From the Institute for Movement Therapy

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Functional Performance Testing for Prevention and Rehabilitation Strategies in Training and Therapy - Implications for Research and Practice

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Presented by

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Affidavits following §7 section 2 No. 4 and 5 of the doctoral regulations from the German Sport University Cologne, February 20th 2013:

Hereby I declare:
The work presented in this thesis is the original work of the author except where acknowledged in the text. This material has not been submitted either in whole or in part for a degree at this or any other institution. Those parts or single sentences, which have been taken verbatim from other sources, are identified as citations.

I further declare that I complied with the actual "guidelines of qualified scientific work" of the German Sport University Cologne.

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Giordano Scinicarelli

08/05/23, Cologne

General notes

This cumulative doctoral thesis consists of four scientific articles. All four articles are published and integrated in this thesis. The formats of the articles in this thesis differ slightly from the publications, as a uniform layout is used in this thesis. Tables and figures have been numbered in ascending order in the list of tables and figures. A list with the abbreviations used for the general introduction and discussion is also included. In addition, the references used for the general introduction and discussion were transferred to a uniform bibliography at the end of this work.

For better readability, all genders have not been explicitly mentioned in this work. It is therefore pointed out that the generic masculine used also explicitly includes female and other gender identities.

Unfortunately, after the occurrence of an injury, not every athlete returns to play as desired.
I was an athlete who wanted to return to football after a surgically treated knee patella rupture, but, sadly, I failed.
Hopefully my work can contribute to improve other athlete's injury prevention and rehabilitation process.

Index

I. List of tables and figures

Tables

Figures

II. List of abbreviations

Abbreviation	Meaning
ACL	Anterior Cruciate Ligament
ACL-I	Anterior Cruciate Ligament Injury
ACL-R	Anterior Cruciate Ligament Reconstruction
YBT	Y-Balance Test
SLCMJ	Single-Leg Countermovement Jump Test
SLH	Single-Leg Jump (Hop) For Distance Test
SH	Side Hop Test
SJ	Speedy-Jump Test
LEFT	Lower Extremity Functional Test
AT	Agility-T Test
LSI	Limb Symmetry Index
DBP	Dynamic Balance Performance
MDS	Multidirectional Speed Performance
RTA	Return To Activity
RTS	Return To Sport
RTP	Return To Play
RTC	Return To Competition
ICC	Intraclass Correlation Coefficient
PO	Post-Operation
T1	Test Session One (First)
T2	Test Session Two (Second)
No.	Number
p	P-Value
α	Cronbach's Alpha
This list only refers to the abbreviations of the introduction and general discussion of this doctoral thesis. The abbreviations of each individual article can be found in the text of their respective chapters.	

III. Abstract (English)

Pre-injury screening and rehabilitation monitoring are two sides of the same medal in sports science research. One of the strategies on which both are based is the precise measurement of the functional performance, in order to optimize the decision-making process. The ultimate goals of functional testing can be varied: to decrease injury risk factors (prevention), to bring injured athletes back to sports as well as to avoid the risk of re-injury (rehabilitation). In the current literature, several testing measurements have been investigated for this purpose. However, they differ in the way functional performance is measured and interpreted. These weaknesses can cause confusion in establishing reliable benchmarks. The present cumulative doctoral thesis therefore investigates the potential of a reliable functional performance testing procedure for the application in injury prevention and rehabilitation practice. To this purpose, four studies were conducted:

Study No. 1 used a test-retest design, within seven-day interval, to examine the reliability of an experimental functional test battery composed by multiple tests for the lower extremities in twenty-two healthy sport student adults (14 males, 8 females; age 23.3 ± 3.9). A secondary aim was to determine the mean range for the limb symmetry index (LSI) for the single-leg tests. The same rater supervised the two different sessions (T1 - T2) under the same conditions. The tests selected from the literature were as follows: Y-balance test (YBT), single-leg countermovement jump (SLCMJ), single-leg hop for distance (SLH), side-hop (SH), speedy-jump (SJ), agility-T (AT), and lower extremity functional test (LEFT). Reliability analysis showed good-to-excellent reliability ($0.89 < ICC < 0.97$; $0.80 < \alpha < 0.98$) for the test battery. LSI ranged from 95.9 ± 6.7% (SH-T1) to 104.4 ± 12.5% (SLCMJ-T2). Therefore, the high reliability of the test battery suggests a potential use in clinical sports practice. In addition, the LSI range of ≥ 95% was proposed as a benchmark for healthy sport student adults.

Studies No. 2 and 3 used a cross-sectional design to investigate the following aims: 1) to provide age-specific mean values and limb symmetry index (LSI) of functional performance in young football players, 2) to detect interlimb asymmetries (LSI ≤ 90%) and 3) to investigate the association of age with single-leg functional performance and LSI. A total of 146 male football players (age 14.2 ± 2.3) performed the test battery (Study No. 1). In the Study No. 2, participants showed on average perfect LSI (103.8 ± 14.2%) amongst all jump tests (SLCMJ, SLH, SH and SJ) and age groups (from under-11 to under-19). Age effect was positively associated with single-leg functional performance ($p < 0.05$), but not with LSI ($p > 0.05$), in all tests and age groups (from under-11 to under-19). In the study No. 3, findings revealed speed scores (LEFT) to have a significant association with chronological age ($p = 0.000$), balance scores (YBT) of the dominant side ($p = 0.019$) and LSI ($p = 0.044$). Participants showed on average perfect LSI (100.1 ± 5.6%) for the balance test (YBT) among all age groups (from under-11 to under-19). To conclude, an LSI ≥ 100% in single-leg jump and balance tests is proposed as a benchmark in young and uninjured football players. Nevertheless, the growth process plays a crucial role in the development of functional capacities: older players may show a higher speed, single-leg jump and balance (dominant) performance, but not a higher limb symmetry index (LSI), than younger players. Therefore, in football practice, preventive intervention is advisable to counteract age-related performance differences, for which unilateral balance, strength, power and plyometric training is recommended. To sum up, the tests used in this study could be useful screening tools for the detection of performance deficits, the implementation of prevention training programs, and the optimization of selection strategies in football academies.

Study No. 4 used a case-report design. The aim was to detect the point in time when interlimb symmetries (LSI) and preinjury levels of performance can be restored, during the first year after

anterior cruciate ligament (ACL) injury and reconstruction. Based on the data obtained, a secondary aim was to identify the proper moment for return to competition (RTC). A 25-year-old female competitive gymnast performed a selected part of the test battery (Study No. 1). The study was conducted over 24 months and included one pre-injury and seven post-injury sessions, in order to monitor the LSI and pre-injury performance progresses. Results showed that LSI was restored at eight-ten months post-operatively (PO) in all tests. Pre-injury performance levels were achieved at six months (PO) in two out of four tests (SLCMJ and SJ). The SLH showed a performance decrease greater than 20% in the injured leg at twelve months PO. To conclude, RTC readiness was identified at ten months after surgery. Nevertheless, the restored LSI did not consider performance decreases in the SLH and YBT tests. Therefore, regular baseline assessments are recommendable to provide data for comparison and to optimize the decision-making process after ACL injury and reconstruction.

While study No. 1 provides a reliable and standardized test battery for the measurement of functional performance of the lower extremities, studies No. 2 and 3 examined possible functional performance deficits and interlimb asymmetries (LSI) in youth and uninjured football players. Finally, study No. 4 applicates the test battery in a rehabilitation protocol after ACL-I in a female gymnast, to detect the right time to RTC based on the restoration of the LSI. As a result of these four studies, it can be stated that current scientific practice in the field of functional performance testing has still much potential for improvement. In addition to an improvement in collecting data, an increased use of more reliable measuring instruments should be aimed for. In this context, compliance with established protocols for the standardised use of testing instruments can be useful to strengthen the informative value of reference data and to increase the amount of replication in research. Furthermore, it is necessary to look for further ways to improve functional testing in movement-oriented prevention and rehabilitation. Improvement of existing protocols and more application of reliable and practicable measurement instruments are needed in sports practice.

IV. Abstract (German)

Das Screening vor einer Verletzung und die Überwachung der Rehabilitation sind zwei Seiten derselben Medaille in der sportwissenschaftlichen Forschung. Eine der Strategien, auf denen beide beruhen, ist die präzise Messung der funktionellen Leistung, um den Entscheidungsprozess zu optimieren. Die letztendlichen Ziele von Funktionstests können vielfältig sein: Verringerung von Risikofaktoren für Verletzungen (Prävention), Rückkehr verletzter Sportler in den Sport und Vermeidung des Risikos einer erneuten Verletzung (Rehabilitation). In der aktuellen Literatur wurden mehrere Testverfahren zu diesem Zweck untersucht. Sie unterscheiden sich jedoch in der Art und Weise, wie die funktionelle Leistung gemessen und interpretiert wird. Diese Schwächen können zu Unklarheiten bei der Festlegung zuverlässiger Benchmarks führen. Die vorliegende kumulative Doktorarbeit untersucht daher das Potenzial eines zuverlässigen funktionellen Leistungstestverfahrens für die Anwendung in der Verletzungsprävention und Rehabilitationspraxis. Zu diesem Zweck wurden vier Studien durchgeführt:

Studie Nr. 1 untersuchte mit einem Test-Retest-Design im Abstand von sieben Tagen die Zuverlässigkeit einer experimentellen funktionellen Testbatterie, bestehend aus mehreren Tests für die unteren Extremitäten, an zweiundzwanzig gesunden erwachsenen Sportstudenten (14 Männer, 8 Frauen; Alter 23,3 ± 3,9). Ein sekundäres Ziel war es, den mittleren Bereich für den Limb Symmetry Index (LSI) für die einbeinigen Tests zu bestimmen. Die beiden verschiedenen Sitzungen (T1 - T2) wurden von demselben Untersucher unter denselben Bedingungen überwacht. Die aus der Literatur ausgewählten Tests waren folgende Y-Balance-Test (YBT), Single-Leg Countermovement Jump Test

(SLCMJ), Single-Leg Hop Test (SLH), Side Hop Test (SH), Speedy-Jump (SJ), Agility-T (AT) und Lower Extremity Functional Test (LEFT). Die Reliabilitätsanalyse ergab eine gute bis sehr gute Zuverlässigkeit (0,89 < ICC < 0,97; 0,80 < α < 0,98) für die Testbatterie. Der LSI reichte von 95,9 ± 6,7% (SH-T1) bis 104,4 ± 12,5% (SLCMJ-T2). Die hohe Zuverlässigkeit der Testbatterie deutet daher auf einen möglichen Einsatz in der klinischen Sportpraxis hin. Darüber hinaus wurde der LSI-Bereich von ≥ 95 % als Richtwert für gesunde erwachsene Sportstudenten vorgeschlagen.

In den Studien Nr. 2 und 3 wurde ein Querschnittsdesign verwendet, um die folgenden Ziele zu untersuchen: 1) Bereitstellung altersspezifischer Mittelwerte und Limb Symmetry Index (LSI) der funktionellen Leistung bei jungen Fußballspielern, 2) Feststellung von Asymmetrien zwischen den Gliedmaßen (LSI ≤ 90%) und 3) Untersuchung des Zusammenhangs zwischen Alter und einbeiniger funktioneller Leistung und LSI. Insgesamt 146 männliche Fußballspieler (Alter 14,2 ± 2,3) führten die Testbatterie durch (Studie Nr. 1). In der Studie Nr. 2 wiesen die Teilnehmer bei allen Sprungtests (SLCMJ, SLH, SH und SJ) und Altersgruppen (von unter 11 bis unter 19 Jahren) im Durchschnitt einen perfekten LSI (103,8 ± 14,2 %) auf. Der Alterseffekt stand in allen Tests und Altersgruppen (von unter 11 bis unter 19 Jahren) in einem positiven Zusammenhang mit der einbeinigen funktionellen Leistung ($p < 0,05$), aber nicht mit dem LSI ($p > 0,05$). In der Studie Nr. 3 zeigten die Ergebnisse, dass die Geschwindigkeitswerte (LEFT) einen signifikanten Zusammenhang mit dem chronologischen Alter ($p = 0,000$), den Gleichgewichtswerten (YBT) der dominanten Seite ($p = 0,019$) und dem LSI ($p = 0,044$) aufweisen. Die Teilnehmer zeigten im Durchschnitt aller Altersgruppen (von unter 11 bis unter 19 Jahren) einen perfekten LSI (100,1 ± 5,6 %) für den Gleichgewichtstest (YBT). Zusammenfassend lässt sich sagen, dass ein LSI ≥ 100 % bei einbeinigen Sprung- und Gleichgewichtstests als Benchmark für junge und unverletzte Fußballspieler vorgeschlagen wird. Dennoch spielt der Wachstumsprozess eine entscheidende Rolle bei der Entwicklung der funktionellen Fähigkeiten: Ältere Spieler können eine höhere Geschwindigkeit, einbeinige Sprung- und Gleichgewichtsleistung (dominant), aber keinen höheren LSI aufweisen als jüngere Spieler. Daher ist in der Fußballpraxis eine präventive Intervention ratsam, um altersbedingten Leistungsunterschieden entgegenzuwirken, wofür einseitiges Gleichgewichts-, Kraft-, Leistungs- und Plyometric Training empfohlen wird. Zusammenfassend lässt sich sagen, dass die in dieser Studie verwendeten Tests nützliche Screening-Instrumente für die Erkennung von Leistungsdefiziten, die Durchführung von präventiven Trainingsprogrammen und die Optimierung von Auswahlstrategien in Fußballakademien sein könnten.

In Studie Nr. 4 wurde ein Fallberichtsdesign verwendet. Ziel war es, den Zeitpunkt zu ermitteln, zu dem die Symmetrie zwischen den Gliedmaßen (LSI) und das Leistungsniveau vor der Verletzung wiederhergestellt werden können, und zwar im ersten Jahr nach der Verletzung und Rekonstruktion des vorderen Kreuzbandes (VKB). Auf der Grundlage der gewonnenen Daten sollte außerdem der richtige Zeitpunkt für die Rückkehr zum Wettkampf ermittelt werden. Eine 25-jährige Leistungsturnerin führte einen ausgewählten Teil der Testbatterie durch (Studie Nr. 1). Die Studie wurde über einen Zeitraum von 24 Monaten durchgeführt und umfasste eine Sitzung vor der Verletzung und sieben Sitzungen nach der Verletzung, um die Entwicklung des LSI und der Leistung vor der Verletzung zu beobachten. Die Ergebnisse zeigten, dass die LSI acht bis zehn Monate nach der Operation (PO) in allen Tests wiederhergestellt war. Das Leistungsniveau vor der Verletzung wurde nach sechs Monaten (PO) in zwei von vier Tests (SLCMJ und SJ) erreicht. Bei der SLH zeigte sich im verletzten Bein nach zwölf Monaten PO ein Leistungsabfall von mehr als 20 %. Zusammenfassend lässt sich sagen, dass zehn Monate nach der Operation die Bereitschaft zur Wiederherstellung des Return-to-Competition festgestellt wurde. Der wiederhergestellte LSI berücksichtigte jedoch nicht die Leistungseinbußen bei den Tests SLH und YBT. Daher sind regelmäßige Baseline-Untersuchungen empfehlenswert, um Vergleichsdaten zu erhalten und den Entscheidungsprozess nach einer VKB-Verletzung und -Rekonstruktion zu optimieren.

Während Studie Nr. 1 eine zuverlässige und standardisierte Testbatterie zur Messung der funktionellen Leistungsfähigkeit der unteren Extremitäten bereitstellt, untersuchten die Studien Nr. 2 und 3 mögliche funktionelle Leistungsdefizite und Asymmetrien zwischen den Gliedmaßen (LSI) bei jugendlichen und unverletzten Fußballspielern. Studie 4 schließlich wendet die Testbatterie in einem Rehabilitationsprotokoll nach ACL-I bei einer Turnerin an, um anhand der Wiederherstellung des LSI den richtigen Zeitpunkt für eine RTC zu ermitteln. Als Ergebnis dieser vier Studien kann festgehalten werden, dass die derzeitige wissenschaftliche Praxis im Bereich der funktionellen Leistungstests noch viel Verbesserungspotenzial aufweist. Neben einer Verbesserung der Datenerhebung sollte ein verstärkter Einsatz von zuverlässigeren Messinstrumenten angestrebt werden. In diesem Zusammenhang kann die Einhaltung etablierter Protokolle für den standardisierten Einsatz von Testinstrumenten nützlich sein, um die Aussagekraft von Referenzdaten zu stärken und die Replikationsrate in der Forschung zu erhöhen. Darüber hinaus ist es notwendig, nach weiteren Möglichkeiten zur Verbesserung funktioneller Tests in der bewegungsorientierten Prävention und Rehabilitation zu suchen. Die Verbesserung bestehender Protokolle und die verstärkte Anwendung zuverlässiger und praktikabler Messinstrumente in der Sportpraxis sind notwendig.

1. Introduction

Over the past years, the concept of functional performance has received increasing attention in injury prevention and rehabilitation practice [2,11,16,29,75,93]. In this context, functional performance testing represents a multidimensional, preventive and prospective approach to assess sport-specific skills based on the individual level of athletes, in order to recognise information and translate it into knowledge and action for the maintenance and promotion of athlete's health [12,126]. The use and interpretation of functional testing in prevention and rehabilitation strategies is diverse, and includes links between the detection of injury risk factors and the gradual return to sport practice after injuries [21,111].

Sports participation leads to positive effects on children's and adolescent's physical and mental health, education and behaviours [40]. Nevertheless, it cannot be denied that sports participation also implies a high risk of injuries. A sports injury is defined as a traumatic event that occurs during the course of a sporting activity [46], that results in either medical expenses or incapacity for further sport practice [162]. For young athletes, sports injuries can have negative short-term consequences such as reduced performance, inability to play and psychological impairment [42,60]. In the worst case, an injury can lead also to negative long-term consequences such as loss of performance and the end of career [16,160].

The adolescent age range (≤ 19 years) can be described as more susceptible to injury compared to adult athletes: due to their sensitive growth phase, the adolescent age-group is more prone to changes of functional capacities and health-related effects, representing a critically highly relevant target group in view of positive future changes [44,65]. In addition, football participation represents an extrinsic risk factor for long-term and growth-related knee injuries in young athletes (≤ 18 years), such as anterior cruciate ligament (ACL) injuries. [33,149,150,151] Therefore, since football is the most played sport in Germany (45% of children are enrolled in football clubs), functional screening tests in order to detect injury risk factors, appear to be a fundamentally promising approach in the context of health and talent promotion in youth sports (e.g. football) [33,40].

In youth athletes, interlimb asymmetries and single-leg deficits in functional performance have been associated with an elevated risk of injury to the lower limbs and with a better chance to advance in the elite categories [19,20,24,25,84]. For this reason, functional parameters (e.g. balance, hop and speed) have been extensively used for performance screening and scouting strategies in young athletes [19,20,24,25,84,87,135,136,137,138,139,140,141]. Preventive measures through the implementation of pre-injury screening of functional performance can support the identification of injury risk factors and the development of corrective training programmes, with the final goal to improve performance of athletes and to reduce injury risk factors [7,104].

Therefore, optimal functional performance seems to be a crucial component for the maintenance of sport-specific skills and in order to perform at high levels without injury. [55,135,136,137,138,139,140,141] The monitoring of functional performance may be also helpful in increasing international competitiveness and this create pressure for action to optimise prevention strategies in elite sport.

A fundamental step for the prevention of injuries is therefore to find analytical tools that can reveal the presence of risk factors [127]. The literature is full of valid and reproducible functional tests, but there is a lack of a reliable test battery which comprises different factors of functional performance (e.g. dynamic balance, jumping abilities in different planes, speed, agility) In fact, comparability of the results and transferability from theory to practice have to be based on essential components: reliable testing tools, standardization of testing procedures and objectivity of the outcomes [80].

In prevention practice, pre-injury screening is becoming increasingly popular for the health of the athletes in youth sport. Pre-injury screening represents a prospective data collection, as part of the preparation for the season, in order to obtain individual benchmarks and to detect injury risk factors, to be used for optimizing physical performance, targeted prevention training and rehabilitation in case of injuries [16]. Pre-injury screening provides comprehensive knowledge for the performance diagnostics, which can be used for better training plans and for performance-oriented comparison with reference values from uninjured population [16]. In addition, reference values of the non-injured players could be also available and, in the event of an injury, it could be helpful to rely on these values in order to better orientate the rehabilitation process [16]. Since the highest injury incidence (47.4%) is among young athletes (≤ 19 years), there is an urgent need to optimise and improve injury prevention strategies [76]. Therefore, detecting injury risk indicators and analysing unilateral performance and interlimb asymmetries in young and uninjured athletes could help to better understand age-related performance trends and to further improve injury prevention strategies.

In rehabilitation practice, functional tests have been commonly used also as standard criteria for returning to sport after injury. [175] Functional performance tests are widely used to determine the right time to return to sport, based on the individual level of the injured athlete and on the benchmarks offered in literature [111]. However, differences due to age, gender and practiced sport may influence the rehabilitation process. In fact, according to sport, gender and age, it is still unclear when interlimb asymmetries and functional deficits could be restored after anterior cruciate ligament injury (ACL-I). In addition, the right time to return to competition after an ACL rupture may be various. Therefore, monitoring the entire rehabilitation of injured athletes until their return to the field can be useful to establish relative benchmarks for sport, age and gender and to finally optimize the decision-making process to return to competition.

Based on this, the main question of this cumulative doctoral thesis is therefore how a reliable, objective and standardized functional performance test battery for the lower extremities can be promoted in young sports athletes, for both rehabilitation and preventive purposes, through the use of systematic screening tests. The core of the doctoral thesis is formed by four scientific publications: The Study No. 1 deals with the selection, standardisation and reliability of the test battery in healthy athletes (Study No. 1). The Studies No. 2 and 3 deal with the execution of pre-injury performance screening tests in youth and uninjured football players, in order to detect interlimb asymmetries and age-related correlations during single-leg jump tests (Study No. 2) and single-leg dynamic balance and multidirectional speed tests (Study No. 3). The Study No. 4 deals with the rehabilitation monitoring of a female gymnast after anterior cruciate ligament reconstruction, to find out how long it takes for interlimb symmetries and pre-injury level of performance to be restored and to determine the right time to return to competition (Study No. 4). Building on the overall discussion, implications for research and practice concerning the promotion of injury prevention and rehabilitation strategies will be formulated.

2. Theoretical Background

2.1. Functional performance testing

Generally, it is imperative for young players to train efficiently and effectively in order to achieve goals in sports. Functional performance tests measure the body performance during exercise and activity and could provide valuable training data, both for injury prevention and rehabilitation purposes.

