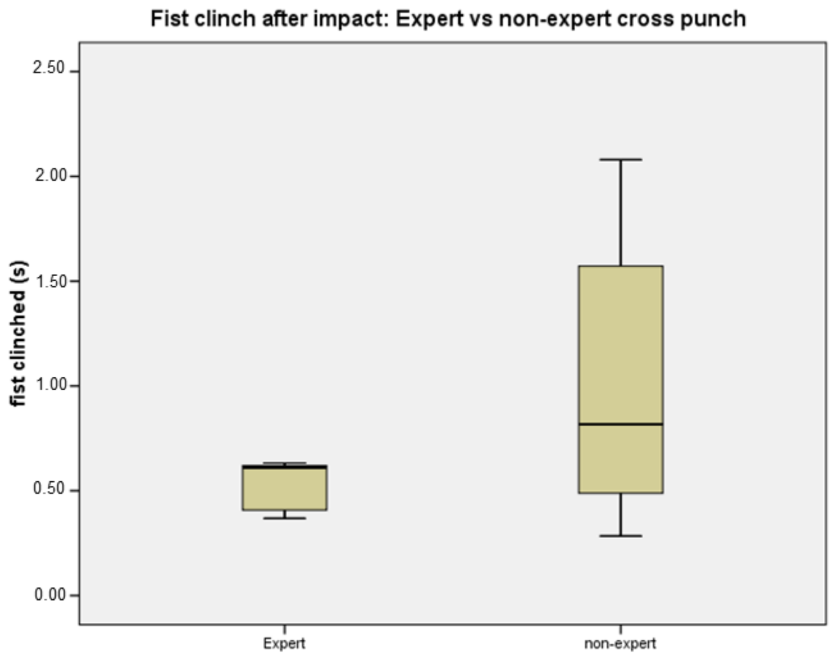


Figure 127: Fist clinch after impact expert vs non-expert cross punch

Normal distribution of the experimental data for the examined release of the clinched fist, after impact of the cross punch, was shown similar to the fist clinch before impact for both groups of experienced and non-experienced participants. This was assessed by the Shapiro-Wilk test (p > .05).

The statistical data evaluation shows that the fist opening of inexperienced boxing athletes is performed at a mean of 1.03 seconds (SD = 0.62 sec.) after the fist releases at the object to be hit. The group of the tested experienced boxing athletes performed the fist opening 0.54 seconds (SD = 0.12 sec.) after the impact occurred (Figure 127 and Figure 128). The expert group unclenched the fist 0.49 seconds (95% - CI [-0.81, -0.17]) earlier than the inexperienced group of test subjects after the impact event. The analysis has shown a statistically significant difference between the fist re-opening of the investigated experienced and non-experienced group with $p < .005$.

The effect size based on Pearson´s product-moment coefficient *r* shows with a result of 0.36 an intermediate effect between the two tested groups regarding the opening of the fist after the time of impact (Table 26).

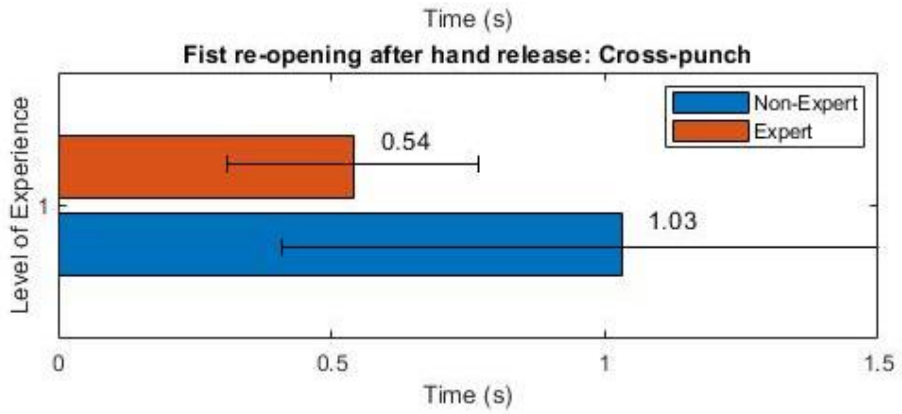


Figure 128: Fist re-opening after hand release: Comparison Expert vs. Non-Expert cross-punch

Table 26: Comparison of fist clinch experienced vs non-experienced subjects cross punch

	Experienced	**Non-experienced**	**p-value**	**ES (rating)**
Cross punch fist clinch before impact*	0.17 sec. ± 0.05 sec.	0.75 sec. ± 0.48 sec.	$p < .001$	0.6 (large)
Cross punch length of fist clinch after impact*	0.54 sec. ± 0.12 sec.	1.03 sec. ± 0.62 sec.	$p < .005$	0.36 (moderate)

* All values presented are means ± standard deviation; ES = Effect size;

Hook punch results

In the second blow, no outliers were analysed in the data sets of the fist clench during the forward movement, as well as for the fist opening after the impact during the retraction phase, of the hook punch technique for the analysis of the fist clench of experienced and non-experienced boxing athletes (Figure 129 and Figure 130).

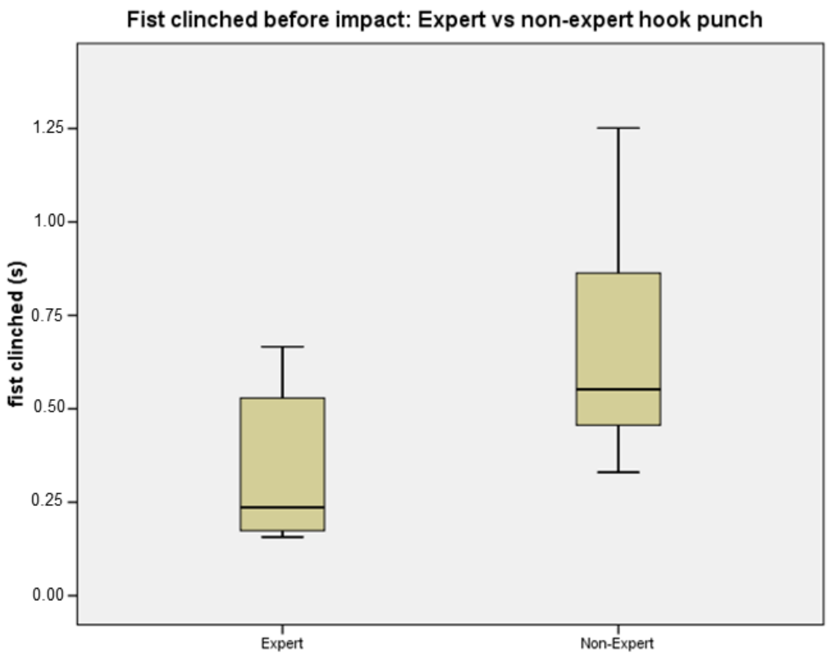


Figure 129: Fist clinch before impact expert vs non-expert hook punch

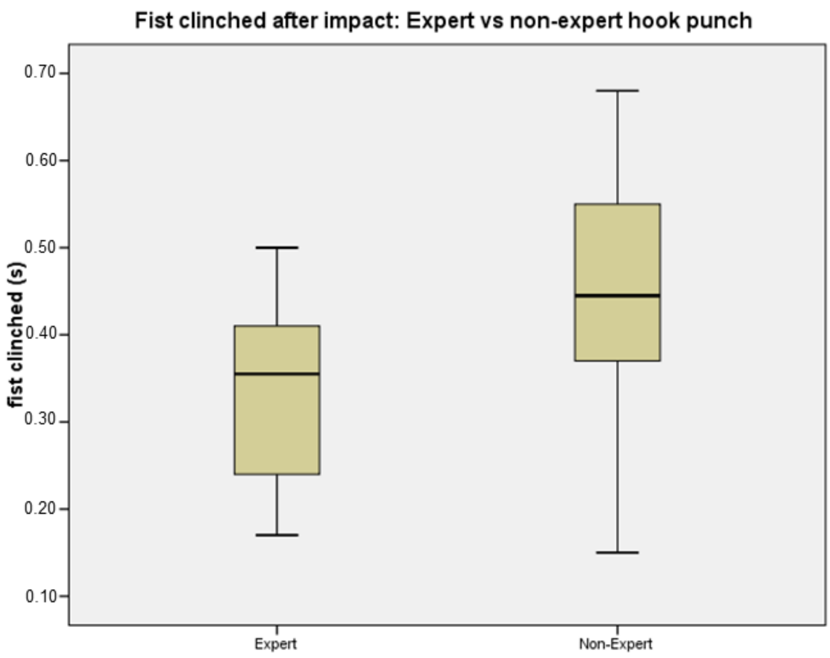


Figure 130: Fist clinch after impact expert vs non-expert hook punch

Figure 129 and Figure 130 display the mean time of the fist closure until the re-opening of the fist during the execution of the hook punch technique for both tested groups of participants. The experimental data of both groups of subjects, as well as of both phases of the hook punch (throw and retraction phase) were tested positive on normal distribution using the Shapiro-Wilk test (p > .05).

The analysis of the statistical data shows that the group of inexperienced subjects close their fist at an average of 0.65 seconds (SD = 0.28 sec.) before the fist hits the targeting object. The group of experienced boxers performed the fist closure 0.33 seconds (SD = 0.2 sec.) before the impact. Thus, the fist closure was performed 0.32 seconds (95% - CI [-0.54, -0.08]) earlier by the non-experienced group of subjects compared to the experienced subject group of the boxing athletes (Figure 131). This leads to a statistically significant difference between the fist clinch of the experienced and the non-experienced group of p = .011 and an effect size of 0.72, based on Pearson product-moment coefficient r. The results indicate a strong effect between the two tested groups.

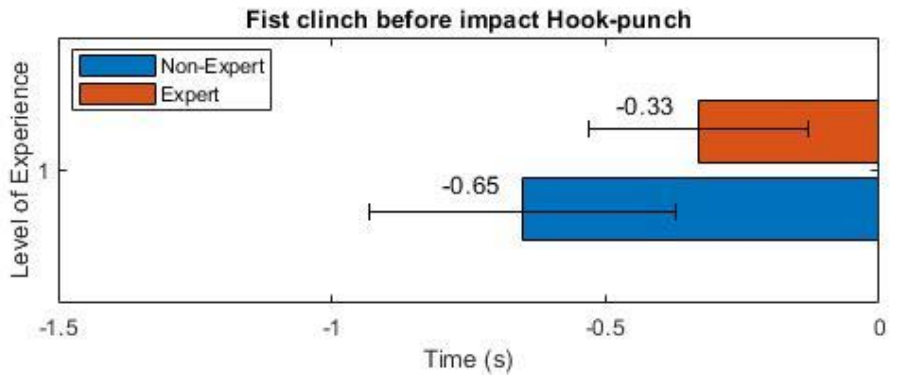


Figure 131: Fist clinch before impact: Comparison Expert vs. Non-Expert hook-punch

Examining the second activation phase of the fist, the re-opening of the fist during the hook punch, it is determined that non-experienced boxing athletes execute this movement on average 0.43 seconds (SD = 0.17 sec.) after the release of the fist on the object occurred. In comparison, experienced boxing athletes execute the fist opening 0.1 seconds earlier (95% - CI [-0.81, -0.17]], 0.33 seconds (SD = 0.11 sec.) after the release occurred (Figure 132). The minor delay of the second phase has shown no statistically significant difference between the fist clinch release after the impact between the experienced and the non-experienced group (p = 0.15). The effect size shows with a result of 0.2 merely a small effect between the two tested groups (Table 27).

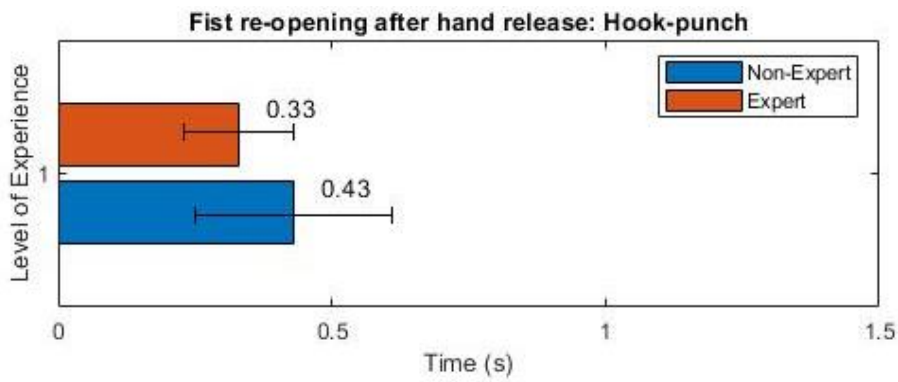


Figure 132: Fist re-opening after hand release: Comparison Expert vs. Non-Expert hook-punch

Table 27: Comparison of fist clinch experienced vs non-experienced subjects hook punch

	Experienced	Non-experienced	p-value	ES (rating)
Hook punch fist clinch before impact*	0.33 sec. ± 0.2 sec.	0.65 sec. ± 0.28 sec.	p = .011	0.72 (large)
Hook punch length of fist clinch after impact*	0.33 sec. ± 0.11 sec.	0.43 sec. ± 0.17 sec.	p = .15	0.2 (small)

* All values presented are means ± standard deviation; ES = Effect size;

Jab punch results

The analysis of the third striking technique, of the jab punch, shows no outliers for the analysis of the fist clinch before impact for both data sets of the experienced and non-experienced group of test participants (Figure 133). In contrast, the data set of the re-opening of the fist after the impact as presented in Figure 134. In this case an outlier was detected in the group of non-experts at 2.0 seconds after the hand release of the object.