In clinical sports practice, functional tests are used to identify potential injury risk factors. Due to their ease of implementation, functional tests are particularly suitable in the context of team sports and represent assessment tools reproducing the mechanism of injury [1,13]. Systematic functional testing procedures should be performed as a basis for movement therapy interventions for the lower extremities [111,176]. Due to their economy, practicality and the fact that they reflect game-like situations, functional testing predominates in the literature [13,19,20,47,48,66,75,105,107,111,130,153].

Due to sport-related lateral differences, it is recommended to test single-leg functional performance separately in order to detect possible deficits [67]. In addition, this is exacerbated by the fact that the mechanisms of ACL-I generally occur when the load is shifted mainly to one leg. To quantify the results of single-leg performance, the limb symmetry index (LSI) is most commonly used in the literature. The LSI cut-off value indicates at least 90% of symmetry of the injured (or non-dominant leg) compared to the uninjured (or dominant leg) side [47,48,105]. Differences in the percentage ratio between the injured and uninjured leg that exceed 10% reveal an increased risk of injury or the inability to return to sports after injuries [111]. The most commonly used functional tests are largely based on neuromuscular control (e.g. single-leg balance and jump tests), which is considered a significant predictor of ACL (re)rupture and reflect real game situation deficits in functional performance. [128]. Therefore, functional performance tests for the neuromuscular control are able to detect aberrant movement deviations that are related to lower limb injuries [19,20].

To date, the focus has been particularly on the quantitative evaluation of functional performance by the use of the so-called test batteries [35,36,105,107,160,170,178]. For example, besides to assess the lower extremities functionality, test batteries are also used to measure strength capacity, neuromuscular control and stability of the trunk-pelvis-leg axis [56,116,158]. A test battery should include different movement principles that reflect the requirements for dynamic knee stability during sporting activities. Among the most frequently used objective criteria are: flexibility, balance, jump, endurance, change of direction, speed, accelerations and stopping manoeuvres [160,177]. In particular, a combination of multiple functional tests is recommended and used to increase sensitivity and to be able to control as many functional parameters as possible [73,75]. In this context, the combination of different jump tests in multiple plane directions for the measurement of functional performance after ACL injuries has been already proposed [125,142]. Additionally, several studies show that jump tests provide equally valid information about leg strength ratios as more expensive isokinetic strength measurements [75,83,100,132,178,180]. Furthermore, the results of jump tests (height and distance) and neuromuscular control tests (e.g. y-balance test) are used to determine performance status and assess injury risk [75,111,175,176]. In addition, these tests are used to early diagnose sport motor performance deficits or asymmetries [105,176] and to assess when it is safe to return to sport [18,147].

However, sport motor (functional) tests are standardised measurement that require a precise movement execution for performance diagnostics [27,80,85,99,123,145]. Furthermore, tests must be feasible under standard conditions and satisfy the statistical quality criteria of the respective test-theoretical model [27,80,85,99,123,145]. Accordingly, test procedures must be as reliable, accurate, valid and above all objective as possible. They should also be simple and meaningful in order to measure clinically significant changes in injured athletes [27,80,85,99,123,145]. The quality of the measurement process has a decisive influence on the success of the examination and the meaningfulness of the results [27,80,85,99,123,145]. Nevertheless, measurement errors are usually unavoidable during test procedures, consequently the goal must be both to assess measurement quality and to minimise measurement errors [27,80,85,99,123,145]. Test quality criteria are an important instrument for assessing the effectiveness of test procedures [27,80,85,99,123,145]. The best-known classical tests for quality criteria are reliability, validity and objectivity [27,80,85,99,123,145]. Reliability describes the measurement accuracy of a test without measurement error [27,80,85,99,123,145]. The measure of reliability is indicated by means of the reliability coefficient, the intraclass correlation coefficient (ICC). This can assume a value between zero and one, a coefficient of one indicates freedom from measurement errors [27,80,85,99,123,145]. Thus, in order to rely on high quality reference data, functional test procedures must be carried out uniformly and, above all, as reliably as possible [27,80,85,99,123,145]. Therefore, without standardised implementation conditions, comparability of test results is not possible [27,80,85,99,123,145].

2.2. Pre-injury screening

In Germany occur almost two million sport injuries per year [148,163,164]. Despite the diversity of disciplines, about two thirds of the total injuries are reported in sports like football, basketball, handball and volleyball [65]. Lower limb injuries represent a large proportion of injuries in both professional and amateur sports [164,167]. Especially, about 70% of all sports injuries affect the lower extremities, with the knee joint being the most frequently injured part [96]. Knee ligamentous ruptures represent the second most common injury also during childhood [9,10,28,130,134]. In this context, the ACL rupture is one of the most unfavourable non-contact knee joint injuries, which seriously affects the development of sport athletes and their future careers [122].

Becoming a professional footballer and playing in the stadium of one's favourite team is the dream of one in two children in Germany [33,40]. However, injuries can be a massive setback for the hopes of junior footballers or even the end of the big dream. Football is one of the most popular sports worldwide, but also one of the team sports with the highest lower extremities injury rates [65,162]. Football is classified as one of the major sports with increased risk of injury for young athletes [38]. In general, 86% of thigh muscle injuries and 47% of knee joint injuries result from non-contact or indirect contact situations [162]. For example, 85% of ACL ruptures result from non-contact or indirect contact situations [5,6,39,179]. This shows that a large proportion of lower limb injuries occur without direct contact with a counterpart and could therefore be prevented or avoided [34]. The avoidance of injuries, especially to the knee joint, can have far-reaching positive effects on the player sporting career [5,6,39,179].

Generally, prevention refers to measures to avoid illness and disease and to achieve a temporary optimal physical, cognitive and psychosocial performance status [45]. In movement-oriented therapy, prevention is divided into three areas: a distinction is made depending on the time of the intervention between primary, secondary and tertiary prevention [4,45,152]. In sports practice, primary prevention aims above all to prevent an injury before it happens, through systematic testing and analysis procedures [4,152].

Whereas functional tests in general were explained in chapter 2.1 (2.1 Functional performance testing), from here on the description will go into more specifics regarding the use of the above-mentioned functional tests in the context of pre-injury screening.

In the course of the last few years, despite a wealth of scientific research and the further development of preventive measures, it has not been possible to reduce the injury rates to a relevant extent. There are different approaches to reduce the frequency of injuries. A precise understanding of the mechanisms of injury is of fundamental importance in order to determine risk factors. Through preventive training measures, risk factors can be minimised in a targeted manner and thus reduce the likelihood of an injury [21]. A first step in developing effective training interventions based on the current performance level of the players are the so-called pre-injury screenings by the use of functional performance testing. The reasons for the particular relevance of pre-injury screening are numerous and varied. To detect injury risk factors (e.g. neuromuscular deficits) of individual players to be improved throughout the application of preventive training programs. For the optimal detection of injury risk factors (e.g. neuromuscular deficits), functional performance tests seem to be the simplest, most effective and utilised option [3,130]. Thus, functional screening tests are carried out to identify performance deficits that, in a sport-specific context, may lead to stress and consequently to injuries [127,128]. Decisive risk factors for injuries can be detected, influenced by preventive measures and therefore the injury incidence can be reduced. This is why the importance of pre-injury screening by the use of functional testing is increasing in youth sports [4].

Preventive training measures must be improved in order to counteract avoidable injuries. The basis for a comprehensive prevention programme is the identification of risk factors through the use of mass pre-injury screenings [103]. Pre-injury screening describes the execution of performance tests with the aim of identifying injury risk factors and performance potential deficits at an early stage, in order to derive appropriate preventive measures [162]. The objective is to detect deviations from the normative values and react accordingly [7]. This baseline data can subsequently be used to design preventive training programs for individual players [7] or to support rehabilitation in the event of an injury [16,111,160]. Pre-injury screening can include, for example, musculoskeletal testing, movement analysis, agility and endurance testing, or sports motor (functional) testing [13,31,172,173,176]. Due to their ease of implementation and low financial investment, functional tests are particularly suitable in the context of team sports [13,62]. The collection of quantitative data has been the main focus so far [75]. The results of jump tests (height and distance) or tests of neuromuscular control (e.g. static/dynamic balance) are then used to determine the performance status, assess the risk of injury or determine the right time of reintegration after injury [16,75,111].

Previously, it was assumed that the frequency of injuries was highest at advancing ages [144,162]. However, recent studies show that youth athletes, compared to all other age groups, have the highest injury incidence, especially with regard to ACL ruptures [149,150]. In fact, in childhood there is basically a high risk of injury due to the musculoskeletal plasticity, while the pubertal growth spurt in adolescent athletes could be a critical phase in terms of athletic resilience, muscular imbalances, coordinative deficits and inharmonious physiques and body structures [76]. In addition, sports injuries in the young age group can result in limb discrepancies and joint instabilities [95]. In particular, an important factor to consider is the chronological age of the players when performing performance screening. [129] In fact, age-related differences in physical abilities and functional capacities are common aspects in elite football academies [70]. It therefore makes sense to use preventive measures at young age, in order to avoid the short- and long-term negative consequences of injuries most effectively [4,152]. Thus, performance screenings are fundamental in sports academies (e.g. football), in order to create the necessary and appropriate foundations for the transition to a professional environment, which is more difficult in terms of physical and mental demands.

The consistent promotion of talent is of particular importance in junior competitive sport. This enables the long-term establishment of young athletes in elite sport. If injury prevention strategies are integrated into training at an early age, the positive effect is increased [162,163,164]. For this to be realised, individualised care by means of pre-injury screening and functional testing is urgently needed, for which, however, standardised procedures are indispensable [111]. These circumstances create a need for further research to develop prevention strategies for youth athletes. As a serious injury to a (junior) athlete can mean a possible career end [16], the importance of effective prevention and understanding of injury mechanisms and risk factors is therefore significant. [144] The basis for a comprehensive prevention strategy is the identification of injury risk factors [103]. Despite the fact that prevention strategies have already been introduced in junior sports, anterior cruciate ligament (ACL) injuries remain a big problem in orthopaedic sports medicine [162,163,164]. In fact, with regard to return to sport after injury, there is often a lack of objective criteria to determine injury risk status, recovery and readiness to play [101,102,111,160].

Thus, pre-injury screenings are helpful in order to detect neuromuscular risk factors and subsequent plan individual training programs. However, they are of enormous importance not only for performance-oriented strategies, but also for providing benchmarks for rehabilitation purposes. In fact, systematic screening tests on healthy players allow valuable side-to-side comparison with the pre-injury level of performance and to support the optimal return to sport in the event of an injury.

2.3. Return to competition after anterior cruciate ligament injury

Injuries cannot be totally avoided in sports. When an athlete gets injured, it represents a concrete problem to be counteracted as fast as possible. Medical investigation and follow-up of any sports injury is important to track the progress of rehabilitation and to support athletes to restore their pre-injury level of knee functions affected by the injury [42,52,146].

The rehabilitation process after an injury can be divided into five key milestones [2,75,111]. Pre-injury screening (PRE) is a prospective data collection process that, in addition to important reference values of the uninjured player, can be used as a basis for the rehabilitation process. Return-to-Activity (RTA) represents the transition from clinical care to general rehabilitation training. Return-to-Sport (RTS) is the transition between general rehabilitation training and sport-specific rehabilitation training, before the individualised limited team training. Return-to-play (RTP) describes the transition to unrestricted team training or competitive training. Return-to-Competition (RTC) describes the complete reintegration process of a player from the time of the injury to the first competitive match. The transition from one phase to the next in the rehabilitation period is decided by the results achieved in the various functional tests, which are fundamental prerequisites for entering the next rehabilitation phase and without which there is a risk of getting stuck in the individual phases without success.

The term return-to-competition, thus, refers to the process of reintegration from the time of injury until the injured athlete's first competition, representing the last stage of the rehabilitation process [111]. The goal is to bring the player through a gradual increase in load back to the original training condition without re-injury risk. The time for this is determined individually by the coach in consultation with the player and the respective doctors [111]. Depending on the sport, the athlete should be able to complete with success different assessment criteria in order to return to sport-specific training or matches after injury [75].

Considering the long downtime, anterior cruciate ligament (ACL) injuries represent a particularly unfavourable diagnosis for athletic development [68,122]. In the case of an ACL injury (ACL-I), long periods of absence are unavoidable and the rehabilitation period is difficult and costly. [28,57,59,159]. After an ACL reconstruction (ACL-R), around one third of professional players are unable to maintain their previous level of performance [16,167]. Further, the risk for a recurrent ACL-I is increased for injured athletes with respect to uninjured athletes [58,64,166]. In particular, ACL re-injury rates can be as high as 19% for the affected side and up to 24% for the contralateral side, while re-injury rate is of 22% in the 15- to 20-year-old age group [30,32,130,131,135,136,137,138,139,140,141,151]. Normally, ACL ruptures are also associated with long-term negative consequences such as increased risk of osteoarthritis, obesity and loss of quality of life [89,95,172,173,174]. Finally, due to the differences in individual healing and rehabilitation processes, the time periods from ACL-R to RTC could be various: in particular, 40% of athletes may return after 4 months, another 40% of athletes may need more time (between 4 to 6 months) while 10% of athletes may return after 6-8 months [58,98,131].

In sports, ACL injuries are caused by a variety of factors that lead to non-physiological actions [81]. These actions often occur during changes of direction or single-leg landing movements [34]. In addition, deficits in postural stability or neuromuscular imbalances are considered risk factors for primary ACL injuries as well as important predictors of recurrent ACL injuries [5,6,39,128,179].

In general, due to the varied and demanding stresses of the lower extremities, rehabilitation periods can vary in relation to return to sport (RTS) [175]. As the rehabilitation process is oriented towards both healing tissue and function, functional testing procedures can quantify deficits, among other things, and thus also serve as a decision-making support for determining when is safe to RTS [75,175]. The state of research shows that there are already quite a few approaches to quantify performance and to determine the right time of return to competition (RTC) after injuries by means of functional testing procedures [175]. In fact, because of an optimal functional performance test simulates the athlete’s sports activities, functional performance testing can identify physical limitation that may negatively affect an athlete’s performance [4]. Thus, functional test batteries are commonly used to assist the rehabilitation after injury and to support the RTC decision-making process [75,111]. A return to competitive sport in particular should be based on objective criteria. However, there is a lack of objective, reliable and standardized test battery for determining functional performance of the lower extremities [160]. Especially in the final phase of rehabilitation, such criteria could facilitate the integration of athletes back into sport. However, although a large number of scientific studies have already been published about the rehabilitation of injured players, there is a lack of clarity on the optimal time for RTC.

Thus, diagnostics by means of test battery not only provide helpful information about the risk of injury and be used as baseline for prevention strategies, but also provide important data for the decision-making process during rehabilitation in the case of injuries (e.g. ACL injury), which can support a sensible, gradual reintegration process from injury to return to sport and later to competition [2,75]. However, objective, standardized and reliable testing measurements are needed in order to implement prevention and rehabilitation strategies.

3. Research Questions

From the previously presented theoretical considerations on the methodological challenges in the procedures of functional performance testing for prevention and rehabilitation strategies, the following aims are planned for the present work:

The primary aim of this doctoral thesis is to select the best and most widely used tests in the literature, in order to provide a reliable, objective and standardized test battery for the measurement of functional performance of the lower extremities in uninjured athletes (Study No. 1). The standardized testing procedures will allow a better transferability of the results for future studies. The normative values from uninjured athletes will support the comparison of results and the implementation of injury prevention and rehabilitation strategies in sports (Study No. 1).

The secondary aim of this doctoral thesis is to conduct a functional performance screening measurement in youth academy footballers, to explore interlimb asymmetries and functional deficits that may be present in uninjured young players (Studies No. 2 and 3). Furthermore, the results of this doctoral thesis not only will provide age- and sport-specific benchmarks, but will also help to explore the relationships between the functional performance tests performed and the chronological age of the footballers in question (Studies No. 2 and 3).

The third aim of this doctoral thesis is to monitor the rehabilitation process of a female gymnast after ACL-R (Study No. 4). To detect the exact time when interlimb symmetries and pre-injury performance level are restored and to determine the right time for RTC. Finally, to observe if any re-injury has occurred at one-year follow-up after RTC (Study No. 4).

From the aims of this doctoral thesis, the following main research question arises:

How can we optimise functional performance testing for prevention and rehabilitation strategies in sports science?

In order to answer this main question, three sub-questions will be examined in greater detail below:

1. Can a combination of different functional tests for the lower extremities result in a standardized, objective and reliable test battery?
2. Is the test battery capable of detecting interlimb asymmetries (LSI ≤ 90%) and the associations of single-leg functional performance with the different age groups in young and uninjured footballers?
3. How long does it take interlimb symmetry (LSI ≥ 90%) to be restored after an ACL-R for a competitive female gymnast? How long does it take single-leg performance to return to the same level as pre-injury? Based exclusively on functional performance outcomes, when RTC can be allowed after ACL-I?

These questions will be examined and answered by four studies in the following chapters.

4. Study Nr. 1: The Reliability of Common Functional Performance Tests within an Experimental Test Battery for the Lower Extremities

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4.1. Abstract

The main aim of this study was to determine the test–retest reliability of an experimental functional test battery: Y-balance test (YBT), single-leg countermovement jump (SLCMJ), single-leg hop for distance (SLH), side-hop (SH), speedy-jump (SJ), agility-T (AT), and lower extremity functional test (LEFT). Secondary aims were (1) to determine the mean range for the limb symmetry index (LSI) and (2) to detect significant differences in performance between test–retest sessions. Twenty-two healthy adults (14 males, 8 females; age 23.3 ± 3.9) were tested by the same rater during two different sessions (T1–T2), with a seven-day interval, under the same conditions. Reliability analysis showed good-to-excellent reliability ($0.89 < ICC < 0.97$; $0.80 < \alpha < 0.98$) for the test battery. LSI ranged from 95.9 ± 6.7% (SH-T1) to 104.4 ± 12.5% (SLCMJ-T2). Repeated measures ANOVA detected significant performance differences between sessions in the LEFT ($p = 0.009$) and for nondominant sides in the SLH ($p = 0.015$), SH ($p = 0.007$), and SJ ($p = 0.011$). The high reliability of the test battery suggests a potential use in clinical sports practice. The LSI range of ≥95% was proposed as a benchmark for healthy adults. Learning effect seems to have played a crucial role in the T2 improvements of the non-dominant side for hop performances (SLH, SH, SJ) and speed performance (LEFT).

Keywords: test-retest design; limb symmetry index; between-session differences; healthy athletes; dynamic-balance test; hop test; sprint test; hop performance; speed performance

4.2. Introduction

A test battery consists of an evaluated and standardized protocol combining single and complementary subtests, which do not require sophisticated equipment and can be carried out multiple times [1]. Test batteries are an efficient screening tool to assess functional movement patterns [2] as well as to provide a multidimensional, objective, and quantitative analysis for the evaluation of functional performance [3]. In sports therapy, functional test batteries are widely used to assess sport-specific functional performance [2,4], to establish prevention strategies (such as pre-injury screenings) for anterior cruciate ligament injury (ACL-I) [5,6], and to plan specific training interventions for the lower extremities [7–10]. Furthermore, they are regularly used in monitoring and decision-making processes of rehabilitation after ACL-I, for return-to-sport clearance, and for movement quality assessments [4,11–14].

In general, functional inter-limb asymmetries in performance are associated with sport activity limitations and might be an injury risk factor for uninjured athletes [2]. Clinically, the limb symmetry index (LSI) can be calculated easily and rapidly. It can provide valuable baseline data for pre-injury screenings or for rehabilitation progression purposes. In order to allow side-to-side performance comparisons, functional tests can be performed unilaterally (on one leg) and the LSI can be detected [15–19]. The LSI is an indicator that quantifies the symmetry of the limbs in percentage and can be calculated in multiple ways: uninjured/injured, non-dominant/dominant, or less-performant/more-performant limbs [20,21]. As a rule, an LSI ≥ 90% is considered a normal range in functional tests for both injured and uninjured populations [4,14,22].

Generally, a valuable test battery should include sport-specific movement patterns (e.g., balancing, landing, sprinting and cutting), in order to provide sport-specific functional performance outcomes in terms of imbalances/weaknesses related to muscle power, dynamic balance, proprioception, speed and agility [2,23,24]. In particular, an effective test battery should encompass several functional tests structured into different levels, gradually organized from simple (less demanding) to complex (more demanding) tests [1,4,14,25,26].

Thus, the design should be primarily based on the assessment of postural control, dynamic balance, and joint stability [4,14,27,28]. Subsequently, measurements of muscular power/strength, proprioception, and neuromuscular control, among which single-leg hop tasks, should be included [4,14,29–31]. Finally, agility, speed, and resistance in a fatigue state should also be assessed [1,4,32–35]. Several studies investigated the reliability of single functional tests in relation to performance differences and future lower extremity injuries [1,4,11,28–30,32,33,35,36]. However, various test–retest reliability designs have been used hitherto and a lack of standardized testing protocols and procedures can be found in the literature [37]. For these reasons, carrying out clinical and methodological comparisons might be quite challenging.

In order to be considered available, believable, and informative, a test battery, along with all the included tests, needs to also be reliable. The tests included in this study are all reliable per se. However, their reliability has not yet been investigated in relation to a sequentially ordered, experimental test battery with evidence-based level design and standardized testing procedures, as was the case in the present study. Test–retest reliability refers to the degree of values similarity between two same repeated measurements under the same conditions on the same individuals [38–48].

Therefore, the main objective of this study was to determine the test–retest reliability of an experimental functional test battery with a seven-day interval. A two-fold secondary objective was to establish whether healthy adults showed a limb symmetry index greater than or equal to 90% and to investigate the presence of significant differences between performances of the two testing sessions (T1 and T2). It was hypothesized that: (1) the test battery should demonstrate at least good reliability coefficients (ICC ≥ 0.75; Cronbach'α ≥ 0.80), and (2) healthy adults should show at least a normal interlimb asymmetry range (LSI ≥ 90%) in all tests performed and should not present significant differences ($p > 0.05$) in performance between the two testing sessions (T1 and T2).

4.3. Material and Methods

4.3.1. Study Design

This study was conducted with a test–retest design, which allowed repeated measures for reliability analysis. A test–retest interval should have adequate time to recover between testing sessions as well as reduce the influence of learning effect and of physical/fitness status changes [34,49]. Two identical testing sessions (T1 and T2) were performed with a seven-day interval time under the same conditions: subjects were tested twice by the same rater (a sports physical therapist with six years of scientific experience in the field); the same indoor laboratory was used for sports therapy purposes; and both sessions were performed in the afternoon. For the sake of consistency, a predefined order of the experimental test battery was applied in both testing sessions, as follows: (1) Y-balance test (YBT); (2) single-leg countermovement jump test (SLCMJ); (3) single-leg hop for distance test (SLH); (4) side hop test (SH); (5) speedy jump test (SJ); (6) agility-T Test (AT); and (7) lower extremity functional test (LEFT). A written informed consent was signed by all subjects and the study was approved by the Ethical Committee of the University (056/2018).