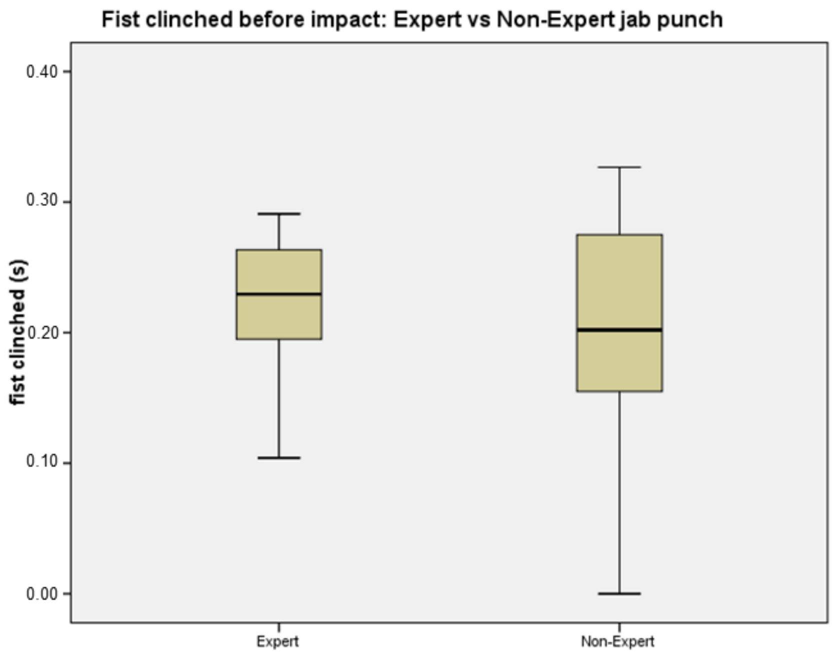


Figure 133: Fist clinch before impact expert vs non-expert jab punch

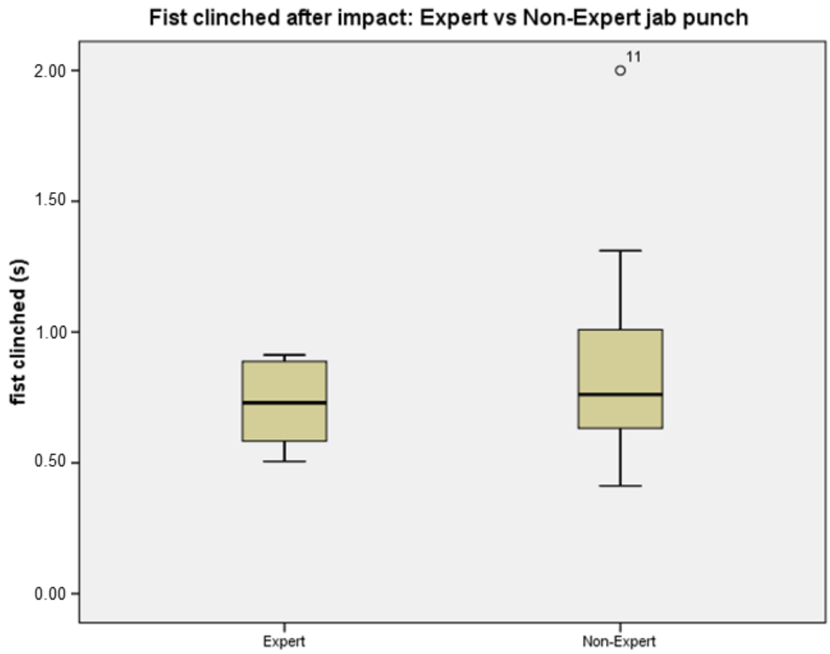


Figure 134: Fist clinch after impact expert vs non-expert jab punch

Figure 133 and Figure 134 presenting the mean time of the fist closure before impact until the re-opening phase of the fist during the execution of the hook punch execution of both tested groups.

With the help of a Shapiro-Wilk test, the experimental data of both groups of participants and both defined activation phases of the fist (throw and retraction phase) were tested positive on normal distribution (p > .05).

The statistical data analysis of the test shows that the average time at which the fist of the experienced group of test persons is closed, was 0.19 seconds (SD = 0.09 sec.) before the impact occurred. The point in time when the fist is closed for the non-experienced group of subjects was executed 0.02 seconds later, at 0.17 seconds before impact (SD = 0.12 sec.) (95% - C [-0.07, 0.12]) (Figure 135). No statistically significance was analysed for the difference between the fist clinch of the experienced and the non-experienced group (p = 0.6). The additionally performed Pearson's product-moment coefficient indicates a small effect size of 0.02.

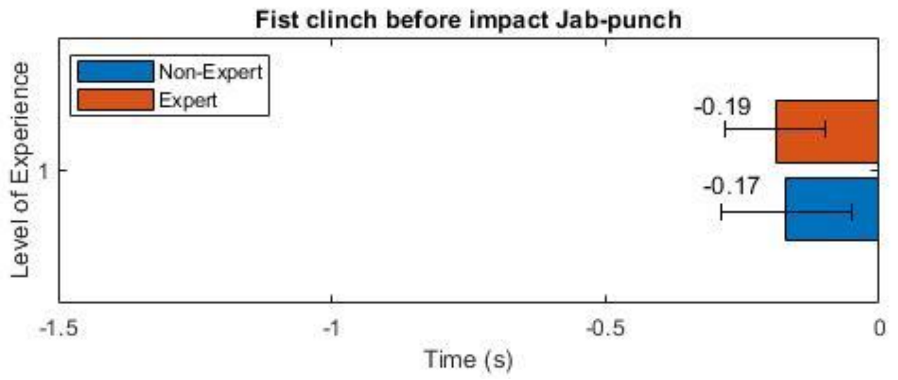


Figure 135: Fist clinch before impact: Comparison Expert vs. Non-Expert jab-punch

The analysis of the second activation phase of the fist during the retraction phase following the hand release reveals that experienced athletes start to open their fist earlier than the subjects in the group of non-experienced subjects. The group of experienced athletes open their fist at a mean of 0.69 seconds (SD = 0.97 sec.) after the hand release. On the other hand, the group of inexperienced athletes open their fist 0.84 seconds (SD = 0.4) after the hand release. This represents an average difference of 0.15 seconds (95% - CI [-0.46, 0.15]) (Figure 136). The mean difference of 0.15 seconds does not represent a significant difference between the group of experienced and non-experienced subjects (p = 0.33). The effect size of 0.1 describes only a small effect between both groups.

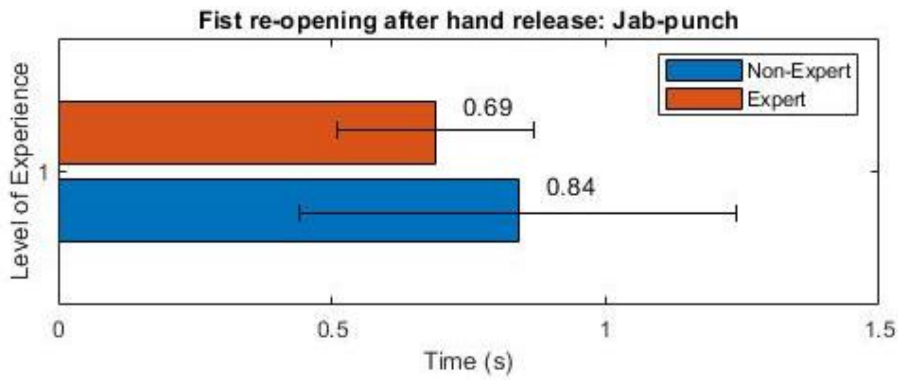


Figure 136: Fist re-opening after hand release: Comparison Expert vs. Non-Expert jab-punch

Table 28: Comparison of fist clinch experienced vs non-experienced subjects jab punch

	Experienced	Non-experienced	p-value	ES (rating)
Jab punch fist clinch before impact*	0.19 sec. ± 0.09 sec.	0.17 sec. ± 0.12 sec.	$p = 0.6$	0.02 (small)
Jab punch length of fist clinch after impact*	0.69 sec. ± 0.97 sec.	0.84 sec. ± 0.4 sec.	$p = 0.33$	0.1 (small)

* All values presented are means ± standard deviation; ES = Effect size;

Uppercut punch results

The fourth and final punching technique tested was the hook strike. No outliers were detected during the statistical analysis of the data sets of experienced and non-experienced subjects for both activation phases, the closing of the fist before impact and the re-opening of the fist after the hand release (Figure 137 and Figure 138).

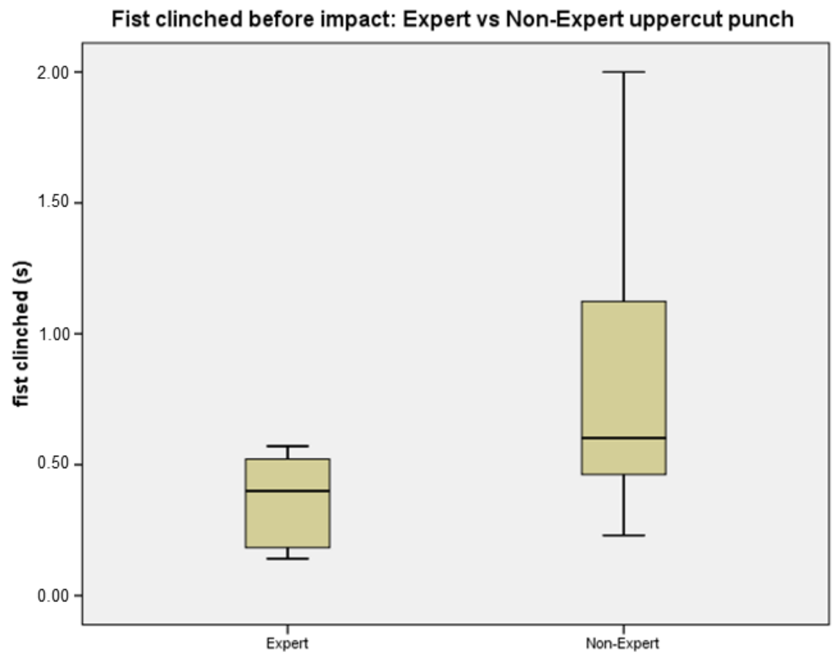


Figure 137: Fist clinched before impact expert vs non-expert uppercut punch

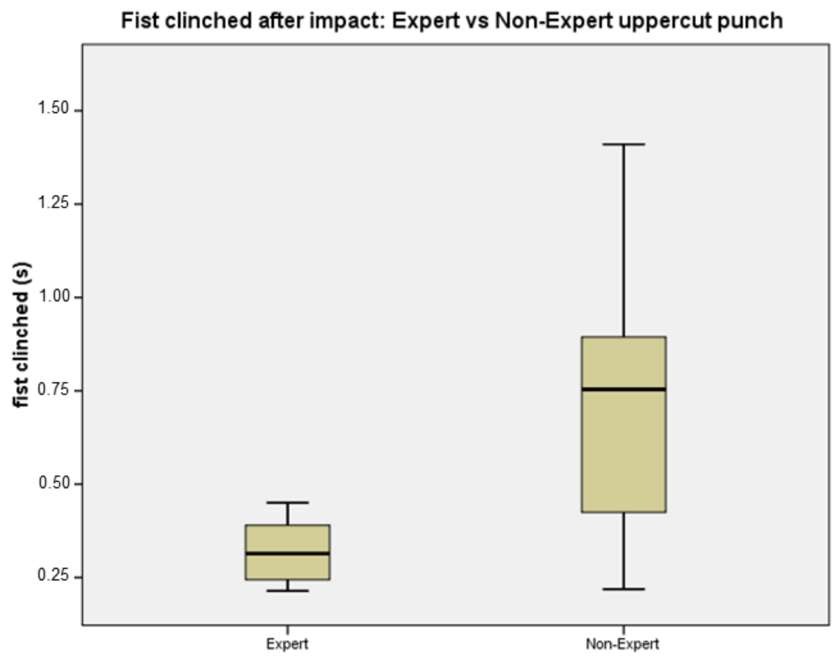


Figure 138: Fist clinched after impact expert vs non-expert uppercut punch

The experimental data of both groups of subjects were tested positive on normal distribution using the Shapiro-Wilk test for the fist clinch and the re-opening phase of the fist (p > .05). Figure 137 and Figure 138 presenting the mean time of the fist closure before impact and the re-opening phase of the fist during the execution of the uppercut punch of both tested groups.