4.3.2. Subjects

Twenty-two healthy adults (8 females and 14 males; age 23.3 ± 3.9) participated in the study. Anthropometrics data are presented in Table 1. Subjects were all volunteers and uninjured collegiate student-athletes from the German Sport University of Cologne. The inclusion criteria for participants were (1) age ranging between 18–30 years and (2) active participation in individual or team sports activity without any restrictions in practices (2–4 x week) or games (1 x week) over the previous twelve months. Additionally, all subjects were not affected by any musculoskeletal disease that could have influenced the results. The exclusion criterion for the study was the presence of a lower extremity major injury (>21 days of absence) over the previous twelve months. All subjects were aware of the potential risks and benefits of the study and complied with the design, protocol, and inclusion criteria; no subject was excluded from the study.

Table 1. Anthropometric data.

	Male (Mean ± SD)	**Female (Mean ± SD)**	**Total (Mean ± SD)**
Number	14	8	22
Age (years)	23.6 ± 2.9	22.8 ± 5.4	23.3 ± 3.9
Mass (kg)	78.4 ± 6.1	65.9 ± 7.3	73.8 ± 8.6
Height (m)	1.80 ± 0.1	1.71 ± 0.1	1.77 ± 0.1
BMI (kg/m^2)	24.1 ± 1.5	22.6 ± 2.3	23.6 ± 1.9
Limb length (cm)	N-Dom 100.9 ± 4.3 Dom 100.9 ± 4.3	N-Dom 97.3 ± 4.9 Dom 97.3 ± 4.7	N-Dom 99.6 ± 4.8 Dom 99.6 ± 4.7

SD = standard deviation; N-Dom = non-dominant leg; Dom = dominant leg; kg = kilograms; m = meters; cm = centimeters; BMI = body mass index.

4.3.3. Procedures

This study was conducted at the Institute of Movement Therapy and Movement-Oriented Prevention and Rehabilitation Science, at the German Sport University of Cologne. Both testing sessions took place during the winter-break in January 2020. Before performing the test battery, all subjects executed a standardized warm-up program including ten minutes of stationary bike at low intensity and five minutes of guided, lower-limb joint mobility. The unilateral tests (YBT, SLCMJ, SLH, SH, and SJ) were executed barefoot on a therapeutic sport mat (FUCHSIUS® multi-media GmbH, Munich, Germany), with the hands necessarily placed on the hips during the entire execution. The bilateral sprint tests (AT and LEFT) were performed on an athletic indoor track and, therefore, subjects were asked to use their own running shoes. All subjects had to wear only sports t-shirt and shorts while performing the test battery. The limb dominance was determined by the leg with which the subjects would kick a ball [50]. In order to familiarize them with the tests, standardized instructions and demonstrations were provided before each test. For the sake of consistency, all subjects were given two practice trials (one per limb) in the unilateral tests and one practice trial in the bilateral sprint tests. Afterward, three maximum valid attempts were performed for each limb in the unilateral tests while two maximum valid attempts were performed in the bilateral tests. A recovery time of 30 s was allowed between practice/valid attempts, while a recovery time of two minutes was applied between each test. In the unilateral tests, the limb to be tested first was randomly selected in order to avoid learning/fatigue effects. The test rater decided in real-time whether the tests were carried out correctly or not. For each test, the best score amongst the valid attempts was used for the data analysis. If no valid attempt was recorded, the subject had to be excluded from the analysis; however, all subjects recorded at least one valid attempt and, therefore, all subjects were included in the analysis. Finally, verbal encouragement and transcription of the scores took place consistently during the two testing measurements (T1 and T2).

4.3.4. Test Battery Standardization and Description

Figure 1 shows the design of the proposed test battery based on the literature. It is divided into four levels: (1) return to activity (RTA); (2) return to sport (RTS); (3) return to play (RTP); and (4) return to competition (RTC). Each level comprises two tests, which are organized from the simplest to the most complex level of difficulty in terms of effort and execution [4,14]. In this context, the following seven tests were selected and included in the present study. The Y-balance test (YBT), a reliable and predictive measure for lower extremity injuries in high school basketball and American football players [28,51], which is also related to chronic ankle instability in normal population [52]. The single-leg countermovement jump test (SLCMJ) is a reliable and appropriate measurement for determining muscle power functions of the lower extremities in healthy or rehabilitated athletes [29] and a useful test for the evaluation of knee function after ACL-reconstruction (ACL-R) [36]. The single-leg hop for distance test (SLH) is a reliable measurement recommended in clinical or sport practice [33]. Additionally, the SLH has proven to be highly valuable in discriminating between injured/uninjured hop performance in patients with an ACL-I/ACL-R [30] and makes it possible to identify competitive athletes at risk for lower back/lower extremity injuries [32]. Furthermore, the SLH is normally used for return-to-sport clearance [4] and has been demonstrated to be a practicable task for the evaluation of knee function after ACL-R [36]. The side-hop test (SH) is a valid and reliable measurement to evaluate knee function after ACL-R [36] and to discriminate between injured/uninjured hop performance in patients with an ACL-I/ACL-R [30]. The speedy-jump test (SJ) is a reliable tool in identifying functional deficits of the knee in clinical environments [1] and to assist the rehabilitation process after ACL-R [11]. The agility T-test (AT) is recommended in clinical and sport practice [33] and is a reliable measurement in determining low or high levels of sports participation in college athletes [35]. The lower extremity functional test (LEFT) is a reliable measurement in identifying competitive athletes at risk for lower back/lower extremity injuries [32]. In the present study, the first level comprised only one test because the step-down test was not performed and not included in the reliability analysis, since it does not provide any quantitative performance data as it is usually used to analyze the quality of movement [53].

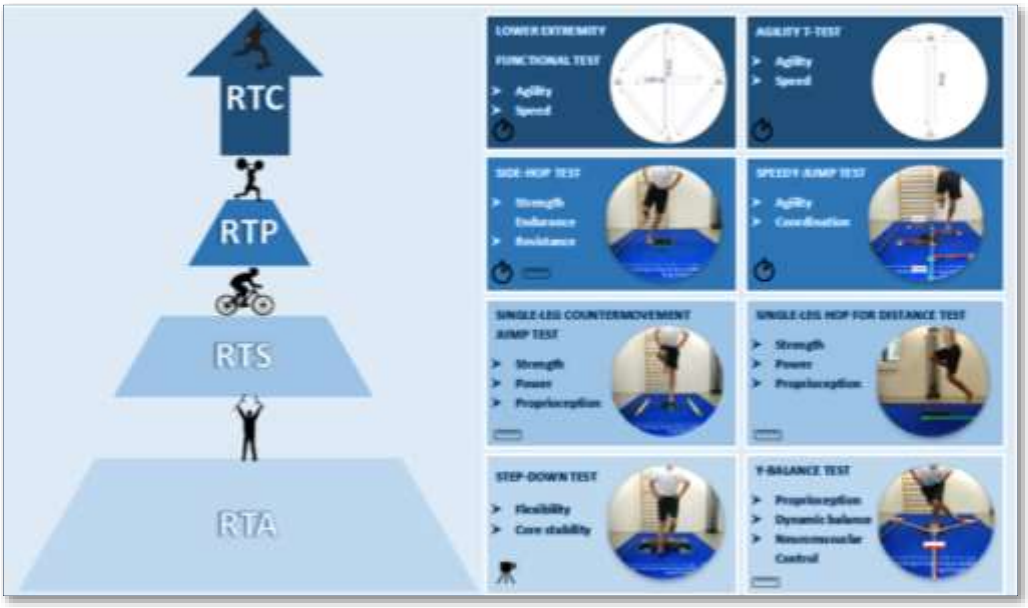

Figure 1. Design of the proposed test battery. Legend for symbols: the camera indicates that only a qualitative analysis of movement is possible (video recording); the meter indicates that a quantitative analysis of the performance can be made (numerical, e.g., in centimeters); the stopwatch indicates that a quantitative analysis of the performance can be made (numerical, e.g., in seconds).

4.3.4.1. Step-Down Test (SD)

According to Park et al., the SD test is performed without shoes and the starting position is on a 20 cm high step. Subjects stand upright on one leg with the toes of the standing leg close to the edge of the step. The free leg is extended in front of the step with the ankle in maximum dorsiflexion. With as much control as possible, subjects are asked to bend the knee of the standing leg until the heel of the extended leg touches the floor and then immediately return to the starting position. During the test execution, the following criteria should be used to mark invalid attempts: single-leg balance is not fully maintained, the trunk is not kept straight, the standing leg does not remain in contact with the step with the whole foot and the hands do not remain fixed at the hips. Subjects have one trial attempt and one valid attempt per leg [53].

4.3.4.2. Y-Balance Test (YBT)

The YBT is a valid, reliable test to assess postural control and balance capacities [4,14,28]. The Y-Balance Test Kit (Move2Perform®, Evansville, IN, USA) was utilized. The subjects started in a standing position on one leg, with the toes of the standing leg positioned at the red line marked on the central platform of the instrument. The sliding elements had to be pushed with the toes of the contralateral leg as far as possible in three directions (anterior, posteromedial, and posterolateral). For correct execution, the standing leg keeps a full stance on the platform and the contralateral leg keeps constant contact with the sliding elements. After that, subjects had to return to the starting point and keep the final balancing position (on one leg) for three seconds (measured with a stopwatch) to be considered as a valid attempt. The following criteria were used to mark invalid attempts: leaving the arms from the hips, loss of balance, contact of the contralateral leg with the ground, lifting up the heel of the standing leg, kicking the sliding element or standing on top of it. For the normalization of the scores, the limb length had to be measured [28]. The performance was then computed as a "composite score" in percentage using this predetermined formula: composite score = (anterior + posteromedial + posterolateral performances in cm) / 3 x limb length in cm) x 100 [28].

4.3.4.3. Single-Leg Countermovement Jump Test (SLCMJ)

The SLCMJ is a valid and reliable test that measures proprioception and neuromuscular control abilities [4,30]. The OptoJump Kit (Version 1.12.1.0—Microgate®, Bolzano, Italy) was utilized. The subjects started in a standing position on one leg, performed a countermovement flexion with the standing leg and then explosively jumped as high as possible [54]. To be considered as a valid attempt, the landing with the same leg had to be maintained stable for three seconds (measured with a stopwatch). The following criteria were used to mark invalid attempts: leaving the arms from the hips, multiple jumps while landing, flexing the jumping leg during the flight phase, a contact with the ground or a swing of the contralateral leg. The vertical jumped height was then measured in centimeters (cm) by using the OptoJump software.

4.3.4.4. Single Leg Hop for Distance Test (SLH)

The SLH is a valid and reliable test useful to assess muscle strength and power deficits [4,49]. The subjects started in a standing position on one leg, with the toes positioned at the starting line marked on the therapeutic mat. The subjects had to jump as far as possible, landing on the same leg. The landing had to be maintained stable for three seconds (measured with a stopwatch), otherwise, the attempt was marked as invalid. The following criteria were used to mark invalid attempts: leaving the arms from the hips, a swing of the contralateral leg, using the contralateral leg as a support, loss of balance or multiple jumps at landing. The jumped distance was then measured in centimeters (cm) with a measuring tape, from the starting line marked on the mat (jump take-off) to the heel of the subjects where the landing took place [54].

4.3.4.5. Side-Hop Test (SH)

The SH is a valid and reliable test to assess strength resistance under fatigue state through controlled, fast, and repetitive lateral jumps [29,30]. The subjects started in a standing position on one leg with their hands on the hips, jumping sideways over two parallel lines (40 cm apart) painted on the therapeutic mat. Subjects performed as many jumps as possible in 30 s, recorded using a stopwatch. After the last jump, a controlled landing had to be maintained for three seconds (measured with a stopwatch), otherwise the attempt was marked as invalid. The following criteria were used to mark invalid attempts: jumping on the painted line whit the tested leg, performing extra/double jumps, supporting of the contra-lateral leg, or leaving the arms from the hips [4,29,30]. The number of successful jumps (score = total jumps ⍰ error jumps) were counted live by the test leader.

4.3.4.6. Speedy-Jump Test (SJ)

The SJ is a valid and reliable test to estimate power, dynamic knee stability, and coordination of the lower extremities while jumping as fast as possible through different plane directions [1]. A predetermined Speedy Basic Jump Set (TST—Trendsport®, Grosshöflein, Austria) was utilized. Subjects started in a standing position on one leg. The subjects executed three jumps on each of the four red bars (jumping forward, backward, and forward) and one jump on each of the four blue bars (jumping sideway), performing sixteen jumps in total [1]. After the last jump, a controlled landing with the same leg had to be maintained for three seconds (measured with a stopwatch), otherwise the attempt was marked as invalid. The following criteria were used to mark invalid attempts: leaving the arms from the hips, a contact with the test instrument and a swing or ground support with the contralateral leg. The execution time was computed in seconds (s) with a stopwatch, from the moment of the first jump (take-off phase) to the moment of the last jump (landing).

4.3.4.7. Agility T-Test (AT)

The AT (Figure 2) is a valid and reliable test for the measurement of agility and change of direction speed by maximum start, side steps, and running backwards [4,33,35,55,56]. The layout is a combination of four cones in T-shape (5 m x 5 m). Subjects started in a standing position behind the starting point at cone A. After the start signal, subjects sprinted to cone B, touching it with their right hand. Then, they performed a side-shuffle to the left to cone C, touching it with their left hand. Next, they performed a side-shuffle to the right to cone D, touching it with their right hand. Then, they performed a side-shuffle to cone B, touching it with their left hand. After that, they performed a backward run to cone A. Attempts were considered invalid if the subjects did not touch the cones, performed the side-shuffle crossing their legs or did not face forward while sprinting or side-shuffling [4,33,35,55,56]. The execution time was computed in seconds (s) with a stopwatch, from the moment of the first sprint as soon as subjects left cone A to the moment of the last sprint as soon as subjects passed cone A.

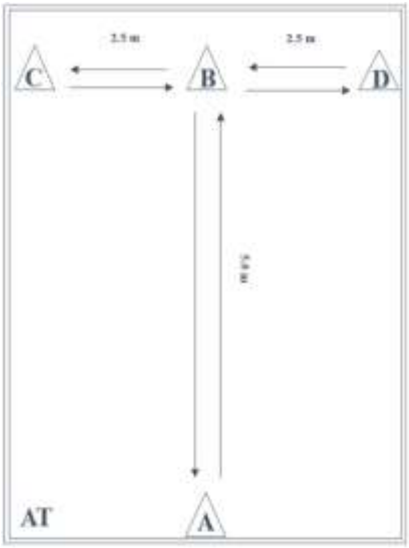

Figure 2. Schematic representation of the agility *T*-test (AT).

4.3.4.8. Lower Extremity Functional Test (LEFT)

The LEFT (Figure 3) is a reliable and valid test for the measurement of athletic fitness, fatigue resistance, and speed by performing a series of 16 specific maneuvers as fast as possible (including forward and backward sprinting, sidestepping, cross-stepping, 45° and 90° cutting) [4,32,34,55]. The layout is a combination of four cones in a diamond-shape (9.14 m x 3.05 m). Test execution was performed in accordance with previously described methods [4,32]. Subjects started in an upright standing position with both feet behind the starting point at cone A. On the command of the instructor, the subjects performed eight different agility tasks, with each task being performed twice (once to the right and once to the left direction). Because of the multidirectional requirements of the test and variety of tasks to be performed, verbal instruction of subsequent movements was provided throughout the test. As such, subjects were required to respond to the external stimuli. Attempts were considered invalid if participants failed to perform the designated maneuvers or dropped a cone by contact. The execution time was computed in seconds (s) with a stopwatch, from the moment of the first sprint after the starting signal as soon as the subjects left cone A to the moment of the last sprint as soon as the subjects passed cone A.

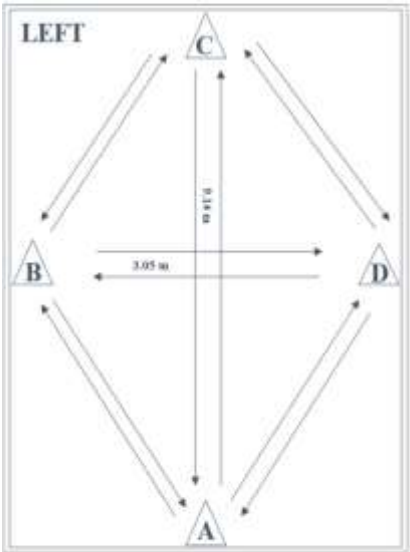

Figure 3. Schematic representation of the lower extremity functional test (LEFT).

4.3.5. Test–Retest Reliability

The main measures of reliability are the intraclass correlation coefficient (ICC) and Cronbach's alpha coefficient (α), which were both considered in the present study. The higher the correlation coefficients, the greater the reliability of measurements [38]. The ICC and Cronbach's α are coefficients ranging from 0 to 1: in general, good coefficients magnitudes (ICC ≥ 0.75; Cronbach's α ≥ 0.80) are required for a measurement to be considered reliable, while excellent coefficients magnitudes (ICC ≥ 0.90; Cronbach's α ≥ 0.90) indicate a highly reliable measurement [26,39–42]. Other adaptable parameters could affect the reliability results and were also considered in the present study, such as sample size heterogeneity, within-subject variations, systematic changes in mean and measurement errors [42,43]. Additionally, attention should be paid to the span of time between the two test measurements as much as to the motor learning effect of the subjects [44–47]; therefore, both aspects were considered in the present study in order to reduce their influence on the test–retest results. Conversely, gender and sport type seem to have no influence on reliability results, which is why these were not considered in the present study [44–47]. Various interval times between the test–retest measurements have been used hitherto in the literature, ranging from ten-minute to one-month intervals. Nevertheless, the most used intervals ranged from two days to two weeks [38,48]. In the present study, a seven-day interval was chosen in order to ensure that participants had sufficient time for recovery between sessions and, at the same time, not too long to be able to produce changes in performance related to training. In addition, between the two testing sessions, participants were explicitly asked to avoid practicing the test battery and were allowed to solely perform their usual sports training.

4.3.6. Statistical Analysis

SPSS for Windows Version 26.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses, significance was set at $p < 0.05$ while the limits of agreement were set at a 95% confidence interval (CI 95%). Normality of data was evaluated by the Shapiro–Wilk Test while homogeneity of variance was established with the Levene's test. Descriptive statistics of anthropometrics were calculated by means and standard deviations (± SD). For each test, mean values and standard deviations (± SD) were calculated from the valid attempt performed with the best score. For the unilateral tests (YBT, SLCMJ, SLH, SH, and SJ), mean values, and standard deviations (± SD) were calculated on three variables: dominant limb, non-dominant limb, and limb symmetry index (LSI). The LSI was calculated using the proposed formula [LSI = (non-dominant/dominant) * 100] for the uninjured population [15,57]. For the bilateral sprint tests (AT and LEFT), mean values, and standard deviations (± SD) were calculated using performance scores on one variable. The tests were analyzed in relation to the following dependent variables: Y-balance test (YBT), dominant/non-dominant composite score (%), and LSI (%); single-leg countermovement jump test (SLCMJ), dominant/non-dominant vertical jumped height (centimeter) and LSI (%); single-leg hop for distance test (SLH), dominant/non-dominant horizontal jumped length (centimeter) and LSI (%); side-hop test (SH), dominant/non-dominant number of jumps (number of jumps) and LSI (%); speedy-jump test (SJ), dominant/non-dominant time of execution (seconds) and LSI (%); agility *T*-test (AT), time of execution (seconds); lower extremity functional test (LEFT), time of execution (seconds). To determine the test–retest reliability of the dependent variables, the intraclass correlation coefficient (ICC) for the reproducibility of quantitative measurements and Cronbach's alpha (α) for the internal consistency were used. The ICC for the single measures was solely considered since the ratings were performed by a single rater. However, other parameters affect the reliability analysis and were therefore included in this study: the coefficient of variation (CV) for the extent of variability, defined as the ratio of the SD to the mean (CV = SD/Mean × 100); the standard error of measurement (SEM) for the effect of measurement error, defined as the SD of an individual's repeated measurements (SEM = SD × √1 − ICC); the smallest real difference (SRD), defined as a measure of sensitivity to change (SRD = 1.96 × √2 × SEM) [42,43]. To assess the magnitude of the reliability analysis, the threshold values were considered as follows: poor (<0.5), moderate (0.50–0.75), good (0.75–0.90), and excellent (>0.90) for the ICC [44]; unacceptable (<0.5), poor (0.5–0.6), questionable (0.6–0.7), acceptable (0.7–0.8), good (0.8–0.9), and excellent (>0.90) for the Cronbach's α [45]; not acceptable (>30), acceptable (20–30), good (10–20) and very good (<10) for the CV [46]; perfectly reliable (equal to 0) and completely unreliable (equal to the SD) for the SEM [46]; acceptable (<30%) for the SRD [47]. Finally, for the analysis of variance of the dependent variables, repeated measures ANOVA ($p < 0.05$) was used separately to compare differences in mean scores between the two testing sessions (T1 and T2). Repeated measures ANOVA was chosen to compare three quantitative dependent variables (dominant, non-dominant and LSI) on the same samples divided per age groups (from U11 to U19), in each of the test performed (except for LEFT and AT, where only one variable was analyzed). It was assumed that the means would have been identical between the two test sessions (T1 and T2). To this end, the within-subjects effect was considered and preferred over the between-subjects effect, since the variances to be analyzed definitely concerned the same subjects, the same leg and the same test, but on two different test occasions across time (T1 and T2).

4.4. Results

The results of the test battery are shown in Table 2. The Shapiro–Wilk test revealed that all data were normally distributed ($p > 0.05$) and the Levene's test revealed the homogeneity of variance ($p > 0.05$). As far as reliability analysis is concerned, the intraclass correlation coefficients (ICC) of dominant limbs ranged from good 0.89 (YBT) to excellent 0.97 (SJ) while Cronbach's α coefficients maintained an excellent range from 0.92 (YBT) to 0.98 (SJ); the intraclass correlation coefficients (ICC) of non-dominant limbs ranged from moderate 0.71 (YBT) to excellent 0.96 (SJ) while the Cronbach's α coefficients ranged from good 0.80 (YBT) to excellent 0.98 (SJ); the intraclass correlation coefficients (ICC) of the LSI ranged from poor 0.41 (SH) to good 0.76 (SLCMJ) while the Cronbach's α coefficients ranged from poor 0.50 (SH) to good 0.83 (SLCMJ). Nevertheless, the test battery showed on average good-to-excellent intraclass correlation coefficients ($0.89 < ICC < 0.97$) for all tests, except for the YBT (N-Dom 0.71; LSI 0.62), SLCMJ (LSI 0.76), SLH (LSI 0.73), SH (LSI 0.41), and SJ (LSI 0.67) tests. In addition, the test battery showed on average good-to-excellent Cronbach's α coefficients ($0.80 < \alpha < 0.98$) for all tests, except for the YBT (LSI 0.70), SH (LSI 0.50), and SJ (LSI 0.74) tests.