The statistical evaluation of the average fist closure shows that the fist of the experienced group of test subjects was executed with a mean at 0.35 seconds (SD = 0.17 sec.) before the impact occurred. With a delayed mean difference of 0.5 seconds the data shows that the group of non-experienced boxers executed the clenching of the fist at 0.85 seconds (SD = 0.57 sec.) before the impact occurred (95% - C [-0.83, 0.17]) (Figure 139). The statistical analysis of this data shows that the deviation of the two experience groups shows a statistically significant difference (p = 0.005). The additionally performed Pearson's product-moment coefficient shows a strong effect size for the difference between both groups of 0.6.

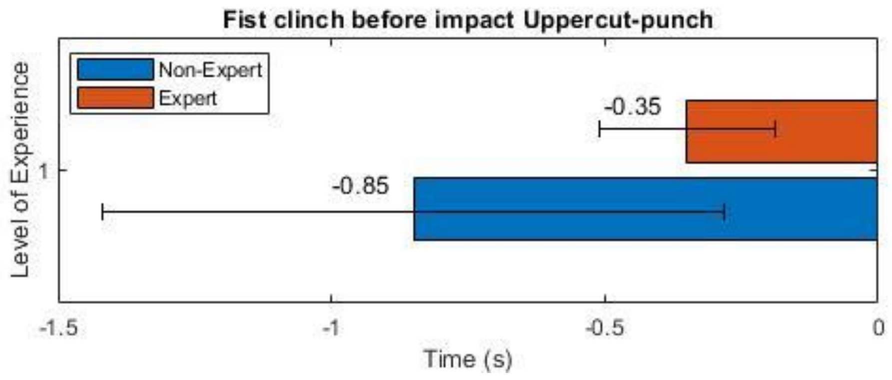


Figure 139: Fist clinch before impact: Comparison Expert vs. Non-Expert uppercut-punch

The analysis of the second activation phase for the renewed opening of the fist during the retraction period presents a greater significance. With a mean difference of 0.41 seconds (95% - CI [-0.63, -0.19]), the opening of the fist is performed with a mean of 0.32 seconds (SD = 0.08 sec.) after the time of the hand release in the group of the experienced subjects. On the other hand, for the inexperienced group of athletes, the re-opening of the fist is carried out at a mean point in time of 0.73 seconds (SD = 0.39 sec.) after the impact (Figure 140). The mean difference of 0.41 seconds represents a statistically significant difference between the group of experienced and non-experienced subjects (p = 0.001). The difference between the two tested groups shows an effect size of 0.91 and thus describes a strong effect between both groups of athletes (Table 29).

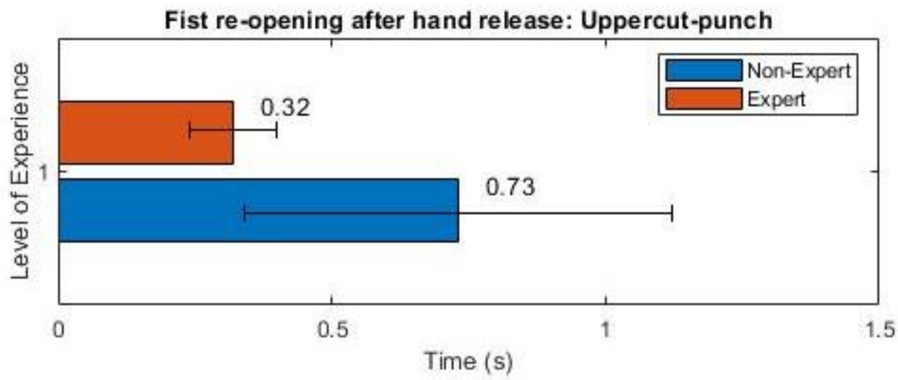


Figure 140: Fist re-opening after hand release: Comparison Expert vs. Non-Expert uppercut-punch

Table 29: Comparison of fist clinch experienced vs non-experienced subjects uppercut punch

	Experienced	Non-experienced	p-value	ES (rating)
Uppercut punch fist clinch before impact*	0.35 sec. ± 0.17 sec.	0.85 sec. ± 0.57 sec.	p = .005	0.6 (large)
Uppercut punch length of fist clinch after impact*	0.32 sec. ± 0.08 sec.	0.73 sec. ± 0.39 sec.	p = .001	0.91 (large)

* All values presented are means ± standard deviation; ES = Effect size;

4.4.4 Discussion

To the authors knowledge, the fist activity in terms of the point in time of the fist clinch before impact and the point of time of the re-opening of the fist after the impact occurred during a boxing punch, has not been investigated in the field of sport biomechanics or boxing and martial arts research. The highlighted research gap as described in chapter 2.3 shows that the second most common region where injuries appear is the area of the hand, especially of the phalanges, metacarpals and carpal bone. Existing research indicate that a cause of hand injuries can be traced back to incorrect or insufficiently executed fist closure at the point of impact (Luchetti et al., 2018; Morgan & Carrier, 2013). Moreover, numerous studies have investigated and documented the severity of punch forces and hand speed that appear in punches thrown in the sport of boxing and martial arts, as outlined in detail in chapter 2.1.1, inter alia on the basis of studies by Loturco et al., (2016), Pierce et al., (2006), Piorkowski et al, (2011) and Smith (2006). Despite the fact that a large number of studies have investigated the kinematic effects occurring at the athlete's hand, no studies on the moment of fist-activation were found by the conducted literature research for the presented experimental study.

The purpose of this research was to develop a novel method for measuring the fist activity separated in two parts, the fist closure and re-opening of the fist while punching. The method developed was successfully tested and is based on the developed boxing monitoring system. Hence, the presented experimental study in this chapter is the first study to the authors knowledge analysing fist activity during boxing, the aim of the study is to investigate the point of time of the fist clinch and re-opening during the period of a boxing punch. The detection of fist activity is offering new information about technical performance of boxing athletes as “motor skills characteristics are the main variable to represent boxing technical performance analysis” (Ashker, 2011, p. 357). Furthermore, the study compares the point in time of the fist activity between experienced and non-experienced athletes. To investigate the fist activity during the throw and retraction phase of the four main punching techniques of the jab, cross, uppercut and hook punch (Thomson & Lamb, 2016), the study investigated and statistically analysed twenty-two subjects, divided into ten experienced and twelve non-experienced boxers.

The developed boxing monitoring used for data generation was tested and validated in advance to ensure accurate detection of the opening and clenching of the subject’s fist.

The statistical results of the ANOVA analysis demonstrated significant performance differences for the four punching techniques tested regarding the fist clinch and re-opening after impact. The results presented about the cross-punch technique for inexperienced athletes show that the fist clinch starts before the point of time the punch movement is initiated by the hand. In addition to the first finding, the results point out that the fist is kept clinched for the entire time of the retraction phase until the hand returns to the defensive position. The experts perform the fist closure 0.17 seconds with a small standard deviation of 0.05 seconds before the fist arrives at the target. As Table 26 is representing, the fist closure takes place 0.57 seconds later than in the non-experienced group of tested subjects. This significant difference of the fist clinch shows that the inexperienced subject group clench their fist four times earlier than the group of experienced athletes. An equally significant difference was observed for the moment when the fist is re-opened. Although the difference was not as significant as in the first fist-activation phase, the inexperienced athletes (1.03 sec. ± 0.62 sec.) hold their fist in a clenched position twice as long after the hand is released from the targeting object, compared to the group of experienced athletes (0.54 sec. ± 0.12 sec.).

When the fist is re-opened during the retraction phase, a larger standard deviation of the tested experienced group of participants is shown in comparison to the fist closure. The same behaviour is observed with the inexperienced test participants with an increased standard deviation from ± 0.48 to ± 0.62 seconds. The experimental results of the study on the cross-punch technique shows that experienced athletes, in the field of martial arts, remain their fist in a relaxed position as long as possible before impact. This technique is used in order not to tense the muscles excessively, to perform the punch in a relaxed state as well as to prevent an energy los caused by an early fist clinch. Thus, the results agree with the recommendation presented in the literature (Blum, 1977; Smith et al., 2000; Werner, 2003; Werner & Lachica, 2000) and the findings of the expert survey that was conducted in advance of the experiment.

The cross is the more advanced of the two straight punch techniques. This is due to the extended strike distance, as an upper body rotation is necessary for the successful execution of the stroke compared to the jab punch. In addition, the jab punch is the most frequently performed stroke in training and sparring or competition. This is due to the primary purpose of the punch. The jab is performed to keep the opponent at a distance, whereas the cross is intended as a solely offensive punch and is therefore used less frequently in boxing than the jab punch.

The data analysis has demonstrated that the cross punch is the only punch of the four tested strokes that does not show a significant difference between the two groups of experienced and non-experienced athletes for the moment of fist clench during the throw ($p = 0.6$) and the retraction period ($p = 0.33$). However, the group of experienced athletes showed a significant similarity in the timing of the jab fist clinch with a difference of +0.02 seconds, and a delay of 0.15 seconds for the fist re-opening phase after the impact occurred between the two straight punches of the jab and cross technique. Interestingly, the group of non-experienced athletes showed an identical fist clenching point in time before impact (0.17 sec. +/- 0.12) with a similar standard deviation for the jab punch compared to the experienced group of subjects (0.19 +/- 0.09).

The results indicate that due to the more frequent use of the jab punch during training and exercise competitions, the group of non-experienced subjects have gained sufficient experience for the technical execution of the jab punch following a professional boxing training period of three months. Thus, the group do not show a significant difference to the expert group with a mean experience of 5.72 years. In contrast, the data analysed for the expert group indicates, that the time of fist clench and fist re-opening in both straight punching techniques of the jab and cross is executed at the same time of 0.18 seconds before impact and 0.61 seconds after the hand release.

The hook punch, is like the cross and uppercut, an advanced punching technique that is performed less frequently than the jab punch (Ashker, 2011). As outlined in the discussion part of the results of the cross punch, the less frequent use of the hook punch is due to the increased time required to execute the punch, as the punch bridges a larger distance than, among others, the jab punch as the leading hand (Piorkowski et al., 2011). Both semi-circular punches tested are usually thrown to cause injuries than to keep the opponent away from themselves or to interrupt the execution of an opponent blow.

The hook punch was therefore the first semi-circular punching technique tested. The results of the fist closure before impact show a significant difference between the experienced group (0.33 sec. ± 0.2 sec.) and the non-experienced group of subjects tested (0.65 sec. ± 0.28 sec.) with a *p* value of 0.01. The calculated significance level of 0.72 represents the second highest effect size analysed in the entire experiment for the analysis of fist activity in amateur boxing while punching.

In contrast to the fist closure, the re-opening of the fist after the hand release does not show a significant difference between the two groups. Although, as shown in Figure 130, the data indicate a trend difference between experienced (0.33 sec. ± 0.11 sec.) and non-experienced athletes (0.43 sec. ± 0.17 sec.). In this context, it has to be emphasized that the re-opening of the fist after the hand release, represents the fastest point in time regarding the re-opening phase of the fist with the least standard deviation compared to the three other tested striking techniques. The re-opening of the fist took place on average at less than half of the time of all tested punching techniques executed by the non-experienced group of subjects.

The second semi-circular punch tested was the uppercut punching technique. The uppercut is similar to the hook punch less frequency thrown than the jab punch (Ashker, 2011; Davis et al., 2013, 2015). Unlike the hook, the uppercut is often performed at close distances to the opponent in order to break through the opponent's defence below the chin and thus to achieve an effective punch and causing injuries to the opponent (Hristovski et al., 2006; Thomson & Lamb, 2016). This punching technique is usually introduced later on in a training with beginners than for example the jab or cross punching technique. Therefore, significant differences between the two groups of experience level were expected as the presented results indicate. Both activation phases of the fist clench and the re-opening of the fist show significant differences between the two tested groups. The phase of the fist clench is performed half a second later by the calculated mean data in the experienced subject group (0.35 sec. ± 0.17 sec.) before impact, compared to the fist closure of the non-experienced subjects (0.85 sec. ± 0.57 sec.), resulting in an effect size of 0.6.

The strongest calculated effect size of 0.91 within this experiment is shown by a significant difference between the experienced (0.32 sec. ± 0.08 sec.) and the non-experienced group (0.73 sec. ± 0.39 sec.) for the re-opening of the fist after the hand is released from the targeting object during the uppercut punch. The data of the expert group also shows that the fist closure for both semi-circular strikes, as represented by the hook and the uppercut, is performed at a significant time of about 0.34 seconds before impact.

In comparison, the two strokes show a deviation of only 0.02 seconds from each other. An even stronger agreement can be seen when comparing the re-opening of the fist after the impact for both types of punches. The comparison shows a marginal difference of 0.01 seconds between the opening of the fist for the hook (0.33 sec. ± 0.11 sec.) and the re-opening of the fist for the executed uppercut punch (0.32 sec. ± 0.08 sec.). This inter-technical variance represents the greatest agreement between the fist-activation times of two different punching techniques tested in this experimental study.

The results of the two straight and the two semi-circular punches show that the clenching and re-opening of the fist is carried out at an identical time by the group of experienced athletes for both of the straight or semi-circular punching techniques. Furthermore, the fist activation outlines that the tested punch types are highly significant and highly internalized reproducible within the group of experienced subjects. Additionally, the data of the straight punching techniques show a later fist clinch of 0.16 seconds closer to the point of impact than the techniques of the semi-circular punches. A controversial aspect in this context is the renewed opening of the fist. The expert group shows a correspondingly inverse behaviour regarding the renewed opening of the fist after the hand is released from the targeting object. The re-opening of the hand takes place 0.2 seconds earlier in the semi-circular punching techniques than in the category of the straight punches.

The research results of this experimental study demonstrated a confirmation of the H1 hypothesis. There is a significant difference between experienced and non-experienced boxers in terms of the point in time when the boxing athletes' clench and re-open their fist during a boxing punch. These results confirm the expert-novice paradigm that experienced boxers show a better technique and a higher reproducibility in technique execution than non-experts as found in previous studies (Cesari & Bertucco, 2008; Lenetsky et al., 2018). The hypotheses developed by the expert survey, stating that non-experts tend to tighten their fists permanently during an exercise or to strike with an open fist, could not be confirmed by the experiment conducted and the data presented. Although some subjects showed a tendency to fist flexion before the punch was executed, no significant permanent fist flexion was observed throughout the punch sequence. The second assumption could also not be confirmed, stating that non-experts perform a high number of punches with a non-clenched fist. This punching behaviour was observed in only two test persons and in this case in only three punches in total. Consequently, no significant behaviour pattern could be concluded. Another critical point to note is the test scenario. Unfortunately, no statement could be made in the study about how tight the fist was clenched. These results would bring further information in the area of punch force and impulse transmission as well as the development of injuries. Further development work is therefore being carried out in order to be able to measure the force of the fist clench with a high degree of validity.

All punches were executed in the course of a normal boxing training session by use of a punching bag as outlined in chapter 4.4.2, as it is performed in daily training sessions. However, at no time data was recorded during a sparring session. This type of scenario can lead to a situation where the clenching of the fist before and the re-opening of the fist after an impact is performed at different times than during boxing bag training. A sparring match, would allow information close to competition, as punches have to be taken out of a fight situation and in this case, there is less preparation time for the punch. In addition, the athlete has to return to an immediate defensive position to protect himself from counter-attacks. Therefore, the situation of a sparring match can lead to an increased tension, especially for boxers with a low level of experience, that can result in a significantly increased number of punches being executed with a permanently clenched fist. In order to investigate this, further studies are in preparation, that will allow direct measurement and analysis of sparring and competition data in order to gain further insights into this topic. As stated in the objective of this study, a further aspect of this experiment was the presentation of the measurement possibilities and the extension of the range of verification, that the use of modern measurement systems like the developed boxing monitoring system are able to provide.

Furthermore, the use of surface EMG can be considered for a subsequent investigation (Lenetsky et al., 2019). With the help of a surface EMG measuring method, further profound knowledge of muscle activation for fist closure and opening within the kinematic chain can be generated.

4.4.5 Conclusion

The current study contributes new information by the developed unique boxing monitoring system in terms of fist activity during boxing punches. Collectively, these results show indeed that experienced boxer perform the fist closure later before impact and re-open their fist earlier after the fist is released from the targeting object than non-experts.

The conducted study illustrates the significant different execution of fist closure and opening of the punches tested between experienced and inexperienced athletes. These findings can be used, with the help of further studies, to ensure that a system developed as it is presented, can be used to apply technique analysis for talent identification and promotion. The results of the study demonstrate that the development and use of advanced instrumentalized training equipment in sport has the potential to increase in-depth knowledge of sport-related movement research and that by this, new fields of investigation can be opened up as it is the case with the representation of fist closure and opening in the event of a blow. The knowledge gained from the experimental data can offer coaches and athletes themselves a tool for analysing the boxers fist clench during a boxing punch, support referees in evaluating the punches thrown and also to provide important data in the case of an injury in the hand area during a boxing punch.

4.5 Validation of a Novel Boxing Monitoring System to Detect and Analyse the Centre of Pressure Movement on the Boxer’s Fist

The specific analysis of the centre of pressure distribution during a boxing punch is presented in chapter 4.5. The research is conducted in particular to demonstrate the further potential and possibilities that the novel development, presented by this thesis, in sports sensor technologies can provide for performance diagnostics. Therefore, to the authors knowledge, this research is presenting the first findings, in analysing and presenting the pressure distribution on the boxer’s fist while punching by use of an instrumented boxing glove.

The chapter presents the results of the experimental study carried out and the methodology used to analyse the centre of pressure in different boxing punching techniques. For this purpose, the four main striking techniques of the jab, cross, uppercut and hook punch were tested.

The chapter is structured by starting to present the objective of the research and in this regard, in particular, the existing research deficit, for that scientifically validated data needs to be generated. Based on this, a detailed description of the research methodology used is presented and the experimental results obtained are outlined. Chapter 4.5 for the presentation of a unique method to detect and analyse the centre of pressure movement of various punching techniques in boxing concludes with a discussion and conclusion of the experimental results and a research outlook based on the data obtained as the last experimental chapter presented in the thesis.

The study presented in this chapter is published in the sensors journal 2021 (Menzel and Potthast, 2021c, 21, 8394).

4.5.1 Objective

The analysis of biomechanical punch data such as punch force, punch acceleration, fist speed and punch time are of great importance for the verification, assessment, and evaluation of punching technique and effectiveness and have therefore been investigated in numerous studies (Atha et al., 1985; Băiţel & Deliu, 2014; Joch et al., 1981; Lenetsky et al., 2018; Piorkowski et al., 2011; Smith, 2006; Smith et al., 2000; Walilko et al., 2005; Whiting et al., 1988).

The results of the previously presented scientific experiments have demonstrated the applicability of the developed sensor system in boxing and martial arts. In addition, the results gained have opened up new insights and research fields in the analysis of biomechanical performance parameters in boxing and were able to demonstrate these findings as presented in the study on the analysis of fist activity in amateur boxing while punching (Chapter 4.4) or the study on the analysis of self-assessment of punching intensity in amateur boxing between experienced and non-experienced athletes (Chapter 4.3). Furthermore, the analysed results were able to demonstrate a consensus with the existing literature in the collection of performance data using the developed sensor system. The punch forces measured with the help of the developed sensor system from chapter 4.2 about the analysis of punching technique in experienced versus non-experienced boxers were able to measure punching forces from 2154.6 N to 4177.47 N and fist velocities from 5.03 m/s to 7.88 m/s in experienced and non-experienced athletes. These study results as well as the results from the literature illustrate the high forces that occur in the hand and finger area during a boxing punch. As outlined in chapter 2.3 about the medical aspects of boxing, the scientific literature shows that the hand and finger area, in addition to the head region, have an increased potential for injury due to the high forces exerted during a punch (Bianco, 2005; Michael Loosemore et al., 2015, 2017; Noble, 1987; Prevel et al., 1995). The most risk-prone regions of the hand for injury are the radial carpals, metacarpals, and phalanges (Loosemore et al., 2017; Noble, 1987). Although it can be assumed, based on the intended point of impact at the second and third metacarpophalangeal joints, that the force generated and transmitted through these joints can lead to an overload of the biological structures and thus be mainly responsible for the injuries, as yet little is known about the cause of hand and finger injuries during a boxing punch.

Furthermore, the examination of the force distribution and centre of pressure (CoP) displacement on the contact surface of the fist can provide valuable information about the area of impact and the striking technique performed by the athlete.

The examination of the CoP displacement and distribution of forces on the surface of the fist during a boxing punch is therefore crucial to understand the effect of the punch on the biological structures of the hand as well as the technical biomechanical aspects of the punching action. In this regard an extensive literature research was carried out.

The examination of the force distribution and CoP displacement under the foot surface is a common method of the examination in biomechanical gait and running analysis (Grimshaw et al., 2006; Huang et al., 2011) and is also taken into account as a performance variable in the execution of athletic movements (Nagahara & Ohshima, 2019; Paillard et al., 2006). By contrast, the investigation of the force progression in martial arts, as represented by boxing, is a new field of investigation. An extensive literature review has revealed only one study which investigated the distribution of force on the boxer's fist during a punch. This study, by Loosemore, Lightfoot, Meswania and Beardsley (2015), investigated the distribution and magnitude of pressure and load between the knuckles using low standard Fuji Film Pressurex® films placed on the knuckles of the boxer's fist. is the first and thus only analysis which has investigated a variation of the impact force distribution across the second, third, fourth, and fifth metacarpophalangeal joints. Despite the utility of its findings, the method used has limited relevance to the analysis of CoP. The low standard Fuji Film Pressurex® method can only be used to investigate single punches, as the pressure film strips can only be used once and must be carefully removed and analysed afterwards. Furthermore, this method does not allow for the examination of the temporal CoP displacement but only the representation of the force distribution between the metacarpophalangeal joints.

This review shows the gap in the existing research on CoP distribution on the fist contact surface during a boxing punch. Consequently, this paper presents an analysis of the CoP distribution during boxing by use of a novel boxing monitoring system. In order to close this research gap, the developed sensor system was extended to be able to represent the point of force application and the CoP distribution on the boxer´s fist surface by means of the developed sensor system. Therefore, the CoP progression measured with the sensor system was validated in a first examination against a Kistler force plate, which is considered as the gold standard (Pires et al. (2016) and Roell et al. (2019)), before the viability of CoP analysis was assessed through real punch tests with the help of an experienced athlete. For this purpose, the four main punching techniques of the cross, jab, hook, and uppercut were performed. This possibility is another unique characteristic of the developed sensor system and shows another unprecedented capability to provide new biomechanical information to the sport boxing and sport performance analysis by the developed monitoring sensor system.

The information obtained through the experimental study has great importance in laying the foundations for further investigation of the technical execution of boxing punches, providing a method to improve the understanding of the etiology of boxing-related hand injuries.