Table 2. Results of the test battery.

Test	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	ANOVA (*p* < 0.05)	Cronbach's Alpha (α)	ICC (95% CI)	CV	SEM	SRD
YBT (cs)								
Dom	86.8 ± 4.7	87.4 ± 4.1	0.273	0.92	0.89 (0.86–0.92)	5.05	1.46	4.03
N-Dom	85.8 ± 4.6	87.2 ± 3.5	0.081	0.80	0.71 (0.62–0.80)	4.74	2.21	6.11
LSI (%)	99.0 ± 5.6	99.9 ± 4.6	0.393	0.70	0.62 (0.53–0.70)	5.13	3.14	8.68
SLCMJ (cm)								
Dom	15.5 ± 4.3	15.8 ± 4.2	0.380	0.96	0.95 (0.93–0.96)	26.92	0.94	2.60
N-Dom	15.5 ± 4.5	16.2 ± 4.1	0.078	0.95	0.93 (0.90–0.95)	27.04	1.14	3.15
LSI (%)	101.3 ± 14.1	104.4 ± 12.5	0.164	0.83	0.76 (0.70–0.82)	12.94	6.52	18.02
SLH (cm)								
Dom	139.6 ± 24.2	143.5 ± 23.3	0.071	0.96	0.93 (0.91–0.95)	16.68	6.24	17.24
N-Dom	134.0 ± 25.0	139.4 ± 23.8	0.015 *	0.96	0.93 (0.90–0.95)	17.78	6.45	17.83
LSI (%)	95.9 ± 6.7	97.2 ± 6.9	0.289	0.80	0.73 (0.66–0.80)	7.04	3.53	9.76
SH (no.)								
Dom	54.7 ± 15.2	57.3 ± 13.0	0.116	0.94	0.90 (0.85–0.92)	25.00	4.46	12.33
N-Dom	54.9 ± 11.0	58.0 ± 11.6	0.007 *	0.95	0.92 (0.90–0.94)	19.87	3.19	8.82
LSI (%)	108.6 ± 45.3	102.3 ± 9.8	0.447	0.50	0.41 (0.31–0.50)	30.90	25.04	69.20
SJ (s)								
Dom	7.9 ± 1.7	7.7 ± 2.1	0.180	0.98	0.97 (0.96–0.98)	24.36	0.33	0.91
N-Dom	8.3 ± 2.8	7.8 ± 2.4	0.011 *	0.98	0.96 (0.95–0.97)	32.50	0.52	1.44
LSI (%)	103.4 ± 13.8	100.7 ± 8.3	0.246	0.74	0.67 (0.60–0.73)	11.17	6.54	18.07
AT (s)	11.6 ± 1.2	11.7 ± 1.0	0.528	0.96	0.95 (0.93–0.96)	9.40	0.25	0.69
LEFT (s)	110.8 ± 11.4	107.7 ± 10.3	0.009 *	0.94	0.90 (0.86–0.92)	9.97	3.45	9.53

Dom = dominant leg; N-Dom = non-dominant leg; LSI = limb symmetry index; SD = standard deviation; cs = composite score; cm = centimeter; no. = number; s = seconds; ICC = intraclass correlation coefficient; CV = coefficient of variation; SEM = standard error of measurement; SRD = smallest real difference; YBT = Y-Balance Test; SLCMJ = Single-Leg Countermovement Jump Test; SLH = Single-Leg Hop for Distance test; SH = Side-Hop Test; SJ = Speedy-Jump Test; AT = Agility *T*-Test; LEFT = Lower Extremity Functional Test. * = significant difference in performance between testing sessions; ICC values in parenthesis are 95% confidence interval.

Coefficients of variations (CV) ranged from good (YBT, 5.05%) to acceptable (SLCMJ, 26.92%) for the dominant limbs, from good (YBT, 4.74%) to not acceptable (SJ, 32.50%) for the non-dominant limbs and from good (YBT, 5.13%) to not acceptable (SH, 30.90%) for the LSI. The SJ (N-Dom, CV 32.50%) and SH (LSI, CV 30.90%) were the only tests reporting not acceptable variability. Standard errors of measurement (SEM) ranged from 0.33 (SJ) to 6.24 (SLH) for the dominant limbs from 0.52 (SJ) to 6.45 (SLH) for the non-dominant limbs and from 3.14 (YBT) to 25.04 (SH) for the LSI. Nevertheless, the most reliable value was recorded in the AT (SEM 0.25). Smallest real differences (SRD) ranged from 0.91 (SJ) to 17.24 (SLH) for the dominant limbs, from 1.44 (SJ) to 17.83 (SLH) for the non-dominant limbs and from 8.68 (YBT) to 69.20 (SH) for the LSI. All SRD values complied with the range of acceptability (SRD < 30%) except for the SH (LSI, SRD 69.20), which was considered not acceptable. Nevertheless, the best SRD value was recorded in the AT (0.69). As for the inter-limb asymmetries, the LSI showed a value greater than or equal to 90% (LSI ≥ 90%) for all tests in both testing sessions (T1 and T2). Average LSI ranged from 95.9 ± 6.7% (SLH) to 108.6 ± 45.3% (SH) in the first testing session (T1) and from 97.2 ± 6.9% (SLH) to 104.4 ± 12.5% (SLCMJ) in the second testing session (T2). Repeated measures ANOVA showed no significant differences ($p > 0.05$) for the LSI between the two testing sessions (T1 vs. T2). Concerning the comparisons of variances, repeated measures ANOVA showed some differences in unilateral/bilateral performance between the two testing sessions (T1 vs. T2): significant results were found for the SLH (N-Dom $p = 0.015$), SH (N-Dom $p = 0.007$), SJ (N-Dom $p = 0.011$), and LEFT ($p = 0.009$) tests. This indicates that subjects performed significantly greater with their non-dominant limb for the SLH, SH, and SJ tests while subjects performed significantly faster for the LEFT in the second testing session (T2) compared to the first testing session (T1).

4.5. Discussion

The main aim of this study was to assess test–retest reliability within a seven-day interval of an experimental test battery for the measurements of functional performance. A two-fold secondary aim was (1) to determine whether limb symmetry indices were greater than or equal to 90% (LSI ≥ 90%) in both testing sessions (T1 and T2) and (2) to establish the presence of significant performance differences between the two testing sessions (T1 vs. T2). It was hypothesized that the reliability analysis should demonstrate at least good ICC (ICC ≥ 0.75) and good Cronbach's α (α ≥ 0.80) coefficients. The results of this study confirmed our main hypothesis, demonstrating on average a good-to-excellent test–retest reliability (0.89 < ICC < 0.97; 0.80 < α < 0.98) for the proposed functional test battery. Nevertheless, as far as the following tests are concerned, the only exceptions were observed in single dependent variables, which failed to meet the expected criteria and demonstrated a poor-to-acceptable reliability: the ICC for N-Dom in the YBT (0.71); the ICC for LSI in the YBT (0.62), SLCMJ (0.76), SLH (0.73), SH (0.41), SJ (0.67) tests, and Cronbach's alpha for LSI in the YBT (0.70), SH (0.50), and SJ (0.74) tests. A high reliability in the assessment of performance variables was necessary to make sound conclusions for sports injury research [41,58]. In clinical sports practice, it is essential to use reliable and objective measurements in order to conduct pre-injury screenings and monitor the rehabilitation process. The findings of the present study partially agree with those of previous research that have already investigated the reliability of different test batteries and single functional tests. The YBT test proved to have good intra-rater reliability (ICC 0.89) and excellent interrater reliability (ICC: right leg 0.99, left leg 0.97) in male collegiate football players [27]. However, the latter research used a different design compared to the one adopted in the present study, namely an observation with multiple raters within a 20-min test–retest interval, with free arms during the entire YBT execution [27]. Our results in the YBT were slightly lower and showed moderate-to-good reliability (ICC: Dom 0.89, N-Dom 0.71). Nevertheless, the present study did not consider the inter-rater reliability nor such a short test–retest interval time and the YBT was executed with the arms fixed to the hips so as to prevent them from affecting the scores. Thus, the little discrepancy in the results might be associated with the differences in terms of methods used for reliability and test execution. In particular, it could be argued that a shorter test–retest time interval and the use of the arms during execution leads to higher reliability results for the YBT. Therefore, it seems that these latter aspects play a critical role for achieving greater reliability for the YBT and it is necessary to determine which method is the most valid. A hop test battery proved to have good-to-excellent test-retest reliability (0.85 < ICC < 0.97) in ACL-injured and reconstructed athletes as a tool to discriminate between injured and uninjured limb power performances [30]. In particular, the SLCMJ (ICC 0.89) and SH (ICC 0.87) showed good reliability while the SLH (ICC 0.94) showed excellent reliability [30]. However, although the latter research used one-rater observation and performed identical test executions for the three hop tests as in the present study, a larger test–retest design was used (3–13 days interval) [30]. Our findings were slightly higher and show excellent reliability for the same hop tests: SLCMJ (ICC: Dom 0.95, N-Dom 0.93), SLH (ICC: Dom 0.93, N-Dom 0.93), and SH (ICC: Dom 0.90, N-Dom 0.92). In this specific case, study design seems to be the most relevant aspect and a shorter test–retest time interval seems to guarantee higher reliability results for the same hop tests when executed in the same way. Another hop test battery proved to have a good-to-excellent test-retest reliability (0.84 < ICC < 0.98) and could be recommended for determining power function in healthy athletes and in the rehabilitation process [29]. More specifically, the SLCMJ (ICC: Right Leg 0.98, Left Leg 0.98) and SLH (ICC: Right Leg 0.97, Left Leg 0.97) showed excellent reliability while the SH (ICC: Right Leg 0.84, Left Leg 0.96) showed good-to-excellent reliability [29]. Our excellent reliability results for the same hop tests almost entirely agreed with those achieved by Kockum and Heijne [29], which used identical test execution for all hop tests and one-rater observation as in the present study, as much as a similar test–retest time interval of 7–10 days. Thus, it seems clear that the more similar the test–retest time intervals of two different studies are, the closer the reliability results for the same hop tests will be, provided that these are carried out with identical test execution. Interestingly, a further functional test battery proved to have a good-to-excellent test–retest reliability (0.84 < ICC < 0.98) in uninjured and non-competitive participants as an assessment tool for decision-making on returning to sport after ACL-I [1]. Hildebrandt et al. showed good test–retest reliability (ICC: Dom 0.79, N-Dom 0.83) for the SJ using a different test execution (free arms), a shorter test–retest design (five-day interval), and the same one-rater observation compared to our study [1]. However, although a shorter test–retest time interval might guarantee higher reliability results for two different studies that assess the same hop test, the latter study showed the opposite trend: in fact, Hildebrandt et al. showed lower reliability results for the SJ compared to the current study, which demonstrated excellent test–retest reliability (ICC: Dom 0.97, N-Dom 0.96) and had a larger test–retest design (seven-day interval). Now, it could be claimed that a larger time interval (seven days) for the test–retest design is more appropriate than a shorter one (five days) to achieve higher reliability results between two different studies that use the same hop test. Seven days could be a valid solution, which is not too long nor too short for the learning effect to affect the results [38,48]. However, Hildebrandt et al. performed the SJ with free arms and not with the hands placed on the hips as in our study, and this difference in test execution might have led to the discrepancy in the results between the two studies. All in all, the current study revealed the same good-to-excellent test–retest reliability (0.89 < ICC < 0.97) in comparison with the three test batteries mentioned hitherto [1,29,30]. However, these batteries did not contain all the tests included in the present study and carrying out a methodologically comprehensive comparison for the entire test battery remains a challenge. The sprint tests included in this study demonstrated excellent test–retest reliability (ICC: AT, 0.95; LEFT, 0.90). Sprint tests have been shown to have excellent test–retest reliability as reported in the literature. The AT proved excellent test–retest reliability (ICC 0.96) in measuring speed and agility in collegiate men and women [35]. Nevertheless, even though Pauole et al. used the same one-rater observation as in the present study, the test–retest design used was between-trial reliability analysis (three trials) [35]. A further study showed a good-to-excellent test–retest reliability for the AT (ICC 0.82–0.96) in recreational athletes using the same test–retest design compared to our study, with a seven-day time interval and one-rater observation, but in three different testing sessions [33]. A multicentre study showed excellent reliability for the LEFT (ICC 0.96) in a student-athlete population by using identical test execution, the same test–retest time interval (seven days), and different observation with multiple raters in three testing sessions compared to our study [34]. Despite this, the divergence of the test–retest designs used in the above-mentioned studies does not seem to have affected the similarity of outcomes with the present study, by using the same test execution. Therefore, although the reliability designs were different, it seems that separate studies can achieve the same reliability results for sprint tests provided that the tests are executed in the same way. In a nutshell, each of the tests in question proved to be highly reliable and their use in clinical sports practice combined in a test battery is highly recommended by the authors of this study. In fact, the current study proposed an experimental test battery for sports therapy, prevention, and rehabilitation purposes with a precise structure: five different unilateral tests including one for dynamic balance (YBT) and four hop tests for power functions in different plane directions (SLCMJ, SLH, SH, and SJ), which should be complemented with two sprint tests with changes of direction, one for agility (AT), and one for speed (LEFT). Furthermore, the present study attempts to fill the gap in the literature by using a specific population, a fixed test sequence, and standardized execution as well as a precise test–retest design (seven-day interval, one rater). First, it was hypothesized that the participants involved in the present study should express a normal inter-limb symmetry range (LSI ≥ 90%) in both testing sessions (T1 and T2) as they represented an uninjured population. The results of this study confirmed our hypothesis. In fact, minimum to maximum LSI scores ranged from 95.9 ± 6.7% (SLH) to 108.6 ± 45.3% (SH) in the first testing session (T1), while from 97.2 ± 6.9% (SLH) to 104.4 ± 12.5% (SLCMJ) in the second testing session (T2). Although the LSI did not confirm our initial hypothesis for reliability, all tests showed at least moderate-to-acceptable coefficients, except for the SH test, which showed poor coefficients. For instance, the ICC for the LSI showed good reliability in the SLCMJ (0.76) test, moderate reliability in the YBT (0.62), SLH (0.73), and SJ (0.67) tests, while poor reliability in the SH (0.41) test. However, no significant differences ($p > 0.05$) were found for the LSI between the two testing sessions (T1 vs. T2), suggesting that learning effect did not have any influence on the LSI scores of two consecutive testing sessions, albeit without excellent reliability coefficients. In general, it is suggested that uninjured subjects should not exhibit inter-limb differences greater than or equal to 10% (LSI ≥ 90%) when performing functional performance tests, despite the presence of a less/more performant limb [20,21,50,59,60]. In contrast, the findings of our study advocate higher LSI ≥ 95% as the benchmark in healthy adults, indicating that the commonly accepted benchmark of LSI ≥ 90% used in clinical practice for an uninjured population may be too low. Another interesting aspect to consider is that, in the case of a dominant and operated leg, the LSI should reach a minimum of 100% to a maximum of 110% after rehabilitation [20,21,50,59,60]. However, these benchmarks (LSI 100–110%) for injured population (dominant, operated leg) were not achieved by the healthy participants included in the present study. Hence, this factor should be deeply investigated in future research. Second, it was hypothesized that subjects should not exhibit significant differences ($p > 0.05$) in performance between the two testing sessions (T1 vs. T2). The results of this study confirmed our hypothesis. Differences were only found for single dependent variables (SLH, N-Dom, $p = 0.015$; SH, N-Dom, $p = 0.007$; SJ, N-Dom, $p = 0.011$; LEFT, $p = 0.009$), indicating that subjects performed significantly higher with their non-dominant limb (SLH, SH and SJ) and executed significantly faster (LEFT) in the second testing session (T2) compared to the first testing session (T1). The learning effect seems to have influenced the performance of the non-dominant limbs for the SLH, SH, and SJ tests in the second testing session (T2). This could be explained by the fact that optimal performance was achieved with the dominant limbs during the first testing session (T1) and was maintained stable during the second testing session (T2) for all of the tests performed. Nevertheless, performance achievements were sub-optimal during the first testing session (T1) for the nondominant limbs and significant ($p < 0.05$) increases in performance have occurred during the second testing session (T2) for the SLH, SH, and SJ tests. Furthermore, the complexity of the execution of the LEFT seems to have played a key role in the scores obtained; plus, the learning effect seems to have led to a greater performance of the LEFT in the second testing session (T2) as subjects might have executed it faster due to their increased familiarity of the LEFT execution. However, although performance increases did occur in these tests during the second testing session (T2), the rationale remains unexplored. Therefore, the authors of the present study recommend considering the possibility of multiple tests with seven-day intervals when carrying out preventive or rehabilitative screening in clinical sports practice. This could be useful to better evaluate those tests that might be affected to a greater extent by the learning effect.

4.5.1 Limitations
This study has four limitations. First, subjects were tested at a specific time of the sporting season (winter break) and they were a mixed (male and female), uninjured collegiate student-athletes' population with a large age range (18–30 years). Additionally, subjects came from both team and individual sports and none competed at a professional level but were all involved at a competitive and regional level. Second, the influence of growth and maturation status, practiced sport, and gender on the test results was not considered. Third, the between-session reliability with one rater was the only type of analysis considered, while intra-rater and interrater reliability analyses were not. Fourth, the proposed baseline values refer to a small number of participants and our results can only be applied to a population of healthy adults.

4.6. Conclusions
The experimental test-battery proposed in this study appears to be highly reliable (ICC ≥ 0.75; Cronbach's α ≥ 0.80) for the measurements of functional performance in healthy adults. Thus, the implementation of its standardized test protocol in sports clinical practice is strongly recommended by the authors for prevention and rehabilitation purposes. Furthermore, if performed on an uninjured population, a normal inter-limb symmetry range (LSI ≥ 90%) can be expected for all unilateral tests. The findings also suggest that the benchmark for clinical practice can be set at LSI ≥ 95%. However, subjects performed significantly greater in three hop tests with the non-dominant limb (SLH, p 0.015; SH, p 0.007; SJ, p 0.011) and performed significantly faster in one sprint test (LEFT, p 0.009) in the second testing session compared to the first testing session. Therefore, an improvement in performance due to the learning effect can be expected in these specific tests and future studies should provide a more in-depth analysis of these aspects.

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4.7. References

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5. Study Nr. 2: Functional performance and interlimb asymmetries of young football players during single-leg jump tests

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5.1. Abstract

Background: Jumps are predominant components in football (soccer). Interlimb functional difference in single-leg jump performance is a risk factor for lower extremities injuries. Screening uninjured athletes is essential to design prevention strategies and implement individual training interventions. The aims of this cross-sectional study were (1) to provide age-specific mean values and limb symmetry index (LSI) in young football players, (2) to detect age effect on LSI and interlimb functional differences and (3) to investigate the association of age with single-leg functional performance and LSI.

Methods: A total of 146 male football players (age 14.2 ± 2.3) performed the countermovement jump, jump for distance, side hop and speedy jump tests. Descriptive statistics, mean values (dominant/nondominant) and LSI were provided according to age groups (U11–U19). Two-way mixed analysis of variance (ANOVA), one-way ANOVA
and Pearson's correlation were used for the statistical analysis.

Results: Participants showed on average perfect LSI (103.8% ± 14.2%) amongst all tests and age groups. Interlimb functional differences occurred in three out of four tests ($p<0.05$), without age interaction ($p>0.05$). Age effect was positively associated with single-leg functional performance ($p<0.05$), but not with LSI ($p>0.05$), in all tests and age groups.

Conclusion: An LSI ≥100% in single-leg jump tests is proposed as a benchmark in young football players, but interlimb performance differences may occur without age interaction. Nevertheless, the growth process plays a crucial role in the development of functional capacities: older players may show a higher single-leg jump performance, but not a higher LSI, than younger players. In football practice, preventive intervention is advisable to counteract interlimb performance differences, for which unilateral strength, power and plyometric training is recommended.

Keywords: Anterior cruciate ligament injury risk; Hop test; Injury prevention; Symmetry index; Test battery

5.2. Introduction

5.2.1. Injury epidemiology in football

Football is one of the most popular sports worldwide, both at professional and amateur level. In Germany, more than about five-hundred thousand young players between 15-18 years old are registered with clubs and regularly participate in training and matches [11]. Sports participation leads to positive effects on children's and adolescents' health, education and behaviors [13], but it cannot be overlooked that football also owns the highest injury incidence (47.4%) among participants below 19 years old [28]. In particular, 10-37% are severe injuries [12]. Football participation represents an extrinsic risk factor for long-term and growth-related knee injuries in young players, such as anterior cruciate ligament (ACL) injuries [7]. ACL rupture is one of the most unfavorable non-contact knee joint injuries that affects the development of sport athletes and their future careers in Europe [38]. Furthermore, ACL injuries are highly frequent in young athletes ≤ 18 years [43]. In professional football, 88% of all ACL injuries occur without direct knee contact [10] due to a combination of mechanisms such as femoral adduction, knee abduction and ankle eversion that contributes to dynamic knee valgus [23]. These mechanisms especially occur during common movements in football such as one-leg landing after a jump or during fast change of direction [49], key actions repeated by the players a multitude of times during matches or training sessions [39], which require greater amount of unilateral strength and power production for optimal performance [47].

5.2.2. Interlimb asymmetries

The limb symmetry index (LSI) is usually defined as the ratio between the injured limb score and the uninjured limb score expressed in percentage [LSI = (injured/uninjured) *100)] and can support injury rehabilitation and the return to sports. Generally, an LSI ≥ 90% cut-off criterion is used to determine whether an interlimb difference can be classified as normal [18]. However, the LSI can be also used as a screening tool in uninjured athletes [3], obtained by dividing the non-dominant by the dominant limb scores expressed in percentage [(LSI = (non-dominant/dominant) *100] [3,30]. Athletes who practice professional or amateur sports with a perpetual dominance of one leg during training or competition (i.e. Football), could develop significant asymmetry between dominant and non-dominant legs in terms of muscular strength and power [1,47]. Leg asymmetry in strength and power is used to assess the risk of hamstring injury in elite sports [5]. The normalization of strength, power and flexibility imbalances may significantly reduce the incidence of hamstring injuries [41]. In addition, several studies already pointed out that young players may have higher interlimb asymmetries in single-leg jump tests and consequently higher risk of lower extremities injuries to the knee and ankle joints [18,21,35,45].