4.5.2 Methodology

The following chapter is intended to present the methodology used to collect measurement data to investigate the centre of pressure displacement during a boxing stroke. For this purpose, the experimental setup as well as the data collection protocol is described in detail. In addition, the data analysis methodology including the applied statistics for the centre of pressure validation are presented.

a) Ethics statement

The fourth scientific study in the field of boxing biomechanics by use of the developed boxing monitoring system for the development of a novel method to detect and analyse the centre of pressure movement of various punching techniques in boxing was reviewed by the Ethics Committee of the German Sport University Cologne (Cologne, Germany). The application was reviewed with regard to its ethically correct design and execution. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by The Ethics Committee of the German Sport University (ethical proposal no. 074/2021).

b) Participants

The primary focus of this scientific experimental investigation was to determine the possibilities of measuring and analysing the CoP displacement during a boxing punch using the developed sensor system. The first part of the study focused on examining the validity of the sensor system against the gold standard of a force plate as the reference system. In the second step, a boxing athlete with more than 10 years of boxing experience was included to test the method in a practical environment, to generate the CoP course data on the boxer’s fist while punching. The subject was briefed in advance of the experiment on data collection and the experimental protocol. In order to avoid technical misinterpretation regarding the execution of the punches, the subject was informed in detail about the four punching techniques to be executed based on the technique model of the cross, jab, uppercut, and hook. These instructions were used to prevent the execution of incorrect punching techniques and to ensure the reproducibility of the punches to be tested. In order to follow the technique model of a realistic punch, the subject was instructed to perform the punching technique as if in a competition. This included the fast execution of the stroke as well as the immediate return to the defensive position. This was to avoid the execution of punches that go beyond the realistic punching technique in sparring or competition in order to analyse and detect the boxing specific CoP progression. After the execution of the blow, the subject was therefore instructed to immediately return to the defensive position. In addition, the test person was informed about the risks and benefits of the experiment. The measurements were conducted in the biomechanical laboratory of the German Sport University Cologne. Prior to the experimental testing, the subject undertook a boxing-specific warm up for muscle activation and to become familiar with the experimental setting and the equipment to be utilised for data acquisition.

c) Experimental setup and protocol

In the first part of the experimental study, a novel data collection method was validated as a means of detecting and analysing the CoP movement in various punching techniques in boxing. In this context, the focus was to validate the CoP movement of the developed sensor system across the x- and y-axis on the surface of the punching fist. The validation of the CoP movement was performed using a force plate, the gold standard in biomechanics (Roell et al., 2019) to validate the developed sensor system against a reference system.

In this validation, different boxing punches were applied with a specially-equipped boxing glove to the centre of a force plate. The developed sensor system was installed in a 12-ounce (340.2 gram) AIBA certified boxing glove (2017 model) from Adidas (Adidas AG, Herzogenaurach, Germany). The data acquisition using the Kistler force plates was performed at a measuring frequency of 10,000 Hz and a measuring frequency of 1,000 Hz for the developed sensor system, in both the validation as well as punching experiment. The sensor-derived data were stored in a buffer to allow a comprehensive post processing and analysis using MATLAB. The measurement data obtained from the Kistler force plate were recorded using Vicon Nexus software for motion capture in life sciences.

Due to the gap of the existing literature, no accepted and generally valid research method or protocol for the validation of the force distribution during a boxing punch yet exists, a limitation also emphasised by Loosemore et al. (2015). Consequently, a customised test report was developed to validate the CoP, determined by the sensor in comparison with the force plate. For the validation of the CoP movement on the fist surface, a total of 25 blows from 500 up to 1800 N were applied to the force plate. The average contact time of the boxing glove with the force plate was 25.5 ms. The experimental protocol consisted of five validation runs. For each validation run, five blows were applied to the force plate for the analysis of CoP movement validation against the force plate (Figure 141). The blows were applied in a frontal direction onto the centre of the force plate to ensure that the sensing area was activated and to validate the sensor-derived CoP movement against the force plate-derived CoP movement.

In the second part of the study, a total of 180 boxing strokes were performed with the help of an experienced athlete on a punching bag. During the experiment, the four main punching techniques of the jab, cross, uppercut, and rear hand hook were tested. The experiment protocol consisted of three test cycles with fifteen punch repetitions each. This protocol was carried out for each of the four striking techniques consecutively.

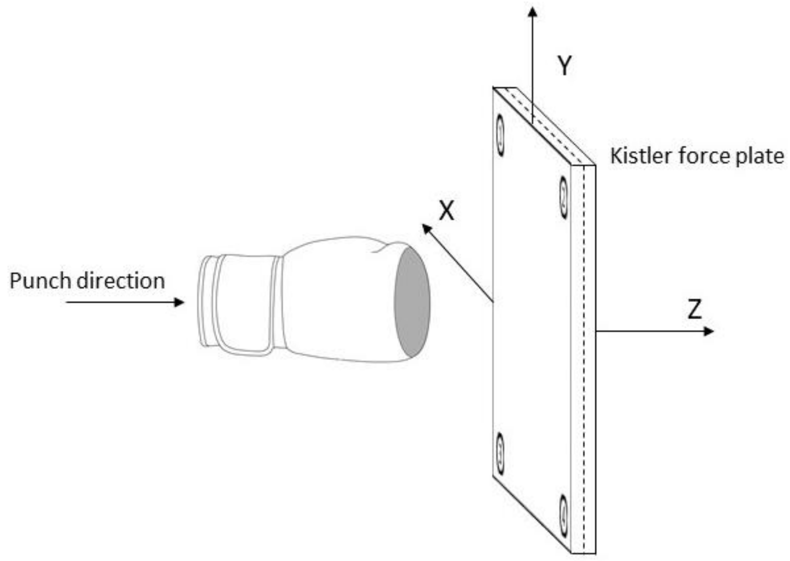


Figure 141: Test setup schematic.

d) Data analysis

For the comparison of the acquired CoP course data of the developed sensor system with the force plate, the measured sensor data had to be interpolated for validation purposes. Data interpolation was performed for a holistic analysis of the CoP course, due to the different data acquisition frequencies of the force plate (10,000 Hz) and the developed sensor system (1000 Hz). The collected biomechanical performance data, including the CoP course, were processed for further data analysis using custom-built MATLAB (2018b) (The MathWorks, Natick, MA, USA) routines. A weighted average filter was applied for data filtering to analyse the centre of pressure progression data.

In order to ensure uniform data analysis of the first part of the sensor validation test, the CoP data obtained from the force plate and the new sensor system were normalized in order to start the centre of pressures at 0x and 0y position within the coordinate system. This ensured that any deviation between the two CoP profiles was clearly evident for validation purposes. For the subsequent experimental investigation of the CoP progression of the four punching techniques, the data were not normalised in this fashion. The centre of pressure course is presented in the form of 3D bubble charts. This form of visual representation enables the course of the centre of pressure in the x- and y-direction to be displayed in the coordinate system with the effective force at the instant in time, expressed in terms of the size of the individual bubbles.

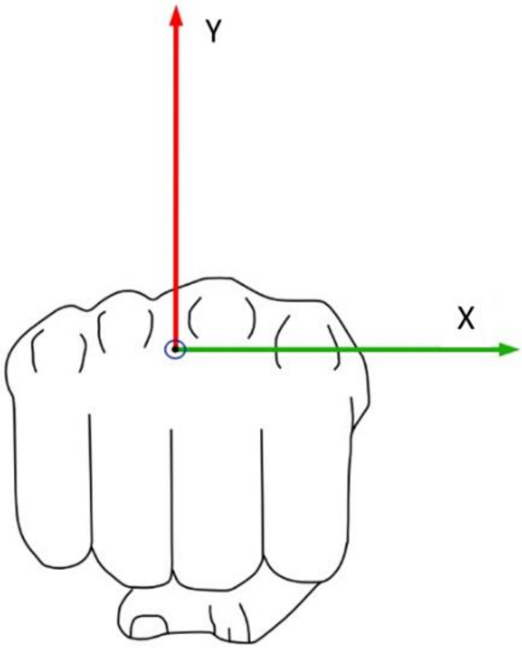


Figure 142: Frontal view of the right punching fist with highlighted metacarpal heads.

The graphical representation of the CoP progression is presented from a frontal view of the punching fist (the athlete's right hand), as illustrated by Figure 142. For the strokes performed, the representation and orientation of the coordinate system of the centre of pressure progression during the cross, hook, and uppercut is to be understood from the frontal view of the athlete's left hand (Figure 142), whereas the centre of pressure progression for the jab stroke technique is to be understood from the athlete's right hand.

e) Statistical Analysis

The first step in analysing the data sets was performed by comparing the mean values and standard deviation. This step served to analyse the data sets in terms of correlation analysis in order to evaluate the magnitude of concordance between the data sets. For the overall analysis, the mean and standard deviation of the test cycles were calculated and reported. A Bland–Altman analysis was applied for the graphical comparison of the displacement in the x- and y-direction as well as punch force for the force plate measurement method with the developed sensor system. Additionally, the root mean square error for the centre of pressure progression in the x- and y-direction was calculated for further comparison. The generated CoP courses of the force plate and sensor system were compared for the validation method using the Pearson correlation coefficient. The statistical data analysis was conducted using the IBM SPSS Statistics software for Windows, version 23.0 (IBM Corporation, New York, NY, USA).

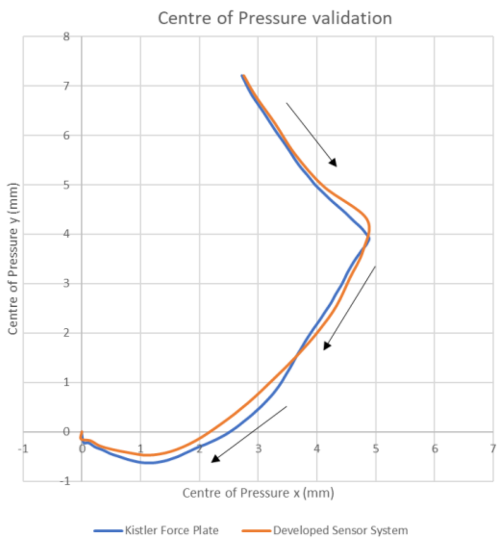
4.5.3 Results

The following chapter serves to present the validation results as well as the results of the study for the presentation of a novel method to illustrate the centre of pressure course and the force distribution on the fist surface during a boxing punch.

The accuracy of the developed boxing monitoring system for measuring the CoP course was analysed by comparing the new sensor system against the gold standard Kistler force plate. To present the validation results, two example impact tests are shown in Figure 143. These figures show the sensor-derived CoP distribution visually compared to the force plate-derived CoP distribution across the x- and y-axes. The visual comparison of both system results shows a high degree of agreement between the centre of pressure distribution in x and y direction. Additionally, Table 30 presents the Pearson correlation coefficient. The Pearson correlation coefficient ranged from 0.93 to 0.97 in the x-direction and from 0.97 to 0.99 in the y-direction. This corresponds to an average Pearson correlation coefficient of 0.96 (SD = 0.03) on the x-axis and an average Pearson correlation coefficient of 0.98 (SD = 0.01) on the y-axis. The quality of the applied calibration routines was also examined and evaluated by means of the Root Mean Square Error. The results presented in Table 30 demonstrate that an average root mean square error of 0.87 mm to 3.13 mm was determined in the CoP x-direction. A large deviation was found in the CoP along the y-axis with an average RMSE of 0.51 mm to 4.19 mm for the impact tests performed against the Kistler force plate. This corresponds to a RMSE percentage of 0.82–2.95% in the x-axis and 0.48–3.95% in the y-axis relative to the sensor area. The overall results of the validation study show an average RMSE of 1.62 mm (SD = 1.30 mm) in the x-direction and an average RMSE of 1.83 mm (SD = 2.05 mm) in the y-direction. The results of the Bland–Altman analysis were used to evaluate the bias between the mean differences of the developed sensor system compared to the gold standard of the force plate. The results show that 95% of the developed sensor system differences compared to the force plate lay within the statistical limits as presented in Figure 144 for the CoP in the x- and y-direction as well as the punch force.

Table 30: Pearson correlation coefficient and Root Mean Square Error (RMSE) for centre of pressure validation.

	Pearson Correlation Coefficient x	Pearson Correlation Coefficient y	RMSE x (mm)	RMSE y (mm)
Min	0.93	0.97	0.87	0.51
Max	0.97	0.99	3.13	4.19
Mean ± Std.	0.96 ± 0.03	0.98 ± 0.01	1.62 ± 1.30	1.83 ± 2.05



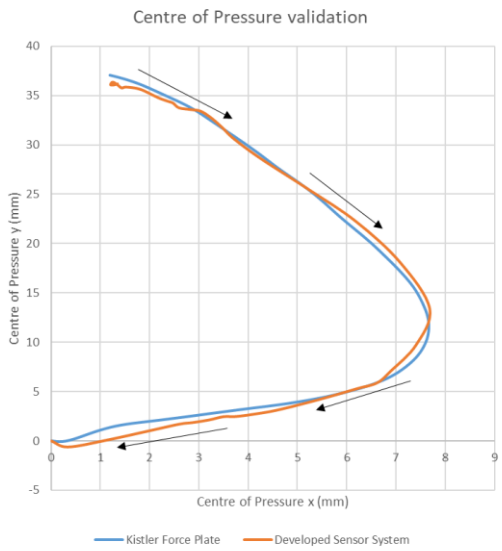


Figure 143: Centre of pressure validation force plate vs. developed sensor system example test runs.

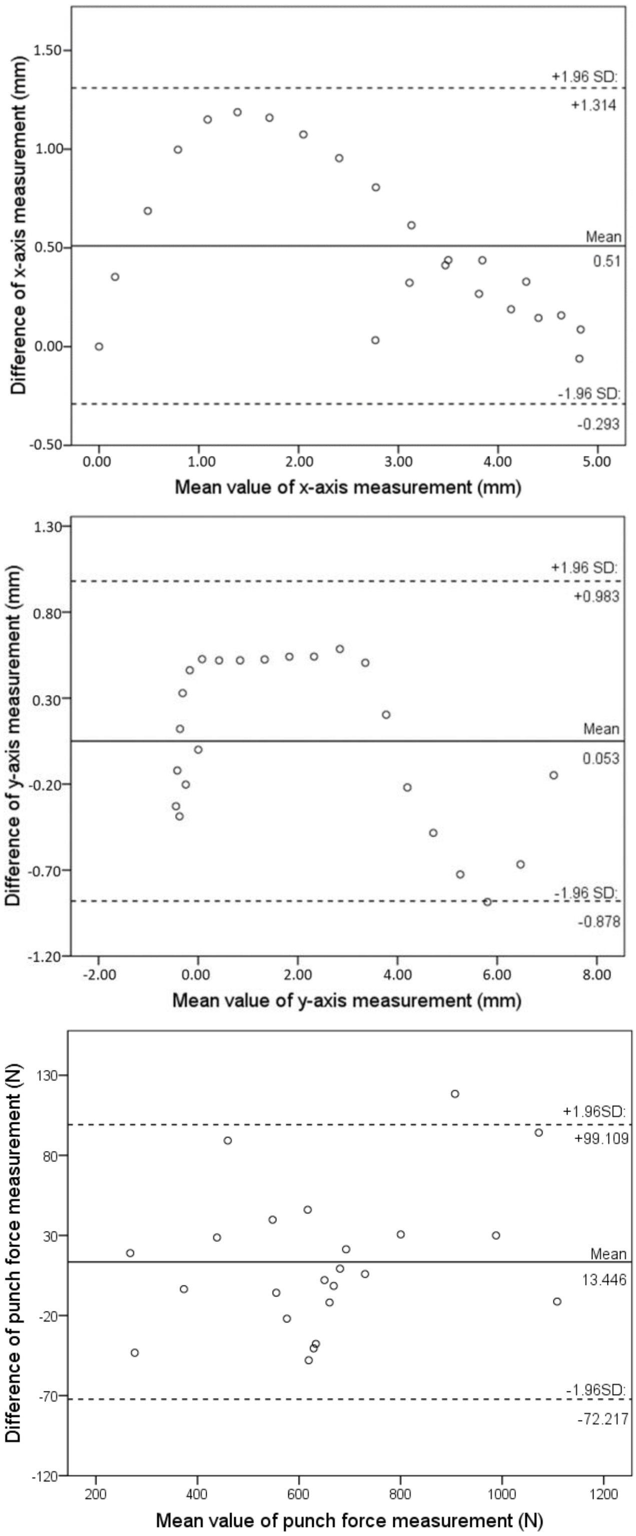


Figure 144: Bland–Altman analysis for force plate vs. developed sensor system example test run.

Based on the validation results, the study continued to investigate the CoP course on the surface of the boxer's fist during a boxing punch. The first punching technique tested was the straight cross. Figure 145 shows the average trajectory of the CoP on the surface of the fist when the fist hits the target with the effective force at the instant in time illustrated by the size of the individual bubbles. The trajectory shows the start of the CoP movement between the second and third metacarpophalangeal joints. From the second and third metacarpophalangeal joints, the centre of pressure is moving in a triangular pattern around -19.03 mm in the x-plane and 11.54 mm of the y-plane in a distal medial direction to the third proximal phalanges. At this point, the impact reaches the maximum impact force of 1753.4 N (SD = 485.92 N) on average for the subject tested. After reaching the maximum impact force the centre of pressure is moving 12.56 mm in the x-direction and 3.4 mm in the y-direction, proximal lateral to the second proximal phalanges. At this point, the fist separates from the target and is returned to the defensive position.

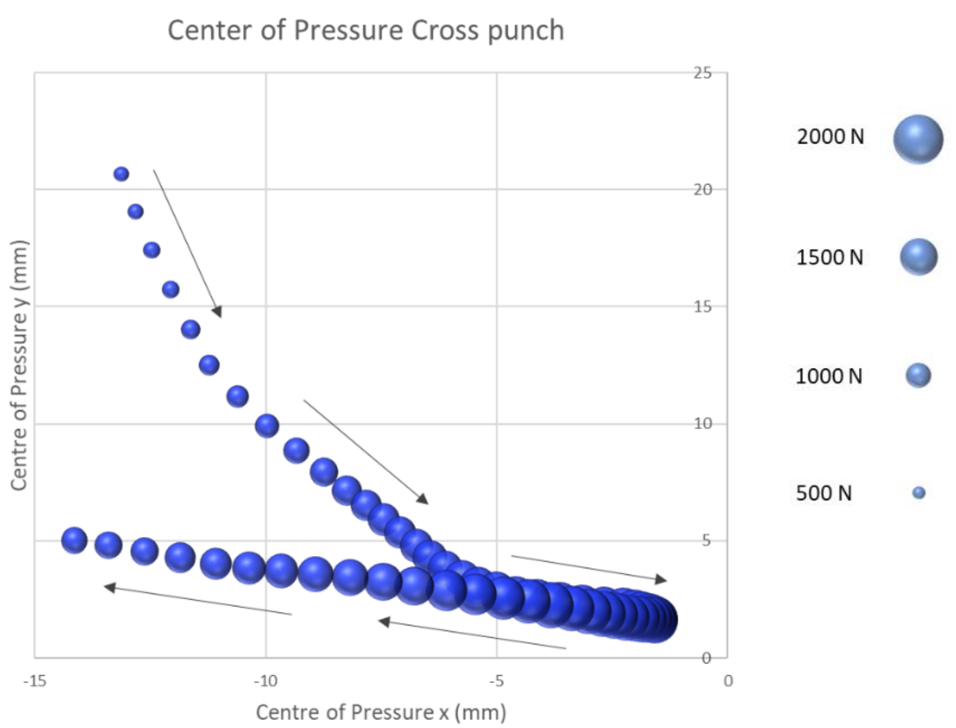


Figure 145: Centre of Pressure Cross punch.

The second straight boxing punch technique tested was the contralateral jab. Similar to the cross, the centre of pressure course for the jab technique starts between the second and third metacarpophalangeal joints (Figure 146). In a triangular course, the centre of pressure leads from the second and third metacarpophalangeal joint by -20.77 mm on the x-axis and -20.63 mm on the y-axis in the direction of the third proximal phalanges. With an average punch force of 973.85 (SD = 542.83 N), the stroke reaches its maximum strike force at the fists anatomical position on the striking hand. After the maximum impact force was obtained, the centre of pressure moves 20.76 mm in medial and 12.48 mm in the proximal orientation in the direction of the second proximal phalanges. From the second proximal phalanges, the fist separates from the object to be hit in order to resume to the defensive position and execute a new strike.

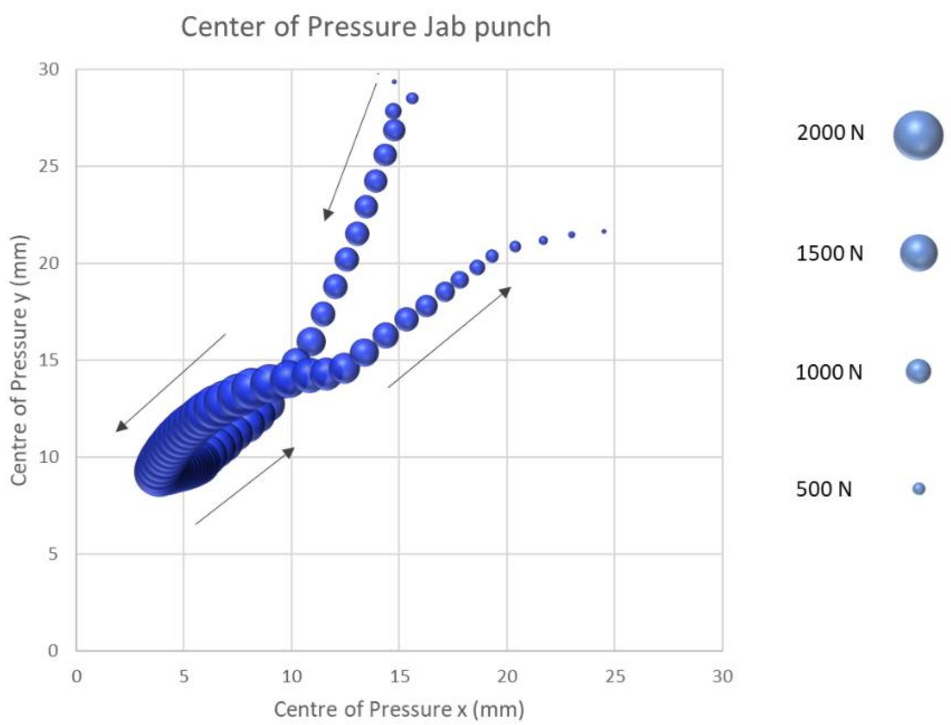


Figure 146: Centre of Pressure Jab punch.

After the successful execution of the two straight punching techniques, the study investigated the first semi-circular punching technique of the rear hand hook followed. The beginning of the rear hand hooks shows a start of the CoP course on the third metacarpophalangeal joint, as presented in Figure 147. From the third metacarpophalangeal joint, the CoP extends 15.04 mm on the x-axis and 9.74 mm on the y-axis in the direction of the fifth proximal phalanges. Without reaching the maximum impact force, the CoP leads in medial direction by -5.0 mm on the x-coordinate and -22.53 mm on the y-coordinate in the direction of the fourth proximal phalanges. At this point, the hook punch reaches the mean maximum impact force of 1407.39 N (SD = 168.27 N). Subsequently, the CoP progresses by an average of 2.63 mm in the medial and 4.08 mm in the distal direction. The fist detaches from the target after the CoP has progressed by 6.41 mm in the medial and 12.16 mm in the proximal direction at the fourth proximal phalanges (Figure 147).

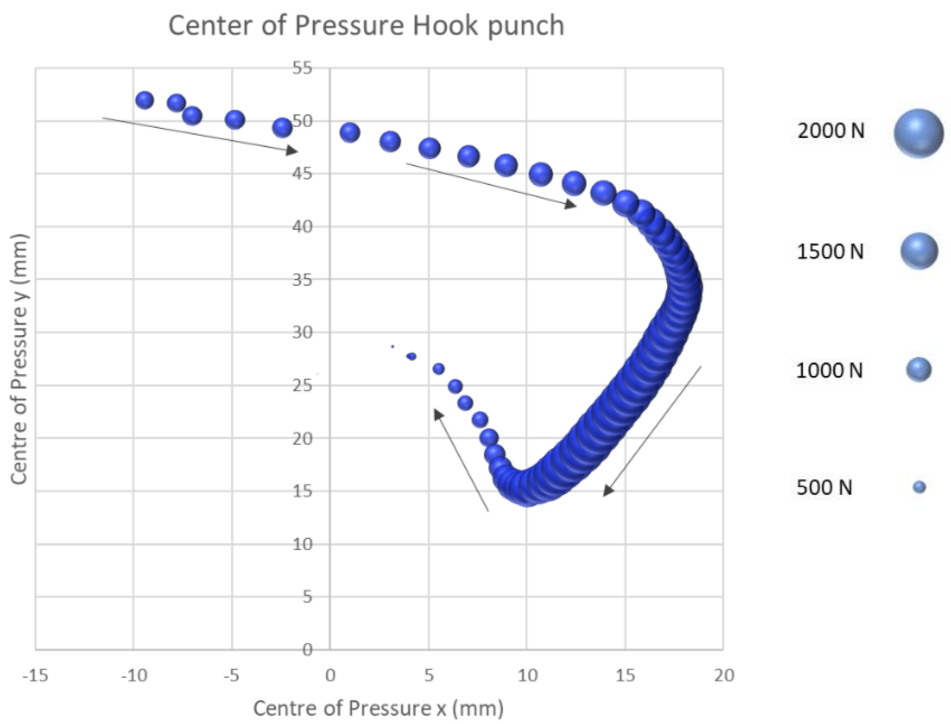


Figure 147: Centre of Pressure Hook punch.

The uppercut was the second semi-circular and thus the last tested punching technique. As shown in Figure 148, the centre of pressures starts at approximately the third proximal phalanges. In a distal lateral movement, the CoP is moving 47.6 mm in the x-direction and 30.64 mm on the y-axis, in the direction of the fifth proximal phalanges. At this anatomical position, the uppercut exhibits the subject's mean maximum impact force of 1397.38 N (SD = 276.88 N). After the maximum impact force is obtained, the CoP moves on average -13.2 mm in the medial and 8.82 mm in the proximal direction to the fourth proximal phalanges. The fist is released from the target at this point and is returned to the subject's defensive position.