5.2.3. Functional jump tests

Physical performance tests (PTTs) including components of sport-specific function (e.g. power), can be useful to measure quantitative differences between dominant/non-dominant leg and to detect interlimb asymmetries (LSI), besides to determine readiness for return to sport especially after ACL injuries [21]. Single-leg jump tests seem to be appropriate for measuring muscle power of the lower extremities [29,37]. Currently, it is well known that LSI ≤ 90% in functional jump tests is categorized as a risk factor for lower extremities injuries among professional or amateur sports athletes [18,21,35,45]. Furthermore, a combination of multiple jump tests is recommendable to broadly assess the functionality of the knee joint and is a crucial part of most functional performance test batteries [46]. The one-leg jump for distance and vertical jump tests are valid and reliable tools for knee stability evaluation [14,21,29]. The side-hop is also a valid and reliable test [20,29] that assesses the strength of the lower extremities under fatigue state through controlled, fast and repetitive lateral jumps [20]. The one-leg speedy jump is shown to be a reliable and easy-to-perform test for detecting interlimb differences and knee functionality during jumps in the frontal, sagittal and transversal planes, representing also an important basis for clinical setting [25].

5.2.4. Prevention screening

The long-term negative consequences of ACL injuries are quite concerning: considerable time lost, increased risk of secondary injuries, knee osteoarthritis and financial burden on the health care system [32]. All of this could be minimised through an injury prevention approach for the identification of possible injury risk factors at young age, with a precautionary medical screening, academic environment and professional supervision [8]. Therefore, it is necessary to examine research evidence on the safety practices that best control injury risk in young football players [40]. For instance, the role of baseline data and mean values allows relevant comparisons, on the basis of the sport-specific athletic prerequisites, gender, age, level of competition and individual athlete´s limb symmetry index [37].

5.2.5. Aims of the study

The first aim of this study was to provide mean values of single-leg jump tests for young (pre-adolescents and adolescents) and uninjured male football players divided into age groups (U11-U19). Besides, to determine a benchmark for LSI in jump tests, assuming that normal range (LSI ≥ 90%) might be guaranteed for all age groups and in all tests. The second aim was to detect whether there was an age effect on interlimb functional performance differences (dominant, non-dominant) within age groups as well as on LSI between age groups, assuming that a significant main age effect might be present. The third aim was to investigate the direction and magnitude of the association between age and single-leg functional performance (dominant, non-dominant) as well as LSI, assuming that a higher age might be correlated with a higher single-leg functional performance and a higher LSI.

5.3. Methods

5.3.1. Participants: One-hundred forty-six young and uninjured male football players from a 3rd division professional German team have been included and tested in the study based on age groups (number of players per age groups: U11, 15. U12, 18. U13, 19. U14, 19. U15, 19. U16, 21. U17, 18. U19, 17). Teams from U11 to U17 competed at regional level while U19 at national level. Anthropometric data of the participants were collected (Table 1). A questionnaire was administered to each participant before performing the tests, to request specific information on date of birth, category of team (U11 to U19), dominant leg and number/type of injuries/surgeries (if any) suffered in the last 12 months. Inclusion criteria were the active involvement in training practices/games without restriction and participants had to be between 10-19 years old. Exclusion criteria consisted of lower limbs major injury (with more of 7 days of absence) or surgery in the previous 12 months. A written informed consent was obtained prior to test participation from full age players (≥ 18 years old) or from the parents of underage players (≤ 18 years old). Additionally, the dominance of the lower limbs was determined by the leg with which the participants would kick the ball [48]. The leg length was measured as the distance from the greater trochanter to the lateral malleolus [22]. The study was approved by the ethical committee of the German Sport University (GSU) of Cologne (reference number 056/2018).

Table 1. Anthropometric data (Mean ± SD).					
Team	**N**	**Mass (Kg ± SD)**	**Height (m ± SD)**	**BMI (Kg/m^2 ± SD)**	**Limb length (cm ± SD)**
U11	15	35.2 ± 4.9	1.5 ± 0.1	16.5 ± 1.4	82.5 ± 4.3 (Dom) – 82.5 ± 4.4 (N-Dom)
U12	18	38.0 ± 3.7	1.5 ± 0.0	17.8 ± 1.2	80.1 ± 3.3 (Dom) – 80.5 ± 3.2 (N-Dom)
U13	19	48.4 ± 8.5	1.6 ± 0.1	18.6 ± 2.1	88.2 ± 6.0 (Dom) – 88.1 ± 5.8 (N-Dom)
U14	19	56.5 ± 8.2	1.7 ± 0.1	20.1 ± 1.8	94.2 ± 4.7 (Dom) – 94.4 ± 5.1 (N-Dom)
U15	19	63.3 ± 9.7	1.7 ± 0.1	20.9 ± 1.9	96.3 ± 4.6 (Dom) – 96.4 ± 4.7 (N-Dom)
U16	21	67.8 ± 8.7	1.8 ± 0.1	21.7 ± 1.8	97.2 ± 6.3 (Dom) - 97.4 ± 6.3 (N-Dom)
U17	18	71.2 ± 7.2	1.8 ± 0.1	22.7 ± 1.5	98.4 ± 3.9 (Dom) - 98.4 ± 3.9 (N-Dom)
U19	17	72.8 ± 8.7	1.8 ± 0.1	22.1 ± 2.1	100.1 ± 5.2 (Dom) - 99.9 ± 5.4 (N-Dom)

Abbreviations: U (under), N (number), BMI (body mass index), SD (standard deviation), Dom (dominant leg), N-Dom (non-dominant leg).

5.3.2. Testing procedures: The tests have been conducted at the German Sport University (GSU) of Cologne and supervised by two research assistants from the Institute of Movement Therapy and Movement-oriented Prevention and Rehabilitation, with scientific experience in the field. All tests were performed in the same indoor gym facility on the same therapeutic mat (FUCHSIUS multi-media GmbH - RehaMatte - München). Participants performed the tests barefoot, dressed only with athletic training shorts and t-shirts. Before the tests, all athletes performed 10 minutes warm-up on a cycle ergometer at moderate-intensity followed by basic lower extremity dynamic stretching and joint mobility. All tests were performed unilaterally and the left leg was tested first. The same standardized test order was used for each participant (figure 1): counter-movement jump test (CMJ), jump for distance test (JFD), side hop test (SH) and speedy-jump test (SJ). To familiarise with the task, participants performed one practice trial before starting three valid attempts (only two for the SH and SJ) with the left leg (first) and the right leg (second), with regeneration time between each attempt of 30s (for the CMJ and JFD) and 60s (for the SH and SJ). All the tests were carried out with the hands fixed on the hip to avoid the influence of arm swing. Compensatory movements (see below in 2.2.1, 2.2.2, 2.2.3, 2.2.4 for each test description) were not allowed, rated as invalid trials and consequently not included in the data analysis.

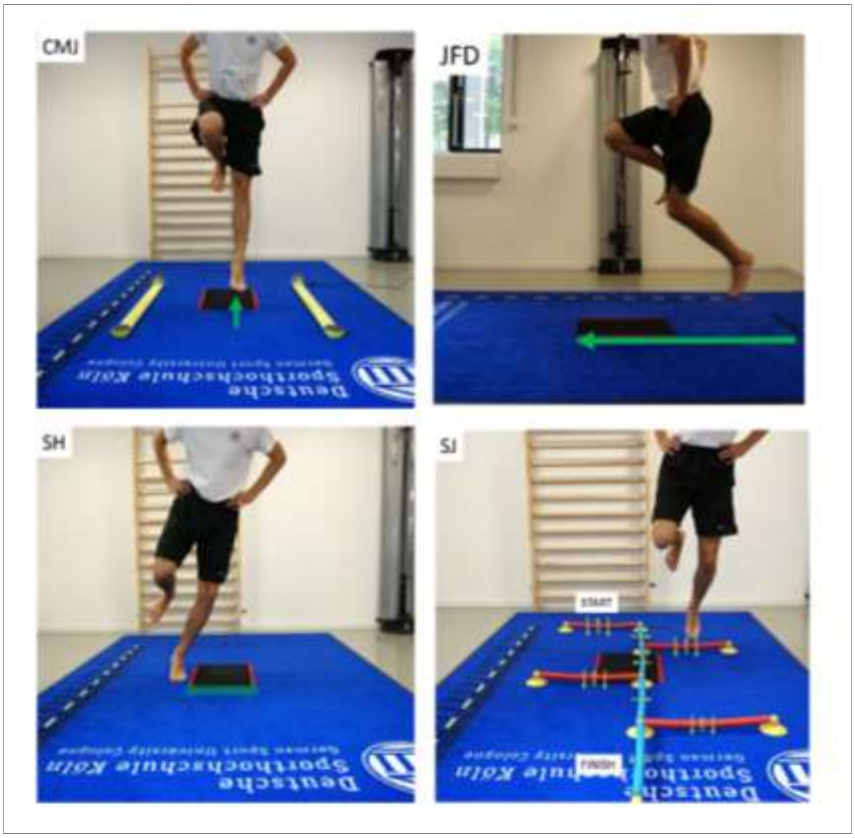

Figure 1. Countermovement jump (CMJ), jump for distance (JFD), side-hop (SH) and speedy-jump (SJ) tests.

5.3.3. Countermovement Jump Test (CMJ): The starting position was one-legged upright standing with the hands fixed on the hips during the entire execution. After a starting electronic signal from the software (Optojump Next Kit Version 1.12.1.0 – Microgate – Bolzano, Italy) the subject performed a countermovement flexion with the standing leg and then explosively jumped as high as possible trying to reach the maximum height, without swinging the contralateral leg or flexing the jumping leg. The landing had to be confident and safe, the final position kept for at least two seconds with no intermediate jumps allowed and legs or arms were not allowed to touch the ground [19,26,34].

5.3.4. Jump for Distance Test (JFD): The starting position was one-legged upright standing, with hands fixed on the hips for the entire execution and with the toes at the marked line (0 cm) on the ground. After the starting oral signal from the examiner, the subject jumped as far as possible and landed on the same leg. The swing of the contralateral leg was not allowed. The landing had to be stable, under complete control and kept for 2 seconds, without loss of balance or other compensatory movements such as extra jumps, support of the contra-lateral leg or help with the arms. One measuring meter was already painted on the therapeutic mat used to carry out the tests and the jumped distance was measured in centimeters (cm) by the examiner from the toe at the push-off (starting marked line) to the heel where the subject landed [19,20,34].

5.3.5. Side Hop Test (SH): Two parallel strips of tape were painted 40 cm apart on the therapeutic mat. Participants had to stay on the tested leg, with their hands on the hips, jumping from side to side over two parallel strips of tape. Participants were instructed to jump as many times as possible during a period of 30 seconds recorded using a stopwatch. The number of successful jumps (score = total jumps – error jumps) performed without touching the tape or committing any other errors (such as extra/double jumps, support of the contra-lateral leg or leave the arms from the hips) were recorded [20,29,34].

5.3.6. Speedy-Jump Test (SJ): Participants performed as fast as possible a total of 16 single-leg jumps with the hands on the hips: three jumps through each of the four red hurdles (front-back-front) in the sagittal plane and one jump through each of the four blue hurdles (sideways) in the frontal plane (Speedy-Jump Test Kit - TST GmbH Austria). After the starting signal, time was measured by using the mean between two stopwatches. It started as soon as the tested foot left the ground and ended as soon as the tested foot landed on the ground after the last jump. The attempt was invalid if the hands were moved out from the hips, the free leg touched the ground or the testing leg touched the instrument. Double jumps at landing were allowed [25,44].

5.3.7 Statistical analysis: Descriptive statistics has been performed. Means and standard deviations according to tests and sorted per dominant/non-dominant leg were calculated for each participant. For all tests, the best valid trial for each leg was used for the data analysis. To determine the limb symmetry index (LSI) between the dominant and non-dominant leg, the proposed formula for uninjured population [LSI = (non-dominant/dominant) *100] was used [3,30]. In order to proceed with the data analysis, the tests were evaluated on the following variables: vertical jumped height (cm) for the CMJ, horizontal jumped distance (cm) for the JFD, number of total valid jumps (n) for the SH and execution time (s) for the SJ. Shapiro-Wilk ($p > .05$), Skewness (range ± 2), Kurtosis (range ± 7) and Levene tests were performed for the normality of distribution ($p > .05$) and homogeneity of variances ($p > .05$). Two-way mixed ANOVA ($p < .05$) for repeated measures on leg (dominant, non-dominant) per jump test (CMJ, JFD, SH and SJ) was run to detect whether there was an age effect on interlimb performance differences (dominant, non-dominant) within age groups (U11 to U19); a post-hoc analysis (Tukey) with multiple comparisons was also provided ($p < .05$). One-way ANOVA ($p < .05$) was run per jump test (CMJ, JFD, SH and SJ) to detect whether there was an age effect on LSI between age groups (U11 to U19). Pearson's analysis was carried out to investigate the significance ($p < .05$) and magnitude (small: $.1 < r < .3$; moderate: $.3 < r < .5$; strong: $.5 < r < 1.0$) of the association between age and single-leg functional performance (dominant, non-dominant) as well as LSI.

5.4. Results

5.4.1. Mean values

Data are presented according to tests and age groups, mean values (SD) are sorted per dominant/non-dominant leg and limb symmetry index (Table 2). In general, the average performance (mean between dominant/non-dominant) and the average limb symmetry index were expressed by the following values for all age groups (U11-U19): countermovement jump test (CMJ: 18.9 ± 4.0 cm / 104.5 ± 15.2 %), jump for distance test (JFD: 143.4 ± 19.6 cm / 101.8 ± 11.3 %), side hop test (SH: 56.8 ± 12.6 jumps / 105.6 ± 18.3 %) and speedy jump test (SJ: 7.1 ± .76 s / 103.4 ± 9.7 %).

Table 2. Mean values (SD)									
		U11	U12	U13	U14	U15	U16	U17	U19
CMJ	Dom (cm)	13.9 ± 2.6	15.0 ± 2.7	16.2 ± 2.2	19.4 ± 3.2	19.3 ± 3.0	21.0 ± 3.5	21.6 ± 3.5	21.9 ± 3.1
	N-Dom (cm)	14.3 ± 3.2	15.7 ± 2.7	17.1 ± 2.8	19.2 ± 3.2	20.5 ± 3.0	20.9 ± 3.1	22.5 ± 4.9	23.5 ± 3.6
	LSI (%)	103.4 ± 19.9	105.9 ± 15.4	106.2 ± 13.2	99.9 ± 14.6	107.6 ± 14.3	100.4 ± 14.1	104.3 ± 13.5	107.9 ± 16.3
JFD	Dom (cm)	120.6 ± 10.3	120.8 ± 15.2	127.3 ± 15.4	146.1 ± 18.2	145.6 ± 16.0	154.0 ± 13.0	152.9 ± 11.3	154.7 ± 10.2
	N-Dom (cm)	117.1 ± 11.2	124.3 ± 11.5	127.4 ± 16.9	143.4 ± 17.8	153.6 ± 18.2	152.8 ± 19.5	161.1 ± 14.9	161.0 ± 15.7
	LSI (%)	97.5 ± 11.1	103.9 ± 12.4	100.6 ± 12.3	98.8 ± 12.3	106.1 ± 13.7	99.7 ± 9.2	104.6 ± 8.5	103.3 ± 10.6
SH	Dom (n)	31.1 ± 6.1	50.0 ± 7.8	49.9 ± 12.6	55.4 ± 10.9	60.3 ± 7.1	65.5 ± 7.6	64.2 ± 9.6	66.5 ± 6.9
	N-Dom (n)	33.6 ± 8.6	53.1 ± 7.4	52.6 ± 8.4	55.8 ± 7.6	61.3 ± 7.0	67.0 ± 6.1	66.6 ± 7.8	67.5 ± 8.8
	LSI (%)	109.8 ± 27.2	107.1 ± 11.2	111.2 ± 31.4	105.1 ± 30.6	102.3 ± 12.8	103.5 ± 8.8	105.2 ± 15.8	100.9 ± 8.9
SJ	Dom (s)	7.6 ± 0.9	7.2 ± 0.6	7.2 ± 0.8	6.8 ± 0.5	7.1 ± 0.6	6.7 ± 0.6	6.2 ± 1.0	6.7 ± 0.6
	N-Dom (s)	7.8 ± 1.1	7.2 ± 0.7	7.7 ± 0.7	7.2 ± 0.8	7.3 ± 0.5	6.7 ± 0.6	6.6 ± 0.9	6.8 ± 0.8
	LSI (%)	103.2 ± 15.8	101.1 ± 9.3	106.0 ± 10.2	105.2 ± 10.3	102.7 ± 7.2	100.3 ± 8.1	106.1 ± 9.1	102.6 ± 7.4

Abbreviations: U (under), Dom (dominant leg), N-Dom (non-dominant leg), LSI (limb symmetry index), Sig. (significance), p (p-value), SD (standard deviation), CMJ (countermovement jump test), JFD (jump for distance test), SH (side hop test), SJ (speedy jump test). *Difference is significant at the 0.05 level (2-tailed).

5.4.2. Analysis of variance (ANOVA)

Two-way mixed ANOVA for repeated measures was run to detect the impact of age on interlimb functional performance differences (dominant, non-dominant) within age groups (Table 3). A significant interaction effect of age on interlimb functional performance differences (dominant, non-dominant) was not found in any of the tests performed: CMJ ($F = .985$; $p = .445$; $\eta p^2 = .048$), JFD ($F = 1.306$; $p = .253$; $\eta p^2 = .068$), SH ($F = .343$; $p = .933$; $\eta p^2 = .018$) and SJ ($F = .614$; $p = .743$; $\eta p^2 = .033$). However, age showed a significant main effect on single-leg functional performance scores (dominant, non-dominant) in all tests (CMJ: $F = 20.492$; $p = .000$; $\eta p^2 = .510$; JFD: $F = 20.210$; $p = .000$; $\eta p^2 = .529$; SH: $F = 38.010$; $p = .000$; $\eta p^2 = .667$; SJ: $F = 6.902$; $p = .000$; $\eta p^2 = .276$). Additionally, leg dominance showed a significant main effect on interlimb functional performance differences (dominant, non-dominant) in three out of four tests: CMJ ($F = 8.638$; $p = .004$; $\eta p^2 = .059$), SH ($F = 8.802$; $p = .004$; $\eta p^2 = .062$) and SJ ($F = 11.142$; $p = .001$; $\eta p^2 = .081$), except for the JFD ($F = 2.289$; $p = .133$; $\eta p^2 = .018$). Finally, One-way ANOVA was used to detect the impact of age on LSI between age groups (Table 4). Age showed no significant main effect ($p > .05$) on LSI in any of the tests performed.

Table 3. Two-way ANOVA for age-related effect on performance differences (Dom, N-Dom) within age groups				
Test	**Associations (ANOVA)**			
	df	**F**	**Partial Eta Squared (ηp^2)**	**Sig.**
CMJ				
Score	1	8.638	.059	.004*
Score*Age	7	.985	.048	.445
Age	7	20.492	.510	.000*
JFD				
Score	1	2.289	.018	.133
Score*Age	7	1.306	.068	.253
Age	7	20.201	.529	.000*
SH				
Score	1	8.802	.062	.004*
Score*Age	7	.343	.018	.933
Age	7	38.010	.667	.000*
SJ				
Score	1	11.142	.081	.001*
Score*Age	7	.614	.033	.743
Age	7	6.902	.276	.000*

Abbreviations: df (degrees of freedom), F (F-ratio), Sig. (significance), Score (within subjects), Score*Age (within subjects), Age (between subjects), CMJ (countermovement jump test), JFD (jump for distance test), SH (side hop test), SJ (speedy jump test), Dom (dominant leg), N-Dom (non-dominant leg). *Age-related effect is significant at the 0.05 level.

Table 4. One-way ANOVA for age-related effect on LSI between age groups				
Test	**Associations (ANOVA)**			
	df	**F**	**Mean Square**	**Sig.**
CMJ	7	.769	175.379	.614
JFD	7	1.119	146.765	.355
SH	7	.507	215.869	.828
SJ	7	.869	84.290	.533

Abbreviations: df (degrees of freedom), F (F-ratio), Sig. (significance), LSI (limb symmetry index), Sig. (significance), F (F-ratio), CMJ (countermovement jump test), JFD (jump for distance test), SH (side hop test), SJ (speedy jump test).

5.4.3. Normal distribution, homogeneity of variances and correlation between age and performance

Table 5 contains the results of the analysis for normal distribution and homogeneity of variances. The homogeneity of variances was confirmed in all tests for all variables (dominant, non-dominant and LSI). Thus, the veracity of ANOVA can be assumed. The only exception was observed for LSI of SH test (p .027), which was the only heterogeneous variable. Shapiro-Wilk test ($p < 0.05$) revealed that variables (dominant, non-dominant and LSI) were not normally distributed in all tests, except for LSI of CMJ test (p .115). However, Skewness maintained the assumption of symmetric distribution (within the range ± 2) in two out of four tests (CMJ and SH). In addition, Kurtosis maintained the assumption of symmetric distribution (within the range ± 7) in all tests, except for single variables of the SH (LSI) and SJ (dominant and non-dominant) tests. Table 5 contains the results of the Pearson's correlation analysis. Age and single-leg functional performance (dominant, non-dominant) showed a significant linear correlation ($p < .05$), with a positive direction and strong ($.5 < r < 1.0$) magnitude of the association for the CMJ, JFD and SH tests; the only exception was found in a single variable of the JFD (dominant: r .381), which revealed a moderate (.3 < r < .5) magnitude effect. A negative and weak (.1 < r < .3) correlation was found for the SJ test (dominant: r -.271; non-dominant r -.211). Finally, no correlation was found (p > .05) between age and LSI in any of the jump tests performed.

Table 5. Pearson´s correlation of age with performance (Dom, N-Dom, LSI), normal distribution of data and homogeneity of variances

Test	Correlation		Shapiro-Wilk Test		Normal distribution		Homogeneity of variances (Levene)	
	Pearson	Sig. (2-tailed)	Statistic	Sig. (2-tailed)	Skewness	Kurtosis	Statistic	Sig. (2-tailed)
CMJ								
Dom	.654	.000*	.981	.038**	.344	-.133	.892	.515
N-Dom	.654	.000*	.982	.047**	.381	-.005	2.063	.052
LSI	.042	.616	.985	.115	.303	-.046	.972	.454
JFD								
Dom	.381	.000*	.715	.000**	-2.211	4.679	1.184	.317
N-Dom	.549	.000*	.768	.000**	-2.164	5.586	1.302	.255
LSI	.096	.276	.659	.000**	-2.325	5.137	.494	.837
SH								
Dom	.553	.000*	.908	.000**	-1.244	1.853	1.174	.322
N-Dom	.510	.000*	.902	.000**	-1.407	2.917	.494	.838
LSI	-.119	.162	.741	.000**	-.311	9.422	2.355	.027***
SJ								
Dom	-.271	.001*	.669	.000**	-2.696	8.064	1.870	.080
N-Dom	-.211	.011*	.697	.000**	-2.798	9.983	1.719	.110
LSI	.021	.807	.605	.000**	-2.651	6.432	1.756	.102

Abbreviations: LSI (limb symmetry index), Dom (dominant leg), N-Dom (non-dominant leg), Sig. (significance), CMJ (countermovement jump test), JFD (jump for distance test), SH (side hop test), SJ (speedy jump test). *Pearson correlation is assumed at the 0.05 level (2-tailed). **Normal distribution of the data is not assumed at the 0.05 level (2-tailed). ***Homogeneity of variances is not assumed at the 0.05 level (2-tailed).