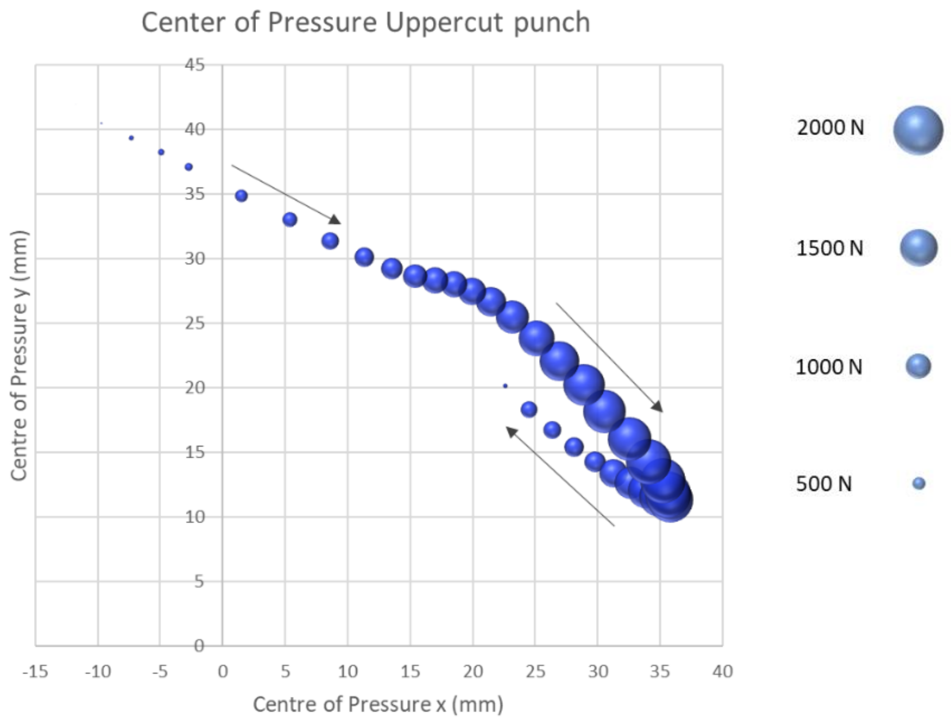


Figure 148: Centre of Pressure Uppercut punch.

4.5.4 Discussion

To the authors knowledge, this is the first study that has analysed the CoP course on the boxer's fist. Therefore, it is the first time that a differentiation was made with respect to the course of the CoP on a boxer's fist between the four main punching techniques of the jab, cross, rear hand hook, and uppercut.

The investigation carried out in the first part of the presented scientific study, validating the CoP progression using a newly developed sensor system, demonstrated good results when compared with a force plate. The statistical analysis of the presented CoP courses was performed using the Pearson correlation coefficient, the RMSE, and the Bland–Altman analysis. The results, shown in Table 30, demonstrate a high correlation between the measurements of the developed sensor system and the Kistler force plate as a low RMSE relative to the sensor area (>4.0 %). The calculated Pearson correlation coefficient ranges from 0.93 to 0.97 on the x-axis with a mean of 0.96 (SD = 0.03). The validated y-axis determination of the CoP course showed a higher correlation, ranging from 0.97 to 0.99, with a mean of 0.98 (SD = 0.01). The calculated RMSE showed an error range of 0.87 mm to 3.13 mm for the CoP on the x-axis. By contrast, the y-axis displayed an error range from 0.51 mm to 4.19 mm. With all validation cycles performed, the overall RMSE was 1.62 mm (SD = 1.30 mm) on the x-axis and 1.83 mm (SD = 2.05 mm) on the y-axis. No statistically significant difference was analysed between the RMSE in the x- and y-direction. Possible causes for the deviation in the x- and y-axis of the CoP curve and the RMSE are, for instance, the positioning of the sensors on the boxer's fists and the particular size of the individual sensors within the matrix. The sensor positioning in the glove was designed and developed in order to cover the entire potential impact surface as described in chapter 3 about the system design. Although the official contact area can be covered by the sensor system, hits with the side of the glove or the open glove, for example, which do not comply with the official rules, can lead to a displacement of the contact area and thus of the CoP. The size of the individual sensors was minimized and positioned in order to analyse crucial areas of the fist anatomy, such as the metacarpophalangeal joints and proximal phalanges, with a maximum number of sensors. Since the centre of pressure is calculated with the help of the sensors starting from the sensor´s centre, slight deviations may occur due to the calculation method and thus the course of the CoP. These limitations were reduced to a minimum due to the sensor design and developed, providing excellent accuracy in reproducing the CoP on the surface of the fist during a boxing punch compared to a Kistler force plate. It has to be considered that even the gold standard of a force plate has its limitations (Schmiedmayer and Kastner, 1999 and Chesnin, Selby-Silverstein and Besser, 2000). The error of a force plate is not zero. Studies have shown that especially when the normal forces perpendicular to the plates surface are small compared to the horizontal forces and/or when the force application point is located at the edge of the force plate, the force plate error will increase. An error can be caused by the different impact techniques in the second part of the study, since different horizontal forces are generated in relation to the normal forces, which could lead to errors. Especially at the very beginning and the end of the contact phase, these errors can occur, since at these times the forces are relatively small. To reduce these errors, special care was taken in the execution of the impact on the force plate (Schmiedmayer et al. 1999 and Chesnin, et al., 2000).

The results of the second part of the study demonstrated that the start of the CoP in all four punching techniques tested started between the second and third metacarpophalangeal joint. By comparison, the two semi-circular impact techniques of the rear hand hook and the uppercut show a shift of the start of the CoP by about 5.0 mm in the medial direction and by 22.5 mm in the proximal direction. This shift can be explained by the stronger diffraction in the transversal axis of the fist at the moment of impact compared to the jab or cross and can be understood as the first technical optimization approach.

Following the start of the force application, the CoP in all punches proceeds in a distal lateral direction to the centre of the striking fist. For the two straight punching techniques, the cross and the jab, the maximum punching force is reached in the centre of the fist. By contrast, the rear hand hook and uppercut punching techniques exhibit a CoP which continues beyond the centre in a lateral direction towards the fourth and fifth proximal phalanges until the maximum punching force is obtained. After the maximum force was reached, the centre of pressure proceeds in a medially proximal orientation back towards the second and third metacarpophalangeal joint for all punches tested. For the rear hand hook and uppercut techniques, the CoP ends at the height of the third proximal phalangeal joint. For the two straight punching techniques, the CoP ends at the level of the second proximal phalanges. Subsequently, the fist is released from the target and returned to the defensive position. This investigation showed unique displacement patterns in the different punching techniques.

The results of this study suggest that the developed sensor system provides a novel method for determining the CoP on the surface of the fist. Furthermore, the results were able to represent a specific course of the CoP of the four tested types of boxing punches on the surface of the fist. These results could therefore be a further means for evaluating the striking technique in order to assess the CoP of the second and third metacarpal according to Arus (2018) for optimal force transmission. The results of this study cannot only be used for a technical analysis but can also provide incisive insights into the detection and prevention of hand and finger injuries. As described above, the subject in this study showed a strongly laterally aligned CoP course and a maximum impact force at approximately the fourth and fifth proximal phalanges of the two semi-circular impact techniques, which exposes the anatomical structures to a significantly higher load than compared to the straight punching techniques of the cross and jab punch. A more detailed examination of the injury history of the subject could be of great importance in follow-up studies to determine whether injuries have occurred in these hand areas in the past.

Since the research field of the CoP and the force distribution on the surface of the fist during a punch is a novel one, there are no existing findings which show a connection between the force of the punch and the force distribution with resulting injuries. Additionally, there are currently no scientific studies investigating risk factors which predominate for hand and finger injuries. Based on the current state of research, it is thus only possible to make cautious inferences regarding the factors that may lead to these types of injuries (Loosemore et al., 2015). Potential influencing factors include the magnitude of the impact force, the striking technique used, and thus the distribution of the force, as well as the CoP progression on the fist and the degree of fist clench at the time of impact of the fist on the targeting object.

Further studies are necessary to investigate the relationship between impact techniques, impact forces, the CoP distribution, and possible injury risks. For this purpose, a larger number of test persons with different levels of experience should be tested to investigate this issue in depth. The analysis of variation between experienced and inexperienced test persons has already shown significant differences in the executed impact technique in the previous presented study results. Moreover, the results of the previously presented study of punching technique in experienced and non-experienced athletes presented in Chapter 4.2, as well as the results of Joch, Fritsche and Krause (1981), Smith, Dyson, Hale and Dyson (2000) and Lenetsky, Brughelli, Nates, Cross and Lormier (2018), showed a significant difference in the achieved punch force between athletes with different levels of experience. Such investigations of different levels of experience are crucial, as Zazryn et al. (2006) have demonstrated that more injuries occur in amateur boxing than in professional boxing. Currently, no scientific literature provides information about the causes of this difference in injury frequency between experienced and inexperienced subjects. A study of different levels of experience is therefore critical for understanding punching force and punching technique as a variable affecting the frequency of hand and finger injuries. In addition, the injury history of the participating subjects should be included in follow-up studies. Consequently, a possible connection with the executed punch technique and the overstrain of anatomical structures of the hand would be possible. Investigation during real competition and sparring matches would be an additional enlightening extension of the current study, since, as shown in the results of the study by Porter and O'Brien (1996), as well as by Zazryn, Cameron and McCroy (2006), the frequency of injuries was significantly higher during competition than during training. Thus, the results of a follow-up study could provide information on a change in punching technique and/or punch force during competition and training situations that are associated with potential hand injuries.

A further limitation of the current study is the investigation of the CoP as a technique constant in single executed punches. Davis and Wittekind (2013) have shown in their study that punch combinations account for a large proportion of the punches performed during a competition. In order to further investigate the CoP during a boxing punch and the punching technique performed, follow-up studies should therefore focus not only on single punches but also punch combinations and the course of the CoP between punches within a combination frequency. Furthermore, it should be noted that the punches were made against a punching bag. The course of the CoP cannot therefore be assimilated to a punch against a head or a different body part. In order to investigate the CoP with a blow to the head, sparring or competition would have to be analysed as described above. Alternatively, a head imitation as presented in Figure 17 could be used for further studies, with the punches being delivered against the head. The subject investigated in this experimental study did not use hand bandages during the tests. Prusak et al. (2014) have shown that special taping techniques cause a change in the CoP course on the foot and thus limit the risk of injuries. It is therefore essential to further investigate to what extent the use of tape or hand bandages and the applied technique causes a change in the CoP course and thus could provide preventive protection against excessive strain on anatomical areas due to the punching technique performed.

4.5.5 Conclusion

The main purpose of this study was to display the sensor system´s potential for detecting and presenting the course of the CoP in the four tested boxing punching techniques. The results demonstrate that the newly developed boxing monitoring system enables the examination and display of the centre of pressure on the surface of the fist during a boxing punch with great accuracy of up to R 0.99 when compared to the gold standard force plate. The study has not only shown the viability of the method to use piezo-resistive pressure sensors for CoP determination, but has also provided new insights into CoP progression during various boxing techniques of the cross, jab, uppercut, and hook. Consequently, this study shows that the punching technique has a decisive influence on the change of the CoP on the surface of the fist, as well as how the acting force evolves throughout the contact period and thus to the biological structures of the striking fist. The results of the study showed that the CoP progression is strongly dependent on the impact technique performed and that these techniques contain a unique individual repeatable CoP progression for the tested experienced athlete. The results indicate that the two straight punching techniques show a triangular force progression between the second and third metacarpophalangeal joint while the two semi-circular punching techniques display a CoP progression that extends to the fourth and fifth metacarpophalangeal joint, respectively, in the tested athlete. These results also reveal the area that is exposed most during a boxing punch and how long the biological structure is exposed to the acting force.

The information obtained based on the presented method of force progression representation is fundamental for applying and conducting future field studies to expand the scientific understanding in terms of biological loaded structures in the sport of boxing. Further studies, building on this preliminary work, are necessary to investigate the potential link between changing CoP during a punch and hand and finger injuries. The results of the study can also be used in a future application as a performance monitoring tool. With such a monitoring solution, coaches and athletes can perform an in-depth technique analysis in order to optimise the striking technique and efficiency while reducing the potential risk of injury at the same time.