5.5. Discussion

To date, there is little evidence data that supports the use of sport-specific standards for jump tests in football players with the same test executions, therefore further studies are required. Specifically, studies need to examine dominant/non-dominant performances and limb symmetry indices (LSI) as mean values (SD) in jump tests within large populations grouped by sport, age and gender [37].

5.5.1. Mean values (SD)

Single-leg jump tests in different plane directions should be included in football-specific muscular power assessment as well as talent identification protocols at elite and non-elite level [36]. Unfortunately, different test executions and standard procedures have been used hitherto amongst young football players and therefore any comparisons result is difficult. The participants of this study performed the CMJ test with an average jumped height of 18.5±2.9cm (dom) /19.2±3.3cm (n-dom) and the JFD test with an average jumped distance of 1.40±13.7m (dom) / 1.42±15.7m (n-dom). According to the “VBG-Return to competition manual”, the interlimb difference for the JFD test should not exceed 20cm to be categorised as normal [34]. The outcomes of this study support this assumption, as on average the interlimb difference in the JFD test was 4.2cm among all age groups, with the minimum peak presented by the U15 (mean interlimb difference of 8cm) but still considered in the normal range. Nonetheless, adult male football players from the third Spanish division showed greater jumped height (CMJ) of 22.81±3.45cm (dom) / 23.34±2.73cm (n-dom) and greater jumped distance (JFD) of 1.80±.13m (dom) / 1.81±0.12m (n-dom) [50]. These performance differences can be explained by the age and performance level gaps of the two cohorts of participants, as in the present study only the U19 age group was competing at professional youth level (1st German U19 division). Interestingly, the U12 (dom 50.0±7.8 jumps / n-dom 53.1±7.4 jumps), U13 (dom 49.9±12.6 jumps / n-dom 52.6±8.4 jumps) and U14 (dom 55.4±10.9 jumps / n-dom 55.8±7.6 jumps) have performed the SH test with almost similar results compared to healthy male adults (55±6.0 jumps) [20]. This can be interpreted as a consequence of the higher levels of performance for the above-mentioned age groups (U12-13-14), despite the great age difference with the compared adult population. It is worth noting that the age groups mostly involved in competitive-oriented levels such as the U15 (dom 60.3±7.1 jumps / n-dom 61.3±7.0 jumps), U16 (dom 65.5±7.6 jumps / n-dom 67.0±6.1 jumps), U17 (dom 64.2±9.6 jumps / n-dom 66.6±7.8 jumps) and U19 (dom 66.5±6.9 jumps / n-dom 67.5±8.8 jumps) also showed greater results in the SH test when compared to mixed adult population (right leg 49.6±13.5 jumps / left leg 47.4±13.0 jumps) involved at recreational and competitive sports level [29]. In addition, to the best authors' knowledge, no investigation has been carried out yet on young football players with regard to the speedy-jump test (SJ). The participants involved in this study (dom 7.0±0.8s / n-dom 7.2±0.9s) have performed not much lower than healthy subjects aged 10-50 years (dom 6.3±0.8s / n-dom 6.4±0.9s) [25] and this slight performance variation could be explained by the non-conformity of the age groups and the specific practiced sports.

5.5.2. Age effect on dominant/non-dominant performance differences and LSI

Firstly, it was assumed an age-related effect on interlimb functional performance differences (dominant, non-dominant) within age groups (U11-U19). The results of this study rejected this assumption. Two-way mixed ANOVA ($p < .05$) revealed that significant interlimb functional performance differences (dominant, non-dominant) can be assumed within age groups in three out of four tests (CMJ, SH and SJ), except for the JFD. However, although age demonstrated to have a significant effect ($p < .05$) on single-leg performance scores (dominant, non-dominant), a significant age interaction ($p > .05$) with interlimb functional performance differences (dominant, non-dominant) within age groups was not found. Nevertheless, the age groups (U11-U19) involved in this study might need specific training interventions on plyometrics and power reinforcement in unilateral and multidirectional jumps, in order to counteract the detected interlimb functional performance differences (dominant, non-dominant). Quite differently, previous studies showed no evidence for significant interlimb differences (dominant, non-dominant) in young and professional football players in terms of knee flexor/extensor muscles [16], H/Q ratio [51] and strength/power capacities [4]. However, in case of significant interlimb functional differences (dominant, non-dominant), the performance of football players could be negatively affected during training sessions and games [3]. Thus, jump tests are strongly recommended for providing pre-injury data. Not only are these helpful as an index criterion for reducing re-injury risk, but they also serve as a measure to help athletes to reach the previous performance capacity [6]. Secondly, it was assumed a normal limb symmetry index (LSI ≥ 90%) for all age groups in all tests. The results of this study confirmed this assumption, showing an LSI of 103.8 ± 14.2% (as the average between all tests and age groups). Previous studies pointed out an LSI ≥ 90% for healthy recreational athletes to be considered as normal range [21,35], while healthy male collegiate football players revealed a statistical impressive symmetry [9]. The findings of the current study completely agree with the above-mentioned studies, as an LSI ≥ 90% was showed in each single test and in all age groups. Furthermore, based on the results obtained in the present study, an LSI ≥ 100% in the jump tests performed can be suggested as a benchmark for young and uninjured football players. Conversely, Fousekis et al. describes interlimb isokinetic strength asymmetry in knee flexor/extensor muscles as adaptations which mainly occur in football players with short (5-7 years) and intermediate (8-10 years) professional training age, while players with a longer (> 11 years) professional training age are more balanced and with less musculoskeletal asymmetries [15]. However, this must be interpreted cautiously due to the different measuring systems between isokinetic tests and functional jump tests. Thirdly, it was assumed an age-related effect on LSI between age groups

(U11-U19). The results of this study rejected this assumption. In fact, One-way ANOVA revealed no significant age-related effect ($p > .05$) on LSI between age groups. Therefore, LSI does not differ significantly between age groups and it could be deduced that their variations are not related to the age of the participants. However, several authors already pointed out that youngest categories (age groups) may have a higher risk of lower extremities muscle and joint injury due to their higher limb asymmetries, thus further research is needed to better investigate this aspect [17,18,21,35,45]. In fact, knee extensor muscles may exert significant interlimb differences (dominant, non-dominant) in sub-elite football players, with the dominant leg being the weakest one, according to Rahnama et al. This could be explained by the differential use of these muscles during the kicking action, which in turn may lead to muscular imbalance, commonly associated to injury risk factor [42]. Contrarily, another research showed the dominant side performed significantly greater than the non-dominant side during jump tests in uninjured adult population [1]. Nevertheless, in the present study it was not statistically evaluated which was the most performant leg (dominant or non-dominant) during single-leg jump tests. Therefore, a suggestion for future researches is to investigate if the dominant leg is also the best performing leg or vice versa during single-leg jump tests in young and uninjured football players.

5.5.3. Associations of age with functional performance and LSI

It was assumed that a higher age was positively associated with a higher single-leg functional performance (dominant, non-dominant) and a higher LSI. The results of the present study partially confirmed this assumption. Pearson's correlation was used to investigate the direction and magnitude effect of age on single-leg performance scores (dominant, non-dominant) and LSI. The analysis demonstrated age (years) and single-leg functional performance (dominant, non-dominant) to have a significant linear correlation ($p < .05$), with a positive direction and strong magnitude of the association for the CMJ (dominant: r .654; non-dominant: r .654), JFD (non-dominant: r .549) and SH (dominant: r .553; non-dominant: r .510) tests, a moderate magnitude effect for the JFD (dominant: r .381) test while a negative and weak correlation for the SJ (dominant: r -.271; non-dominant r -.211) test. Time reductions (s), however, are considered to be an improvement in the SJ test results, where the less the better. Hence, it can be assumed that in the four jump tests performed in the present study, a higher single-leg functional performance (dominant, non-dominant) was significantly associated with a higher age and these variables increased together. Nevertheless, age was not associated ($p > .05$) with LSI in none of the tests performed. This would mean that football players may or may not show a high LSI value, regardless of the age group. According to a recent study, older players are presumably stronger and faster than younger players and in particular they can perform better in physical condition tests [33]. Several studies have already shown correlations between age and physical performance in football players, but the applicability in one-leg jump tests has not been fully addressed yet. For example, in male and female young athletes (9-17 years), increases in quadriceps and hamstrings strength performance are significantly correlated with age [2]. Furthermore, in male amateur adolescent football players the physical performance improves markedly in age groups between U15 to U19 [27]. Besides, linear improvements of the cognitive-motor performance are also positively correlated with age in young elite football players [24]. Generally speaking, age and level of competition may play a key role in performance analysis concerning single-leg jump tests. Thus, special attention must necessarily be paid from future researches to these two aspects in young and uninjured football players.

Conclusively, this cross-sectional study concerns three fundamental strengths. Firstly, the evaluation of a large number of young football players divided into age groups provides a practical insight into sport-specific functional performance. Secondly, the uninjured group of participants is a good starting point for creating general guidelines and for the observation of their performance trends. Thirdly, the standardised tests execution could also improve the transferability of the study to other samples. In a preventive approach, this study can be helpful in order to allow useful comparisons in youth football academies, as well as to promote decision-making processes and performance-oriented observations.

With regard to the practical applications of this study, the tests conducted on young and uninjured football players allow functional performance to be assessed in a clear and effective manner: for example, the better results achieved by the older age groups seem to be normal, due to the significant association demonstrated between age and single-leg functional performance (dominant, non-dominant). Conversely, age showed no effect on LSI between age groups and no interaction with interlimb functional performance differences (dominant, non-dominant) within age groups. Thus, the planning of specific and individualised training programs may be needed for all the age groups involved in this study, so as to reduce the detected interlimb functional performance differences (dominant, non-dominant). Furthermore, in the event of a future injury, the available pre-injury data might be useful for a better rehabilitation protocol based on the individual level of the athletes.

There are several key directions for future research on jump tests in young football players. Further studies should assess a larger number of football players and ought to consider to the female population. Moreover, more research studies should implement the so-called pre-injury screenings, suggested at least twice a season (at the beginning and in the middle of the season), to optimise both injury prevention and performance-oriented decisions. Studies are called to provide jump performance data according to activity level and field position, to better categorise the individual results. Finally, future studies need to observe correlations of single-leg functional performance (dominant, non-dominant) in jump tests and LSI with future injuries, to find out whether they could be prevented more frequently or to identify those players most at risk and intervene accordingly.

5.6. Limitations

The present study has few limitations. First, the results cannot be extended to a football population older than 19 years, neither to females nor to other sports. Data were also not examined according to field position and activity level. Moreover, the results include mean values but not reference data, which does not allow a clear distinction between positive and negative performance.

5.7. Conclusion

The combination of four single-leg jump tests, performed in different plane directions, seems to be appropriate for the detection of interlimb functional performance differences and limb symmetry indices. This study showed that significant interlimb functional performance differences (dominant, non-dominant) can be expected in young and uninjured football players. However, these differences have no interaction with age. In spite of this, age and growth process play a decisive role in the development of functional capacities and are positively associated with single-leg functional performance (dominant, non-dominant), but not with limb symmetry index (LSI). Thus, a higher single-leg functional performance, but not a higher LSI, could be considered normal in older age groups compared to younger age groups in the four jump tests performed. Furthermore, an LSI ≥ 100% can be proposed as a benchmark for this specific population. To conclude, football players included in this study might need a preventive intervention to counteract the detected inter-limb functional performance differences, for which unilateral strength, power and plyometric training is recommended in football practice.

Compliance with ethical guidelines

Funding: Not applicable.

Conflicts of interest: The corresponding author indicates for himself and his co-authors that there is no conflict of interest.

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5.8. References

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6. Study Nr. 3: The Association between Multidirectional Speed Performance, Dynamic Balance and Chronological Age in Young Soccer Players

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6.1. Abstract

The ability to maintain a stable single-leg balance stance during a fast change of direction movement is a fundamental aspect both for improving sport-specific skills and for prevention strategies. The aim of this cross-sectional study was to investigate the associations between multidirectional speed performance (MDS), dynamic balance performance (DBP), and chronological age in young and uninjured soccer players. In addition, it was examined whether chronological age and balance can predict variance in speed performance. One-hundred forty-six young male soccer players (age range 11–19) performed the y-balance test (YBT) and the lower extremity functional test (LEFT). Descriptive statistics, Pearson correlation, and multiple regression analysis were executed. The analyses were carried out on the further variables: for the DBP, the YBT composite score % (CS dominant leg/CS non-dominant leg) and limb symmetry index % (LSI) were used; for the MDS, the LEFT time in seconds (s) was used. Findings revealed LEFT scores to have a significant association with chronological age (p = 0.000), CS dominant (p = 0.019) and LSI (p = 0.044) of the YBT. In addition, CS dominant and chronological age explained the variance of the LEFT by 44%, regardless of LSI. To conclude, MDS revealed a strong association with DBP of the dominant side but a small association with LSI. In addition, a small association was found between quick LEFT times and older players. Finally, MDS variance can be predicted from DBP of the dominant side and chronological age in young soccer players. The tests used in this study could be useful screening tools for the detection of performance deficits, the implementation of prevention training programs, and the optimization of selection strategies in soccer academies.

Keywords: prevention; youth athletes; screening tests; y-balance test; lower extremity functional test; limb symmetry index; knee stability; change-of-direction speed; postural control

6.2. Introduction

6.2.1. Functional Performance in Soccer Players

Functional performance is a crucial component in order to be a successful player and to perform at high levels without injury [1,2]. Functional parameters such as speed and single-leg balance are fundamental for soccer players. [3]. Another important factor to consider is the chronological age [4]. A recent study defined age-related differences in physical abilities as common aspects in elite soccer academies [5]. In youth athletes, speed and balance tests, i.e., lower extremity functional test (LEFT) and y-balance test (YBT) have been extensively used for screening and scouting strategies [6–8]. Their results have been associated with an elevated risk of injury to the lower limbs and with a better chance to advance in the elite categories [6–8]. In addition, these tests have been commonly used as standard criteria for returning to sport after injury [9].

6.2.2. Speed Performance in Soccer Players

For soccer players, it is essential to prevail over the opponent on the pitch. High speed performance levels may be helpful to succeed in decisive moments of the game, such as winning a sprint to get to the ball first. The multidirectional speed performance (MDS), i.e., the ability to accelerate, decelerate and perform fast changes of direction in the shortest possible time, is one of the major components of the soccer player's profile [10,11]. Sheppard & Young defined change of direction as a rapid whole-body movement with a change of velocity or direction, with no perceptual and decision-making factors involved [12]. Multi-faceted influencing factors are involved in change of direction performance, in particular technique, straight sprinting speed, anthropometry, and leg muscle qualities such as left-right muscle imbalances [12]. Also, chronological age has been found to have a significant effect on sports motor competencies such as speed performance [13]. In addition, faster change of direction speed times strongly correlated with greater dynamic balance stability in field sport athletes, including soccer players [3]. Contrarily, no significant age-related effects on speed performance were found during linear-sprint tests (10 m, 30 m) in young soccer players [14]. The lower extremity functional test (LEFT) includes both change of direction and linear sprint movements [6–8], but it has been rarely used for association studies with chronological age and single-leg dynamic balance.

6.2.3. Balance Performance in Soccer Players

Soccer is considered a dominant single-legged sport, and balance abilities are extremely required while playing [15]. In fact, not only do soccer players need to perform actions and movements as quickly as possible, but they also need further qualities to perform well such as adequate stability, postural control, and dynamic balance of the lower limbs [16,17]. The dynamic balance performance (DBP) is the ability to maintain proper postural control and stability of the knee while standing on one leg and performing a specific action with the other leg, such as passing or shooting the ball [18]. Significant main effects of age have been already found also for the balance performance in previous research [16]. DBP and postural control of the dominant leg revealed a significant positive correlation with age in young soccer players [19]. Also, previous studies showed that adequate balance capacity could lead to faster speed performances among male youth soccer players [16–18]. On the other side, dynamic balance stability was not able to differentiate between faster and slower recreational team sport athletes, including soccer players [20].

6.2.4. Aims

Previous research leads to controversial findings and it remains still unclear the association that MDS could display with DBP and chronological age, as measured with the LEFT and YBT. In addition, we still know little about whether and to what extent speed performance can be associated with and predicted by balance performance and chronological age in young soccer players. Therefore, the aim of this cross-sectional study was to investigate the association between MDS (LEFT), DBP (YBT), and chronological age in young and uninjured soccer players. In addition, to observe whether DBP and chronological age could be significant predictors of MDS. The authors of the present study hypothesised that MDS, DBP, and chronological age might be positively associated. In addition, it was hypothesised that DBP and chronological age might be significant predictors of MDS.

6.3. Material and Methods

6.3.1. Participants

One hundred and forty-six young and uninjured male soccer players from a 3rd division professional German team were included in this cross-sectional study. Anthropometrics data are presented in Table 1. Players were divided into age groups from under-11 (U11) to under-19 (U19), in accordance with the club organization. Players were involved at competitive (U19) and regional levels (from U11 to U17). The training frequency was 2–4 training sessions per week (1–2 h per training session) and 1 match per week (30–90 min per match) for all players. The inclusion criteria were age ranging between 10–19 years and active participation in soccer activity without any restrictions in practices (2–4 × week) or games (1 × week) over the previous 12 months. The exclusion criterion for this study was the presence, over the previous 12 months, of a lower extremity surgery as well as a lower extremity moderate (between 8–28 days of absence) or severe (>28 days of absence) injury [21]. Written informed consent was obtained prior to test participation from all players or relatives and the study was approved by the ethical committee of the German Sport University (GSU) of Cologne (reference number 056/2018). All players were aware of the potential risks and benefits of the study and complied with the design, protocol, and inclusion criteria. No player has been excluded from the study.

Table 1. Anthropometric data (Mean ± SD).

Age Groups (N)	*Mass (kg ± SD)*	*Height (m ± SD)*	*BMI (kg/m² ± SD)*	*Limb Length Dom/N-Dom (cm ± SD)*
U11 (15)	37.2 ± 5.8	1.4 ± 0.5	18.4 ± 2.5	81.4 ± 5.4/81.8 ± 5.5
95% CI	±0.9	N.A.	±0.2	±0.8/±0.8
COV (%)	13.6%	4.1%	8.0%	5.4%/5.5%
U12 (18)	39.1 ± 4.8	1.5 ± 0.5	18.9 ± 2.3	81.2 ± 4.4/81.6 ± 3.3
95% CI	±0.6	N.A.	±0.2	±0.5/±0.5
COV (%)	9.8%	3.4%	6.6%	4.1%/4.0%
U13 (19)	49.5 ± 9.6	1.6 ± 0.5	19.7 ± 3.2	89.3 ± 7.1/89.2 ± 6.9
95% CI	±1.3	N.A.	±0.3	±0.9/±0.9
COV (%)	17.5%	5.9%	11.2	6.8%/6.8%
U14 (19)	57.6 ± 9.3	1.7 ± 0.5	21.2 ± 2.9	95.3 ± 5.8/95.5 ± 6.2
95% CI	±0.3	N.A.	±1.3	±0.7/±0.8
COV (%)	9.1%	5.2%	14.6%	5.0%/5.4%
U15 (19)	64.4 ± 9.8	1.7 ± 0.5	21.8 ± 2.9	97.4 ± 5.7/97.5 ± 5.8
95% CI	±1.5	N.A.	±0.3	±0.7/±0.7
COV (%)	15.3%	4.4%	9.0%	4.8%/4.9%
U16 (21)	68.9 ± 9.9	1.8 ± 0.5	22.8 ± 2.9	98.3 ± 7.5/98.5 ± 7.6
95% CI	±1.3	N.A.	±0.3	±0.9/±1.0
COV (%)	8.7%	4.7%	8.7%	6.6%/6.6%
U17 (18)	72.3 ± 8.5	1.8 ± 0.5	23.8 ± 2.7	99.5 ± 5.2/99.5 ± 5.1
95% CI	±1.2	N.A.	±0.3	±0.6/±0.6
COV (%)	10.4%	3.1%	7.0%	4.1%/4.1%
U19 (17)	73.9 ± 9.9	1.8 ± 0.5	23.3 ± 3.3	101.2 ± 6.5/100.1 ± 6.7
95% CI	±0.4	N.A.	±0.4	±0.9/±0.9
COV (%)	9.8%	3.9%	9.8%	5.4%/5.6%
Total (146)	57.9 ± 8.5	1.8 ± 0.5	21.2 ± 2.8	92.9 ± 5.9/92.9 ± 5.9
95% CI	±0.9	N.A.	±0.4	±0.8/±0.8
COV (%)	11.8%	4.3%	9.4%	5.3%/5.4%

Abbreviations: U, under; N, number of players; BMI, body mass index; Dom, dominant leg; N-Dom, non-dominant leg; SD, standard deviation; CI, confidence interval; COV, coefficient of variation; N.A., not available (≅ 0.0); kg, kilograms; m, meters; m^2, square meters; cm, centimeters.

6.3.2. Test Procedures

This study was conducted at the German Sport University (GSU) of Cologne. The tests were supervised by two research assistants. The same test order was used for all players, the YBT first and the LEFT second. Players had to wear only sports t-shirts and shorts while performing the tests. The YBT was performed barefoot in an indoor gym facility on a therapeutic mat (FUCHSIUS multi-media GmbH—RehaMatte—München, Germany) while the LEFT was performed with players' own running shoes on an athletic indoor track. In the beginning, players were measured in kilograms (kg) using a standard scale for weight and measured in metres (m) using a standard tape measure for height. In order to familiarise them with the tests, standardised instructions and demonstrations were provided at the beginning. Before performing the tests, all players executed a standardised warm-up program including ten min of stationary cycling at low intensity (70 watts) and five min of guided, lower extremity joint mobility consisting of flexion/extension, adduction/abduction, and intra/extra rotation exercises for the pelvis, knee, and ankle joints. For the sake of consistency, players were given three practice trials (per leg) before starting three valid attempts (per leg) for the YBT, while one practice trial before starting two valid attempts for the LEFT. Adequate recovery time was allowed between practice trials (30 sec) and valid attempts (60 sec) for the YBT as well as between valid attempts (120–180 sec) for the LEFT. A 5-min break was applied between the YBT and LEFT tests. The test supervisors decided in real-time whether the tests were carried out correctly or not. If no valid attempt was recorded, the player had to be excluded from the analysis; however, all players recorded at least one valid attempt, and, therefore, all players were included in the analysis. Lastly, verbal encouragement and transcription of the scores took place consistently for all players.