5 Discussion

Following the experimental results, chapter five serves as an overall discussion of the conducted research process regarding the development of the boxing monitoring sensor system, as well as an overall discussion of the conducted experiments for the measurement and analysis of boxing related biomechanical parameters. The results of the individually conducted studies are brought into context with the existing scientific literature presented at the state of research. Furthermore, the findings of the studies will be critically reviewed in order to give a final conclusion of the conducted research and to provide an outlook on further studies in the following and final conclusion chapter.

Research gap

The state of research presented in chapter two has illustrated that there is a multitude of different scientific measurement instruments in the field of martial arts. These instruments range from stationary measuring instruments such as ballistic pendulums (Atha et al., 1985; Villani & Preli, 2003), to instrumentalised boxing bags (Broker & Crawley, 2001) and Hybrid III crash dummies (Walilko et al., 2005, Viano et al. 2005). The measurement methods are laboratory restricted and therefore are not suitable for the analysis of performance data in a realistic sport setting as it is during normal training, sparring or competition. In order to collect performance data beyond a laboratory environment, the literature research has revealed that the primarily used systems for the measurement of performance data in boxing are based on inertial sensors (Camomilla et al., 2018; Worsey et al., 2019). Therefore, the literature research was able to point out clearly that there is a lack of comprehensive sensor systems available in the field of martial arts, that are able to measure, analyse and represent kinetic as well as kinematic boxing related biomechanical parameters. This shows that the integration field of wearables in combat sports is under-researched and outlines the significance of the presented research and development work.

Development

The aim of the present thesis was therefore the research into and the development of, smart boxing gear for the measurement and analysis of boxing related biomechanical parameters. Therefore, the boxing monitoring system was developed specifically for the boxing specific requirements like high impact acceleration, high sampling rate or the limited space available in the considered sport equipment of the boxing glove.

During the development process different sensor components were designed, developed and tested for their applicability, validity and reliability. Based on the knowledge gained during the research work on a comprehensive sensor system for the sport of boxing, the system was extended with new sensors in the course of the scientific research work. This development work served to be able to collect kinetic as well as kinematic information in comparison to the literature such as the bestshot system or purely inertial based sensor devices (Pierce et al., 2006). The development of a new comprehensive sensor solution was then used for the experiments presented and performed in the course of the thesis.

The results of the scientific investigation of the developed sensor system have shown the potential of the developed sensor technology. The design demonstrated excellent correlations in the calibration and validation experiment compared with a Kistler force plate and a Vicon motion capture system. Furthermore, the possibility of implementation into the sports equipment of the boxing glove was demonstrated. In the validation study presented in chapter 4.1, inter alia impact forces, accelerations and velocities were demonstrated with a correlation of up to $R^2 = 0.99$.

A calibration routine was investigated, following the identified key performance parameters in the sport of boxing for performance monitoring.

The elaboration of the research question, how a calibration routine has to be designed to calibrate the developed sensor system, has shown that the calibration method applied in this work was carried out using a Kistler force plate. The calibration solely with a Zwick / Roell measuring device would have been possible only to a limited extent and would have led to a reduction in the measuring accuracy. This is due to the fact that the Zwick / Roell material testing machine available was not able to carry out impacts close to the simulated punch and therefore exerted a different kind of dynamic force on the sensor system compared to the Kistler force plate application. These limitations would have led to a change in the calibration routines, as a test during the calibration process has demonstrated. Calibration using a Kistler force plate was found to give the best results and was therefore defined as the optimum calibration method at that time and was applied in the further research course.

Furthermore, it should be discussed that the sensor design was evolved in the course of the research work and adapted to the characteristics of the field of application and equipment to be integrated. A primary objective of the conducted research work was the direct measurement of the punch force by means of the developed sensor system instrumented to a boxing glove. In order to enable this, the potential contact area was analysed and determined in pre-tests and in consideration of the impact area defined by the AIBA. The sensor design was then developed on the basis of these test results. In contrast to Dyer and Bamberg (2011), the sensor design allowed an even more precise analysis of the centre of pressure curve and a reduction of possible sources of interference (Dyer & Bamberg, 2011) during the contact phase of a boxing punch.

In order to be able to analyse kinematic performance data in addition to kinetic parameters, the developed sensor system was extended with inertial sensors. The use of inertial sensor technology has highlighted the problem of singularity effects during a boxing punch and considered therefore the extension to the quaternion theorem. The use of the Madgwick Quaternion Filter demonstrated, as in the study by Shepherd et al. (2017), an optimal way to represent the movement of the fist in three-dimensional space outside of a laboratory environment. This step of development allowed the further addition of punch variables to further investigate the punching techniques of the subjects tested.

In addition to the sensor design, the limited transmission frequency due to the transmission rate must be critically discussed. In order to reduce battery consumption and the associated battery size, Bluetooth® transmission was used instead of WIFI data transmission. To ensure the required measurement frequency of 1,000 Hz, the data was filtered and processed on the microcontroller to ensure real-time transmission for subsequent field investigations.

Experimental research

Based on the development work, field studies were conducted for the first time with the developed sensor system in the presented thesis. The focus of the studies was on the investigation of the technical execution of the stroke, since according to McGarry et al. (2013) the athletic performance is depending to a large extent on the technical execution of the athletic motion in order to exploit the potential for maximum effectiveness of the physical performance, in attacking as well as defensive situations. In addition to the investigation of experienced and non-experienced athletes, the four experimental studies carried out have highlighted significant results and new insights into performance parameters in the sport of boxing.

The four studies clearly demonstrated that the technical execution of the jab, cross, uppercut and rear hand hook punches examined in the research showed significant differences in fist rotation, punching force, punching speed, fist clench and opening as well as self-assessment between experienced and non-experienced athletes. A particular difference was found in the fist rotation from the defensive position to the punching object and back to the starting position.

The position of the fist on the target is of particular importance, since pronation is of special importance for an optimal impact area to hit the target with the second to fourth heads of the metacarpals and the metacarpophalangeal joints (Arus, 2018). In the fifth study carried out to analyse the centre of pressure course on the stroke hand, the statements of Arus (2018) are presented in chapter 4.5 for the first time in science with statistical data. The results of the study have demonstrated in a successful pilot study the start of the centre of pressure course, for the four tested striking techniques between the second and third metacarpophalangeal joint. Following the start of the force application, the centre of pressure proceeds in all punches in a distal lateral direction to the centre of the striking fist. After the maximum force was reached, the centre of pressure proceeds in a medially proximal orientation back towards the second and third metacarpophalangeal joint area.

The significant differences shown in the resulting measurement data of the achieved impact force and impact speed with the developed sensor system demonstrate a consensus with the results of existing studies (Băiţel & Deliu, 2014; Lenetsky et al., 2018; Whiting et al., 1988). A significant difference between the two groups of test subjects, of experienced and non-experienced athletes, was not only shown in the maximum punch forces achieved, but also in the self-assessment of different impact intensities. The results of the fourth study presented in chapter 4.3 demonstrate the difficulty in the accuracy with which non-experienced boxing athletes can control and assess their punching intensity and the strong deviation from the actual default punch level. The group of non-experienced athletes have shown in this experiment a greater variance of up to 58% in punch intensities than experienced athletes with a mean maximum variance of 7% in the punching techniques and intensities tested.

The analysis of sport-specific time-motion variations was another focus of the scientific experiments carried out as a non-invasive method of performance diagnostics for the examination of performance characteristics and movement patterns (Slimani et al., 2017). This analysis included, among others, the experiment of studying the fist clench before the time of impact. The investigation revealed again a significant difference between experienced and non-experienced athletes. The inexperienced athletes showed a particularly early clenching of the fist before the impact, whereas experienced athletes closed the fist just before the impact, up to 0.17 seconds (SD = 0.05 seconds). This result comes to a consensus with the existing literature, to perform the punch in a relaxed state as well as to prevent an energy los caused by an early fist clinch (Blum, 1977; Smith et al., 2000; Werner, 2003; Werner & Lachica, 2000).

Critical review and follow up experiments

A critical review of the applied experimental methodology shows that the experimental studies carried out were conducted within the framework of normal training sessions of a boxing group. At no point in the experimental studies was data obtained during a competition or near-competition training, as represented by a sparring match, as in the study of Pierce et al. (2006). The study protocol allowed the tested subjects to concentrate and to execute individual strokes at a time. This punch preparation is not possible in a competition situation. This type of competition situation does not allow the athletes to focus on a single maximum stroke, as the athlete is influenced by the reaction of the opponent in his stroke execution. Furthermore, the study by Davis and Wittekind (2013) has shown, that punch combinations account for a large proportion of the punches performed during a competition. Furthermore, the study by Piorkowski et al. (2011) showed that there is a significant difference between punch combinations and single maximal punches with respect to the resulting punch speed. A competition therefore shows a deviation in maximum punch force, speed and to conclude from this, also the technical-temporal movement sequences. In follow-up studies, these results must therefore be taken into account in order to obtain further scientific insights in the sport of boxing. In addition to the factors influencing technical punch execution, studies by Porter and O'Brien (1996), as well as by Zazryn, Cameron and McCroy (2006) show a significant difference in the frequency of injuries between training and competition. In order to obtain information on the cause of injury with the help of the developed sensor system, a field investigation in a competition situation is therefore of fundamental importance.

The experimental comparison of different experience levels showed a significant difference in the technical impact execution in the conducted experiments. The investigation of different levels of experience is crucial, as Zazryn and colleagues (2006) have discovered in their research that more injuries occur in amateur boxing than in professional boxing. It is therefore important to continue to investigate different levels of experience in follow-up studies, as there is no scientific evidence available to provide information on the causes of injury and injury processes of these different injury frequencies. An investigation of different levels of experience is therefore important to further investigate the impact techniques, punch forces, speed, the centre of pressure distribution etc. as a factor for potential hand and finger injuries. In addition, the injury history of the participating subjects should be included in follow-up studies. In this way, a possible connection with the executed punching technique and the overstrain of anatomical structures of the hand can offer in depth knowledge. For this purpose, a larger number of test persons with different levels of experience should be further tested.

6 Conclusion

Successful development of a reliable sensor system.

In conclusion, the presented results of the research work have shown the successful development of a new and unique sensor system for the sport of boxing. The developed sensor system provides a solution to the existing research gap, that no system is available so far, that is able to measure, analyse and to display kinetic as well as kinematic biomechanical performance data in martial arts, outside laboratory conditions. In the development process, the key performance parameters in the sport of boxing were identified based on the existing literature, in order to design and develop the comprehensive sensor system including the necessary sensor technologies and calibration routines.

Presentation of new scientific data in the field of boxing

The results of the conducted experimental research have also shown significant differences in the technical execution between experienced and non-experienced subjects in the four main punching techniques of the jab, cross, rear hand hook and uppercut. The presented research work has not only revealed new areas of research in the field of martial arts, but moreover provides new information in terms of fist activity, centre of pressure distribution and expert versus non-expert performance exertion with regard to the biomechanical punch parameters and musculoskeletal forces that occur. The results of the study demonstrate that the development and use of advanced instrumentalized training equipment in sport has the potential to increase in-depth knowledge of sport-related biomechanical research.

Expanding the current state of research

The knowledge gained from the experimental data can offer coaches and athletes a tool for analysing the requirements of a specific punching movement pattern with the help of the developed boxing monitoring system. The findings can be used to apply technology analysis for talent identification and promotion in martial arts. Coaches and performance support centres in particular can thus benefit from the developed boxing monitoring system, with which the technical performance of boxing punches can be analysed and potential technique correction can be made in the interests of the athlete. Furthermore, the knowledge gained from the experimental data can offer a support system to referees in evaluating the punches thrown and also to provide important data in the case of an injury in the hand area during a boxing punch. The developed sensor system has proven that it cannot only be of great value in performance diagnostics for competitive sports, but that the system can also make a decisive contribution to its application in social and educative institutions for violence prevention. The system can be an important support when it comes to providing a direct biofeedback to students and participants with the help of a predefined intensity limit, to adhere to the rules and regulations of the event in a consistent manner. Additionally, the possibility of recognising stroke intensities can of course also be transferred to competitive sports, among other things for training control and load management.

The presented research provides the fundamental framework for necessary research and data acquisition in boxing competition to obtain information about the performance parameters during a competition. In addition, data collected during competition can provide new information on the causes and risks of injuries, that can be used in the future for prevention and health protection of athletes.

To further investigate the biomechanics in a competition setting, research is currently planned to concentrate on this information and to identify the risk factors for the cause of injuries. Nevertheless, the presented work has demonstrated its applicability and has revealed a unique method as well as provided novel in depth knowledge in to the biomechanics of the sport of boxing and martial arts.

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