6.3.3. Y-Balance Test (YBT)

The YBT (Figure 1) is a reliable and valid test used to measure single-leg DBP, knee stability, and postural control in young populations [22–25]. The Y-Balance Test Kit (Move2Perform®, Evansville, IN, USA) was used for this study. The YBT was performed unilaterally and the leg to be tested first was randomly assigned to avoid learning or fatigue effects. The test was performed in accordance with the standardised procedures proposed in a recent study by Scinicarelli et al. [22]. Players started in a single-leg upright standing position, with the toes of the standing leg at the marked red line of the instrument and the hands fixed on the hip to avoid the influence of arm swing. The sliding elements had to be pushed with the toes of the other leg as far as possible in three given directions: anterior (ANT), posteromedial (PM), and posterolateral (PL). For a correct execution, the standing leg had to maintain a full stance on the platform and the other leg had to maintain constant contact with the sliding elements. The final single-leg balancing position to the starting point had to be maintained for three seconds (s)—measured with a stopwatch—to be considered a valid attempt. Compensatory movements were not allowed, rated as invalid trials, and consequently not included in the data analysis. The following criteria were used to mark invalid attempts: leaving the arms from the hips, inability to maintain balance, touching the ground with the contralateral leg, elevating the heel of the standing leg, kicking the sliding element, or using it as support. Furthermore, limb dominance was determined by the leg with which the player would kick a ball, and used for the calculation of the limb symmetry index (LSI) [26]. The limb length was also measured, as the distance in centimetres (cm) from the greater trochanter to the lateral malleolus, and used for the normalisation of the composite score (CS) [25,27]. Two different performance scores were used: (1) The CS was calculated in percentage (%) using the following formula: [CS = ((ANT + PL + PM)/3 × limb length) × 100] [25]. (2) The CS was used then to calculate the limb symmetry index (LSI) in percentage (%) using the following formula, commonly used for uninjured population: [LSI = (CS non-dominant/CS dominant) * 100] [28,29]. The limb symmetry index (LSI) is usually known as a measure for the level of symmetry in terms of physical or functional performance between the lower limbs [30]. Generally, interlimb differences in performance may occur in single-leg dominant sports such as soccer, regardless of whether or not players have suffered an injury [31]. Therefore, inter-limb symmetry is an adequate investigative method for detecting side-to-side differences in uninjured players. In addition, YBT scores have also been associated with an increased risk of injury to the lower limbs [32], such as CS ≤ 89% [8] and LSI ≤ 90% [6,28,30]. Therefore, the YBT is a useful tool for identifying players with greater DBP and accordingly with a lower risk of injury.

Figure 1. The Y-balance test (YBT).

6.3.4. Lower Extremity Functional Test (LEFT)

The LEFT is a reliable and valid test for the measurement of MDS, athletic fitness, and fatigue resistance by performing a series of 16 specific manoeuvres as fast as possible, including forward and backward sprinting, sidestepping, cross-stepping, 45° and 90° cutting [7,22,24,33]. The LEFT has been chosen because it requires minimal equipment, is quick to perform, and has been demonstrated to assess athletic fitness and return to sport readiness in youth soccer players [7,22,24,33]. The list of the 16 specific manoeuvres to be performed respect the guidelines provided by Brumitt et al. [7]. The layout (Figure 2) is a combination of four cones in a diamond-shape (9.14 m × 3.05 m). The movement sequence of Figure 2 is explained as follows: (1) Forward sprint (ACA), (2) Backward sprint (ACA), (3) Side shuffle right—face in (ADCBA), (4) Side shuffle left—face in (ABCDA), (5) Cariocas right—face in (ADCBA), (6) Cariocas left—face in (ABCDA), (7) Figure of 8 right—face in (ADCBA), (8) Figure of 8 left—face in (ABCDA), (9) 45° Cuts right (ADCBA), (10) 45° Cuts left (ABCDA), (11) 90° Cuts right (ADBA), (12) 90° Cuts left (ABDA), (13) 90° Crossover cuts right (ADBA), (14) 90° Crossover cuts left (ABDA), (15) Forward sprint (ACA), (16) Backward sprint (ACA). The test was performed in accordance with the standardised procedures proposed in a recent study by Scinicarelli et al. [22]. Players started in an upright standing position with both feet behind the starting point at cone A. On the command of one of the test supervisors, the players performed eight different agility tasks, with each task being performed twice (once to the right and once to the left direction). Because of the multidirectional requirements of the test and the variety of tasks to be performed, verbal instruction of subsequent movements was provided throughout the test. Attempts were considered invalid if participants failed to perform the designated manoeuvres or dropped a cone by contact. Time was measured in seconds (s) using a stopwatch by each of the test supervisors, from the first sprint after the starting signal as soon as players left cone A, to the last sprint as soon as players passed cone A. The final score was calculated by using the mean time in seconds (s) between both stopwatches used by the two supervisors [7,22,24]. The LEFT is considered a soccer-specific measurement, by including both linear- and multidirectional- speed parameters. Such specific actions are performed during matches or training on a regular basis, e.g., forward sprint and backward sprint [24,34]. Furthermore, scores obtained through this test have been also associated with a higher risk of injury to the lower limbs, such as speed time (s) ≤ 100 s [7]. Therefore, the LEFT is a useful test to identify players with higher speed performances and eventually with a higher risk of injury.

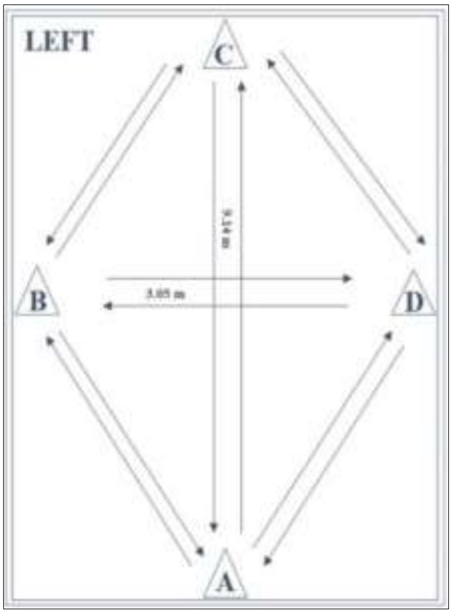

Figure 2. The lower extremity functional test (LEFT) [11,27].

6.3.5. Statistical Analysis

SPSS for Windows (Version 26.0, IBM® Corporation, NY, USA) was used for all statistical analyses with a significance level set at $p < 0.05$. The normality of data was evaluated by Shapiro–Wilk Test, Skewness (range ± 2), and Kurtosis (range ± 7). Descriptive statistics of anthropometrics, as well as performance scores, were calculated by means and standard deviations (±SD). Outliers were not identified. For each test, the best score among the valid attempts was used for the data analysis. Thus, the following variables were used for the analysis: CS dominant leg (%), CS non-dominant leg (%), and LSI (%) for the YBT (i.e., DBP); execution time (s) for the LEFT (i.e., MDS). Pearson correlation analysis was used to detect the magnitude and statistical significance of the associations between MDS and DBP (dominant/non-dominant leg), interlimb balance symmetry (LSI), and chronological age. The magnitude of the association was set as follows: small $0.1 < r < 0.3$; moderate $0.3 < r < 0.5$; strong $0.5 < r < 1.0$. Multiple regression analysis was run to predict the overall variance of MDS and the relative contribution of each of the predictors: DBP (dominant leg), interlimb balance symmetry (LSI), and chronological age. All required assumptions for the analysis were met by our data: 1, continuous scale dependent variable (MDS); 2, continuous scale independent variables (DBP and chronological age), 3, independence of residuals; 4, assumed linear relationships between variables; 5, homoscedasticity of data; 6, no multicollinearity of data; 7, no significant outliers; 8, residuals approximately normally distributed. The forward selection method was used and after fitting the regression model, the residual plots were checked to avoid biased estimates.

6.4. Results

6.4.1. Descriptive Statistics

The results (mean ± SD) of the functional performance tests are provided by age groups in Table 2. Levene's test revealed the equality of variances for both dominant ($p = 0.420$) and non-dominant ($p = 0.584$) leg for the DBP (YBT). Tukey's test revealed homogeneous distribution ($p > 0.05$) for the interlimb balance symmetry (YBT, LSI) and MDS (LEFT). In total (U11-U19), players performed the tests achieving the following results: CS dominant leg (83.8 ± 5.9%), CS non-dominant leg (83.8 ± 5.2%), and LSI (100.1 ± 5.6%) for the YBT; execution time (98.3 ± 6.5 s) for the LEFT. The cut-offs for performance deficits or injury risk indicators for the YBT and LEFT tests previously referred to in the literature are reported at the bottom of Table 2 [7,8,25,30]. All age groups reached poor composite scores in the YBT, for both dominant/non-dominant legs. More than half of the age groups achieved results that are correlated to injury risk in the LEFT (U14-U19).

Table 2. Descriptive statistics of the functional performance tests (Mean ± SD).

Age Groups	*Dynamic Balance (YBT)*		*Multidirectional Speed (LEFT)*
	Composite Score (CS, %)	***Limb Symmetry Index (LSI, %)***	***Execution Time (s)***
U11			
Dom	84.0 ± 8.1	101.8 ± 10.5	111.1 ± 15.7
N-Dom	82.8 ± 6.7		
U12			
Dom	86.3 ± 5.2	97.3 ± 6.8	102.4 ± 3.4
N-Dom	88.8 ± 5.1		
U13			
Dom	84.0 ± 8.2	99.8 ± 6.1	107.1 ± 8.4
N-Dom	84.1 ± 5.7		
U14			
Dom	82.2 ± 4.6	98.9 ± 3.0	98.6 ± 4.4
N-Dom	83.2± 4.1		
U15			
Dom	83.5 ± 5.5	102.1 ± 4.3	93.0 ± 4.2
N-Dom	81.9 ± 5.8		
U16			
Dom	83.0 ± 4.9	98.9 ± 3.9	92.4 ± 5.0
N-Dom	83.9 ± 4.8		
U17			
Dom	83.3 ± 5.6	101.7 ± 5.3	89.9 ± 3.6
N-Dom	82.0 ± 4.7		
U19			
Dom	84.0 ± 5.0	100.2 ± 4.5	92.0 ± 7.3
N-Dom	83.9 ± 4.4		

Abbreviations: U, under; Dom, dominant leg; N-Dom, non-dominant leg; YBT, y-balance test; LEFT, lower extremity functional test; CS, composite score (%); LSI, limb symmetry index (%); s, seconds; %, percentage. Cut-off for performance deficits of injury risk indicators: CS ≤ 89%, LSI ≤ 90%, LEFT ≤ 100 s.

6.4.2. Association Analysis between Functional Performance Variables and Chronological Age

A Pearson correlation analysis was run to analyse the associations of MDS with DBP (dominant/non-dominant leg and LSI) and chronological age. Results are reported in Table 3. Three out of four variables have been found to be statistically associated with MDS ($p < 0.05$), except for the DBP on the non-dominant leg ($p > 0.05$). MDS showed a strong negative association ($p < 0.001$; r = −0.626) with chronological age: i.e., as years of age increased, multidirectional speed decreased in terms of time (s) and thereby produced a faster execution. MDS showed a small negative association with DBP on the dominant leg ($p = 0.019$; r = −0.194) and interlimb balance symmetry ($p = 0.044$; r = −0.167): i.e., as dynamic balance on the dominant leg (CS, %) and interlimb balance symmetry (LSI, %) increased, multidirectional speed decreased in terms of time (s) and thereby produced a faster execution. Furthermore, no association was found between DBP and chronological age ($p > 0.05$).

Table 3. Association analysis.

Pearson Correlation between Variables								
	DBP						**Chronological Age**	
	Dominant Leg (CS, %)		***Non-Dominant Leg (CS, %)***		***Interlimb Symmetry (LSI, %)***		***(Years)***	
	r	*p-value*	*R*	*p-value*	*R*	*p-value*	*r*	*p-value*
MDS (Time, s)	−0.194	0.019 *	−0.060	0.469	−0.167	0.044 *	−0.626	0.000 *
Chronological Age (Years)	−0.068	0.416	−0.138	0.096	0.057	0.491		

Abbreviations: DBP, dynamic balance performance; MDS, multidirectional speed performance; LSI, limb symmetry index; CS, composite score; %, percent; s, seconds; r, Pearson coefficient. *, association is significant (2-tailed) at the 0.05 level.

6.4.3. Multiple Regression Analysis between Functional Performance Variables and Chronological Age

A multiple regression analysis was run to predict MDS from DBP (CS, dominant leg), interlimb balance symmetry (LSI), and chronological age. Results are reported in Table 4. The model summary shows that these variables statistically predicted overall MDS (F, df 3, 142 = 38.312, $p < 0.001$, $R^2 = 0.477$), with a good level of prediction (R = 0.669). In addition, two out of three variables added statistical significance to the prediction ($p < 0.05$), except for the interlimb balance symmetry ($p > 0.05$). From the R Square coefficient, it is assumed that all the predictors explain 44.7% of the variability of the MDS. The formula to predict MDS from DBP and chronological age, can be defined as follows: MDS = 171.8 − [2.7 (s) x years] − [0.4 (s) × CS dominant leg (%)]. This formula is obtained from the relative contribution of each of the predictors contained under the section unstandardized coefficients in Table 4.

Table 4. Multiple regression analysis.

Model Summary							
	R	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*			
MDS	0.669	0.447	0.436	7.5173			
ANOVA—MDS							
	Sum of square	*df*	*Mean Square*	*F*	*Sig.*		
Regression	6494.960	3	2164.987	38.312	<0.001 *		
Residual	8024.288	142	58.509				
Total	14519.248	145					
Coefficients—MDS							
Predictors	*Unstandardized Coefficients*		*Standardized Coefficients*			*95.0% CI for B*	
	B	*Std. Error*	*B*	*T*	*Sig.*	*Lower Bound*	*Upper Bound*
Constant	171.823	11.978		14.345	<0.001 *	148.144	195.501
Chronological Age	−2.649	0.260	−0.640	−10.178	<0.001 *	−3.164	−2.135
DBP	−0.385	0.122	−0.229	−3.162	0.002 *	−0.626	−0.144
Interlimb Balance Symmetry	−0.027	0.124	−0.015	−0.214	0.831	−0.272	0.219

Abbreviations: DBP, dynamic balance performance; MDS, multidirectional speed performance; R, multiple correlation coefficient; df, degrees of freedom; F, F-ratio; Sig., significant; B, Beta; t, t-value; Std., standard; CI, confidence interval. *, multiple regression is significant at the 0.05 level.

6.5. Discussion

The present study explored the associations between MDS, DPB, and chronological age in young and uninjured soccer players. In addition, it was investigated whether MDS can be predicted by DBP and chronological age. The main finding of this study suggests MDS to be significantly associated with single-leg DBP (CS, dominant side), interlimb balance symmetry (LSI), and chronological age. Additionally, single-leg DBP (CS, dominant side) and chronological age were found to be good predictors of MDS variance, regardless of interlimb balance symmetry (LSI). It can therefore be summarised that faster players correspond to the older players and, also, that MDS variance can be predicted by chronological age and DBP of the dominant leg.

6.5.1. Association between Speed and Balance

In the present study, it was assumed that faster MDS may correspond to greater single-leg DBP (CS) and greater limb symmetry index (LSI). Our results confirmed our hypothesis. In fact, greater single-leg balance performance (CS, dominant side: r = −0.194; p = 0.019) and interlimb balance symmetry (LSI: r = −0.167; p = 0.44) were found to have a small negative association with faster MDS for the soccer players in question. Unfortunately, association studies between balance performance, interlimb asymmetries, and speed performance lead to inconsistent findings [31]. In addition, to the best of the author's knowledge, there are almost no previous studies investigating the association between dynamic balance and MDS as measured in this study with the YBT and LEFT tests. Therefore, comparison with previous research remains a challenge, and more association studies are needed in order to investigate functional performance in young populations more thoroughly. However, one study showed the YBT to be significantly correlated with change of direction speed performance in young elite soccer players [35] Another study showed moderate associations between DBP (YBT) and speed performance (10 m and 30 m) in prepubescent soccer players [10]. In addition, it was demonstrated that balance training on both stable and unstable surfaces can lead to improvements in linear speed performance (40-Yard-sprint) [36]. Finally, the authors affirm that the activities requiring explosive power, such as change of direction movement, may reflect the ability to managing a better-balanced posture during fast actions [37]. In fact, in order to deal with previously developed musculoskeletal asymmetries and possibly reduce injury risk, older players with longer professional careers seem to stabilize their own knees and ankle joints more appropriately while executing fast movements [34]. Thus, in agreement with previous literature, it can be confirmed also by this study that enhancements in balance performance are associated with enhancements in speed performance.

6.5.2. Association between Speed and Age

For the present study, it was assumed that faster MDS may correspond to higher chronological age. The results of the present study confirmed our hypothesis and revealed a strong negative association (r = −0.626; p = 0.000) between the two variables, i.e., decreases in speed time (s) while ageing and therefore a faster MDS for older players. Although Ateş et al. found no association between age and speed performance during linear sprint tests (10 m and 30 m) in young soccer players [14], our finding is in line with the majority of previous studies. In fact, change-of-direction and sprint velocities were found to be positively associated with age at amateur level [38]. In addition, when linear sprint and multidirectional speed tests were executed together, their performances were found to be positively associated with age at elite level [39]. Thus, it can be deduced that speed performance is positively associated with age in young soccer players. Consequently, a particular investigative focus would therefore be essential when dealing with functional tests in young players in relation to long-term career goals. For example, this study shows that a higher speed performance can be expected from older players rather than younger players. Therefore, even though a recent study found that the 30 m sprint test was the best predictor of selection into an elite level youth football academy [40], the authors of the present study suggest that speed performance should not be taken as a unique benchmark for scouting strategies in young players. In fact, speed performance outcomes could be influenced by other factors. According to Valente-dos-Santos et al., skeletal maturity status explains inter-individual variability in maximal short-term run performances with and without the ball possession at early ages of participation in competitive soccer [41]. In addition, Bishop et al. reported that more "stable athletes" can run faster in multidirectional speed tests because of their better force distribution during these actions [31].

6.5.3. Speed Performance Prediction

It has been demonstrated that not only chronological age but also the DBP profile, i.e., single-leg scores and interlimb symmetry, could be positively associated with speed performance. To this concern, for the present study, it was assumed that the variance of MDS could be predicted by single-leg DBP and chronological age. Our results confirmed our hypothesis. In fact, chronological age and DBP on the dominant leg, but not limb symmetry index (LSI), were found to be good predictors ($r = 0.669$; $p = 0.001$) of the MDS variance. Our independent variables (chronological age and DBP) predicted the variance of our dependent variable (MDS) by 44.7% (r square = 0.447). Specifically, for each additional year of age, there was a reduction in MDS of 2.7 s ($p < 0.001$), while for each additional percentage in the CS of the dominant leg (YBT), there was a reduction in MDS of 0.4 s ($p = 0.002$). Our findings are in accordance with previous literature. In fact, the Y-balance test explained 68% of the variance of change of direction performance in elite soccer players [42]. In another study, it showed age to be a significant predictor of soccer-specific skills, such as change-of-direction speed performance [43]. However, our prediction rate of 44% is low and it should be interpreted with caution. In fact, speed and sprint performance have also been shown to be significantly associated with other influencing factors in youth academy soccer players, such as biological maturation, relative age-effect, training experience, and explosive strength [44–46]. However, these factors were not investigated in this study and further research is required.

6.5.4. Future Perspectives

A young athlete with a faster speed performance and a better unilateral balance, could provide more guarantees in terms of injury risk and functional performance, which could also be reflected in better skills in football practice and competition. Therefore, a better understanding of functional performance trends based on associations with chronological age could support sports clinicians in optimising pre-injury screening, scouting strategies, return to sport decision-making, and the implementation of preventive training programs. With regard to our findings, it is worth noting that poor results in single-leg balance performance (CS dom/non-dom ≤ 89%) are offset by good interlimb balance symmetry (LSI ≥ 90%) in all players. Additionally, in relation to the MDS, players from U14 to U19 showed faster execution time (≤ 100 s), while players from U11 to U13 showed slower execution time (≥ 100 s) in the LEFT. Nevertheless, if we reason that the cut-offs for YBT and LEFT (Table 1: CS ≤ 89%, LSI ≤ 90%, LEFT ≤ 100 s) have been already associated with a high risk of lower limb injury in young athletes [7,8,25,30], it may be deduced that these results could be a potential injury risk indicator for the players in question. Although injury data were not collected in this study, screening tests should be performed systematically in young and uninjured soccer players, at least twice a season, to identify subjects with greater injury risk indicators for the lower extremities and act preventively with individual training programs. Preventive single-leg balance training, as well as multidirectional speed training, might be the right solution to be integrated at an earlier age (from the u-11) in football academies.

6.5.5. Limitations

This study also has some limitations. First, the influence of height, weight, and BMI were not considered. Second, the effects of biological age and growth process were not evaluated. Also, other maturity-associated variables were not considered as change-of-direction speed determinants. Third, no follow-up nor longitudinal observation for injury documentation were carried out, and thus, no injury risk association can be made. Further studies are required to broader investigate these aspects.

6.6. Conclusions

The present study shows that faster players may correspond to older players in a professional soccer academy. Also, MDS can be predicted by chronological age and DBP of the dominant leg. MDS revealed a strong association with single-leg DBP of the dominant side and a small association with interlimb balance symmetry and chronological age. In addition, single-leg DBP (dominant side) and chronological age explained the variance of MDS by 44%, regardless of interlimb balance symmetry. Furthermore, our participants exhibited single-leg dynamic balance deficits (CS dominant, CS non-dominant ≤ 89%) but good limb symmetry index (LSI ≥ 90%) in all age groups. Therefore, the tests used in this study could be useful screening tools in soccer academies for the implementation of individual and prevention training programs. Specifically, these tests could support talent identification strategies and help sports therapists to detect players with performance deficits or more likely to get injured.

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7. Study Nr. 4: Limb symmetry index and pre-injury performance level after anterior cruciate ligament reconstruction: A case report on a female gymnast

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7.1. Abstract

Background: Functional performance tests serve to monitor the injured leg's resilience after anterior cruciate ligament injuries. The limb symmetry index greater than or equal to 90% represents an objective criterion to evaluate the knee function restoration and to return to sports.

Aims: The aim was to detect the point in time when limb symmetries and pre-injury levels of performance were restored, during the first year after surgery. Based on the data obtained, the proper moment for return to sport readiness was identified.

Methods: A 25-year-old female competitive gymnast performed a single-leg functional test battery. The study was conducted over 24 months and included one pre-injury and seven post-injury sessions.

Results: Inter-limb symmetries were restored at eight-ten months in all tests. Pre-injury performance levels were achieved at six months in two out of four tests. The single-leg hop for distance showed a performance decrease greater than 20% in the injured leg at twelve months.

Conclusion: Return to sport readiness was identified at ten months after surgery. Nevertheless, the restored inter-limb symmetry does not take into account performance decreases in the single-leg hop for distance and y-balance tests. Therefore, regular baseline assessments are recommendable to provide data for comparison and to optimise the decision-making process after injury.

Keywords: dynamic balance control, hop tests, limb asymmetry, knee injuries, return to sport readiness

7.2. Introduction

In artistic gymnastics, 50% of the injuries occur in the lower extremities [6]. Traumatic anterior cruciate ligament (ACL) injuries during landings are among the most frequent both in training and competition [6]. Despite a relatively high ACL-injury (ACL-I) rate of 0.24 per 1.000h of athletic exposure, women's gymnastics has received limited attention as for ACL-I rehabilitation and return to sports (RTS) protocols [2, 19, 20].

A survey among experienced arthroscopic surgeons showed that there is a lack of consensus on the use of appropriate criteria for RTS after ACL-reconstruction (ACL-R). In fact, 43.1% of surgeons declared to use proprioception tests and 39.0% to use single-leg jump tests while only 1.4% of surgeons reported to use a battery of different functional tests (single-leg balance, proprioception and jump tests) as relevant criteria for RTS [16].

Despite this lack of consensus, objective assessments are necessary for the RTS decision-making process after primary ACL-R, as they are a crucial part of most functional test batteries [3, 22]. In order to return to previous sports level without re-injury risk, an in-depth evaluation should be carried out on muscle strength and power deficits, insufficient neuromuscular control, poor balance and deteriorated postural stability [11, 12, 19].

Functional performance tests, such as single-leg hop and dynamic balance tasks, are commonly used to objectively monitor the restoration of physical abilities after ACL-R [1, 14, 18]. Furthermore, a test battery with a combination of hop tasks in different planes (frontal, sagittal and transversal) and dynamic balance tasks is recommendable for a thorough assessment of knee functionality [3, 11, 12, 14, 22]

When carrying out these tasks, the limb symmetry index (LSI) is the most used criterion to take decisions in RTS [11, 12, 25]. In order to determine the LSI (%), the injured (I) limb score in each task is divided by the non-injured (NI) limb score and multiplied by the factor 100 [12]. For single-leg hop and balance tests, a LSI value greater than or equal to 90% is a valid and reliable cut-off point to measure restored knee functions and to safely return to non-contact sports after ACL-I, both at recreational and competitive level [1, 11, 12, 18, 25]. Additionally, women who successfully return to pre-injury sports activity report higher LSI compared to those who do not return to pre-injury sports activity [20]. Nevertheless, the LSI might not take into account a potential decrease in performance of both limbs after ACL-R [7, 22, 23]. Hence, a sports-specific requirement profile and pre-injury performance levels represent further crucial aspects for a safer and more accurate RTS decision-making process [1, 11, 12, 25].

As a general rule, the LSI values are restored in functional tests within twelve months after ACL-R [1], but these criteria might overlook the deterioration in unilateral performance for the I/NI legs [7].

Thus, the goals of the present study were 1) to monitor the restoration process of knee functional symmetry and unilateral performance compared to pre-injury level and 2) to detect the right point in time for the return to sport readiness after ACL-R by means of a functional test battery.

7.3. Methods

This study was conducted at the Institute of Movement Therapy and Movement-oriented Prevention and Rehabilitation, at the German Sport University Cologne. Informed consent and ethical committee approval were obtained before the examination. The research was conducted in accordance with the declaration of Helsinki.

7.3.1. Sample

A female gymnastic athlete (age 25; weight 62.0 kg; height 162 cm; BMI 23.8; right/left limb length 94.5 cm) who competes at the German regional level was involved. At the time of the injury, the participant had an 18-year gymnastics experience and a training load of five sessions per week (2.5 h per session). The gymnast suffered from a non-contact ACL complete tear in the right dominant leg (02.2018). The injury mechanism was a double-leg landing during training. The ACL-R (04.2018) was performed two months after the injury with an autologous quadrupled semitendinosus and gracilis tendon graft. Because of a thin semitendinosus, gracilis tendon was harvested as well to reach the required graft diameter of 8mm, to ensure decreased post-operative knee pain and overall easier surgical recovery. Further reasons why this type of surgery was preferred to the patella tendon graft were the athlete's young age and the active participation in sport.

7.3.2. Study design

This case-report was designed on the basis of multiple testing measurements. The athlete performed a functional test battery for the lower extremities eight times (T1-T8). The entire observation period lasted twenty-four months (04.2017-04.2019). The first test (T1) was performed ten months before ACL-I as a baseline-screening assessment (04.2017). The second test (T2) was performed two months after injury (04.2018), but one week before the surgery. The third test (T3) was performed two months post ACL operation (PO) (06.2018) and subsequently five further tests (T4-T8) were carried out. A two-month interval was applied starting from the second (T2) to the last (T8) test.

7.3.3. Procedures

The test battery (see fig. 1) took approx. 60 minutes and consisted of four single-leg tests, performed barefoot on a therapeutic sport mat (FUCHSIUS® multi-media GmbH, München, Germany). For the sake of consistency, all tests were carried out in the same order and each test execution was supervised by the same sports' physical therapist, who has six years of scientific experience in the field. A ten-minute warm-up on a cycle-ergometer at moderate intensity followed by lower extremities mobility and dynamic stretching were performed before starting each test session. The athlete completed one trial attempt per limb for each test. Then, three valid attempts per limb were performed for each test. The limb to be tested first was randomly selected in each session and test to avoid learning effects in both trial and valid attempts. A regeneration time of 30 seconds between each attempt was allowed, while a two-minute interval between each test was used. All the tests were carried out with the hands positioned on the hips to avoid the effects of arm swing.

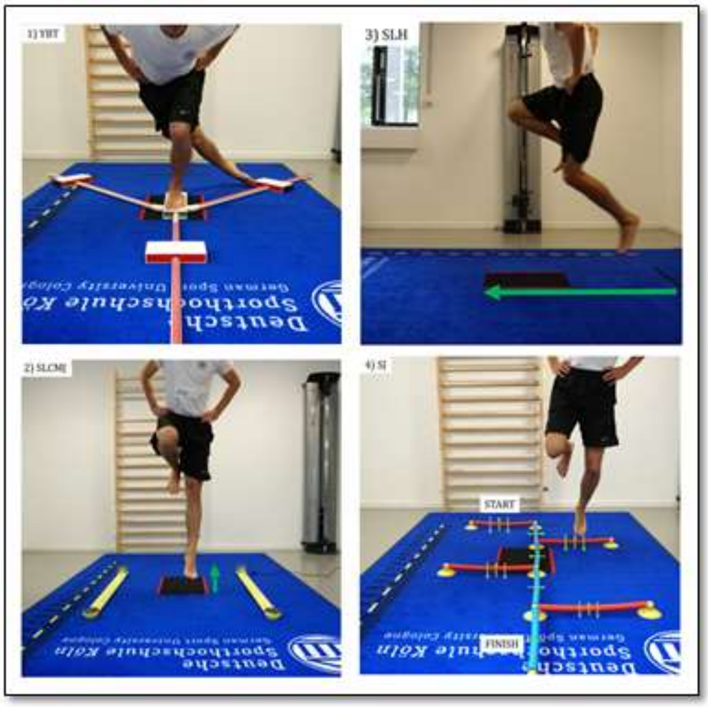

Figure 1. Test battery in order of execution: 1) Y-balance (YBT), 2) Single-leg countermovement jump (SLCMJ), 3) Single-leg hop for distance (SLH), 4) Speedy-jump (SJ).

7.3.4. Test battery

7.3.4.1. Y-balance test (YBT): The YBT is a reliable and valid instrument to measure dynamic balance and postural control stability PO [11, 12, 17]. The Y Balance Test Kit (Move2Perform®, Indiana, United States) was used. The athlete started in a single-leg upright standing position, with the toes of the standing leg at the marked red line of the instrument. With the toes of the contralateral leg, the sliding elements had to be pushed as far as possible in three given directions (anterior, posteromedial and posterolateral). During the execution, the standing leg had to maintain a full stance on the platform and the contralateral leg had to maintain constant contact with the sliding elements. The final single-leg balancing position to the starting point had to be maintained for three seconds, otherwise the test was invalid. The following compensatory movements were not allowed and marked as invalid trials: inability to maintain balance, touching the ground with the contralateral leg, elevating the heel of the tested leg, kicking the sliding element or using it as support. The limb length was measured for the normalisation of the scores [17]. As a performance score, the so-called "composite score" was calculated in percentage using the following formula: composite score = ((anterior + posteromedial + posterolateral performances in cm) / 3 x limb length in cm) x 100 [17].

7.3.4.2. Single-leg countermovement jump test (SLCMJ): The SLCMJ is a reliable and valid test to detect proprioception and neuromuscular control limitations [3, 12, 14]. The athlete started in a single-leg upright standing position and a countermovement flexion with the standing leg followed by an explosive jump was performed to reach the maximum height possible [10]. A stable landing with the same leg had to be kept for three seconds, otherwise the test was invalid. The following compensatory movements were not allowed and marked as invalid trials: intermediate jumps during landing, flexing the tested leg in the air, touching the ground or swinging with the contralateral leg. The OptoJump Kit (Version 1.12.1.0 - Microgate®, Bolzano, Italy) was used to measure the maximal vertical jumped height in centimetres (cm).

7.3.4.3. Single-leg hop for distance test (SLH): The SLH is a reliable and valid test to detect muscle strength and power deficits [3, 12, 14]. The athlete started in a single-leg upright standing position, with the toes placed at the start marked line on the ground. The athlete jumped as far as possible and landed on the same leg. A stable landing with the same leg must be kept for three seconds, otherwise, the test was invalid. The following compensatory movements were not allowed and marked as invalid trials: swinging with the contralateral leg, supporting with the contralateral leg, loss of balance or extra jumps at landing. The horizontal jumped distance was measured in centimetres (cm) from the start marked line (jump take-off) to the heel where the athlete landed [10].

7.3.4.4. Speedy jump test (SJ): The SJ is a reliable test to evaluate lower extremities' coordination, power, and dynamic knee stability while jumping as fast as possible [9]. The Speedy Basic Jump Set (TST - Trendsport®, Grosshöflein, Austria) was used. The starting position was single-leg upright standing. The athlete performed three jumps on each of the four red hurdles (forward-backward-forward jumps) and one jump on each of the four blue hurdles (sideway jumps), completing a total of 16 jumps (see figure 1). This had to be performed as quickly as possible [9]. A controlled landing with the same leg had to be maintained for three seconds, otherwise the test was invalid. The following compensatory movements were not allowed and marked as invalid trials: loss of balance, contralateral leg swinging or supporting on the ground. The test was immediately stopped if the athlete had direct contact with the speedy jump kit. Time was measured in seconds (s) using a stopwatch, from the first jump take-off phase to the last jump landing moment.

7.3.5. Descriptive statistics

For all tests, the best valid trial for each leg was considered as the result of the unilateral performance and was used to determine the LSI ((I-limb score / NI-limb score) x 100). An inverse formula (NI-limb score / I-limb score x 100) was used to calculate the LSI for the SJ, as a reduction in seconds (s) in this test was equivalent to a higher execution speed and therefore better performance. The following variables were used to obtain the results: composite score (%) for the YBT, vertical jumped height (cm) for the SLCMJ, horizontal jumped distance (cm) for the SLH, and execution time (s) for the SJ. The following formula was used to calculate the percentage variation in performance for all tests: $[(X_f/X_i \times 100)-100]$. The value X_f represented the final result (T8) while the value X_i the initial result (T1).

7.4. Results

LSI and I/NI limb results are shown in table 1. Data are divided per test session (T1-T8). The not available (N/A) results indicate that the test was not performed due to the inability of the athlete to properly execute. The RTS criteria (LSI≥90%) were achieved at eight-to-ten months PO for the hop tests, while a constant trend of LSI greater than 90% was shown for the balance test during the entire study period. Based on the restoration of knee functional symmetries, a suitable time for the readiness to return to gymnastics was detected at ten months PO (T7). At 12 months PO (T8), the pre-injury level of performance was achieved and improved in two out of four tests, namely SLCMJ (I: +11.1%; NI: +18.8%) and SJ (I: +21.6%; NI: +23.7%). Conversely, unilateral performance reduction was revealed for the YBT (I: -2%; NI: -2%) and SLH tests (I: -24.7%; NI: -5.8%).

Table 1. Results of the test battery

			T1	T2	T3	T4	T5	T6	T7	T8	Variation
YBT	**LSI (%)**		99.0	98.0	93.0	93.0	97.0	97.0	97.0	99.0	-
	Composite score (%)	**I**	101.0	96.0	91.0	95.0	97.0	98.0	97.0	99.0	-2.0%
		NI	102.0	98.0	97.0	102.0	100.0	101.0	100.0	100.0	-2.0%
SLCMJ	**LSI (%)**		112.0	N/A	N/A	53.0	89.0	94.0	94.0	105.0	-7.1%
	Jumped height (cm)	**I**	18.0	N/A	N/A	10.0	17.0	17.0	17.0	20.0	+11.1%
		NI	16.0	14.0	17.0	19.0	19.0	18.0	18.0	19.0	+18.8%
SLH	**LSI (%)**		121.0	N/A	N/A	74.0	88.0	77.0	94.0	97.0	-19.8%
	Jumped distance (cm)	**I**	186.0	N/A	N/A	110.0	130.0	116.0	139.0	140.0	-24.7%
		NI	154.0	145.0	149.0	147.0	147.0	151.0	148.0	145.0	-5.8%
SJ	**LSI (%)**		103.0	N/A	N/A	21.0	84.0	99.0	102.0	100.0	-2.9%
	Execution time (s)	**I**	7.4	N/A	N/A	35.2	7.8	6.4	6.0	5.8	+21.6%
		NI	7.6	7.0	7.0	7.4	6.5	6.3	6.2	5.8	+23.7%

Abbreviations: LSI: Limb symmetry index. I: Injured leg. NI: Non-injured leg. N/A: Not available. YBT: Y-balance test. SLCMJ: Single-leg countermovement jump test. SLH: Single-leg hop for distance test. SJ: Speedy-jump test. T1: Ten months before the injury. T2: Two months after injury, but two months before surgery. T3: Two months post-surgery. T4: Four months post-surgery. T5: Six months post-surgery. T6: Eight months post-surgery. T7: Ten months post-surgery. T8: Twelve months post-surgery.

7.5. Discussion

A female gymnastics athlete performed a functional test battery during the first year after ACL-R. The peculiarity of the study is that tests were carried out during rehabilitation with two-month interval. Data from 10 months before the injury were also available, which allowed a further comparison with the previous performance level of the athlete.

The main findings of this study were that a value of LSI ≥ 90% has been revealed in each test session with regard to the YBT (lowest value at T3: LSI 93%). Nevertheless, a different trend was observed as for the hop tasks: the SLCMJ (LSI 94%) and SJ (LSI 99%) restored the normal symmetry (LSI≥90%) eight months PO (T6), while the SLH (LSI 94%) reached this symmetry later, i.e. ten months PO (T7). An important aspect to be considered was the decrease in LSI at the end of the rehabilitation period (T8) compared to the pre-injury tests (T1), due to the inactivity of the athlete. All tests, except for the YBT, showed a decrease in the absolute values of the LSI: SLCMJ (-7.1%), SLH (-19.8%) and SJ (-2.9%). This may represent a limitation of the LSI since the contralateral strength was also reduced and the target (LSI ≥ 90%) was therefore not the same as prior to the injury.

According to Keller et al., balance skills can be restored as early as two months PO during the rehabilitation of a professional soccer player after ACL-R [11], while according to Xergia et al. and Carolan et al., functional deficits in single-leg hop tests may persist even up to nine months in athletes after ACL-R [5, 24]. Additionally, Beischer et al. observed that muscle and knee function deficiencies need a period of at least 12 months before being fully restored in young athletes after ACL-R [4]. Furthermore, Welling et al. demonstrate that a low rate of patients fulfil the RTS criteria (LSI≥90%) in functional, isokinetic and psychological tests at nine months after ACL-R [22]. The results obtained in the present study support that LSI values greater than or equal to 90% can be restored as early as ten months PO (T7) for a female gymnast, when measured with balance and hop tests.

The literature is still unclear as to when an athlete is ready to RTS after ACL-R. Normally, RTS at the pre-injury level is possible between 6-12 months if the only criterion is time from surgery [3, 20]. Zumstein et al. determined that if objective assessments and time are combined, a return to general sports may be possible as early as nine months [25]. Conversely, Keller et al. suggested that 12 months after ACL-R are necessary for the restoration of muscle functions and psychological readiness of the athlete for RTS at competitive level [11]. Nonetheless, Nagelli & Hewett argued that if RTS is allowed after 12 months PO, there is a high incidence of re-injury during the first year of sports activity in young athletes [13]. Therefore, they recommend a safe RTS after 24 months at least [13].

That notwithstanding, based on the restoration of knee functional symmetries in the present study, readiness for a safe return to competitive gymnastics has been identified at ten months after ACL-R (T7). Furthermore, LSI values have remained ≥ 90% at 12 months PO (T8) and no re-injury was reported for either the ipsilateral or contralateral leg at one-year follow-up period.

However, some authors [7, 22, 23] criticised LSI as it may not consider decreases in performance of both I/NI leg. Therefore, caution should be exercised when considering only LSI for readiness to RTS. In this context, Moiser & Bloch proposed that baseline data on the pre-injury level of athletes and absolute values could guide decision-making process in RTS by providing greater accuracy [12].

In the present case report, pre-injury levels of unilateral performance were restored in only two out of four tests, namely the SLCMJ at six months PO (T5) and the SJ at four-to-six months PO (T4–T5). In these two tests, the pre-injury performance levels increased for both legs (SLCMJ: I +11.1% and NI +18.8%; SJ: I +21.6% and NI +23.7%) at 12 months (T8). Conversely, in the two other tests (YBT and SLH) a performance decrease was observed for both legs at 12 months (T8). At the end of the rehabilitation (T8), while the YBT showed a minimal reduction in performance (I -2.0%; NI -2.0%), the SLH showed the highest difference (I -19.8%; NI – 24.7%) compared to the pre-injury level (T1). The question is whether the SLH was the only test to be sensitive enough to detect performance differences PO. However, the sensitivity of the test was not analysed, but it is worth noting that although both legs have performed the same strengthening training after ACL-R, there was a notable difference of the I/NI legs compared to the pre-injury performance (T1) in the SLH test at the end of the rehabilitation (T8).

Nawasreh et al. pointed out that the restoration of pre-injury levels in single-leg hop tests at 6 months after ACL-R is a predictor for safe RTS at 12 months [15]. This has also been observed in the present study, with the restoration of pre-injury performance levels in both SLCMJ and SJ tests and the successful RTS of the athlete at the pre-injury level. However, due to the lack of reference cut-off points in the literature, a further investigation of the unilateral performance prior to RTS was not possible for these tests (SLCMJ and SJ). Despite this lack in literature, with the anthropometric and performance values in mind the impression was that the gymnast reacted efficiently after ACL-R, achieving sufficient results to be able to RTS at the same level as before the injury.

Welling et al. stressed instead the suboptimal performance level for the SLH test in rehabilitated athletes at the time of RTS after ACL-R [22]. Our results support and integrate this finding, as not only the SLH but also the YBT revealed a suboptimal performance for both legs when compared to pre-injury levels. However, as far as the SLH is concerned, the difference in results between the I/NI leg was less than 20 cm at time for RTS (T7). This cut-off parameter is normally used to decide whether the athlete is ready to RTS after ACL-I [12]. As for the YBT, both legs showed a composite score greater than or equal to 94% at the time of RTS (T7). This is a cut-off parameter normally associated with low risk of lower extremities injury and RTS readiness [11, 17]. Therefore, despite the aforementioned decrements in performance (with regard to the YBT and SLH tests), the RTS was allowed at ten months PO (T7).

Finally, although pre-injury levels of unilateral performance are important, our results recommend to cautiously evaluate whether it is ideal to reach pre-injury levels for the LSI. As a matter of fact, at ten months before injury (T1), the future I-leg overperformed the NI-leg and the athlete showed an unbalanced LSI for both SLH (121%) and SLCMJ (112%) tests. This greater performance in the two hop tests could be related to a predominance of the quadriceps over the hamstring’s muscles. This predominance is a quite common characteristic in young gymnasts, which represents a high risk of ACL-I [21]. It could be assumed that these prospective deficits might have played a key role in the injury that occurred 10 months later [8]. However, ten months is too long a period during which neuromuscular adaptations can occur and therefore no conclusive relationships can be deduced.

It was shown that pre-injury functional tests are essential to get a more detailed picture of athletes in case an injury occurs. Furthermore, in the present study a two-month time interval was proposed as a suitable solution, to be performed not only in the rehabilitation phase, but also in the preventive phase as a baseline screening.

The strengths of this case report are multiple functional tests and systematic observation of performance development over time. Our findings are intended to stimulate future research, to further investigate ACL-rehabilitation, to create benchmarks for functional testing, as well as to clearly define the optimal timing of RTS in women's gymnastics.

7.5.1. Limitations

Firstly, the study design did not provide a statistical significance of the results. Secondly, it remained unclear whether the ACL-R gymnast was a high or low performer, due to the absence of sport- and age-specific reference data. Thirdly, the tests that were used might not have fully captured the extreme functional and biomechanical demands of competitive gymnastics. In fact, a critical analysis of the quality of motion and landing strategies (such as knee valgus and leg axis) was not performed; this could have provided interesting results and for this reason further studies focusing exclusively on these aspects are necessary. Furthermore, the heterogeneity of ACL-I, of surgical treatments, and of rehabilitation protocols made it difficult to draw any definitive conclusions. Besides, other influencing factors such as psychological-readiness and sport-specific biomechanical demands (such as hamstrings/quadriceps ratio) remained unexplored. Additionally, the clinical application of our results to surgical approaches other than hamstring tendon reconstruction, as much as to other sports and populations could also be a challenge. Further studies are needed to assess all these factors on a larger sample of participants.

7.6. Conclusion

To summarise, this case report is one of the few studies that monitor the rehabilitation process of an ACL-R gymnast, with the application of two-month interval testing measurements. The test battery proposed does not require special tools, it is easy to manage and can be quickly performed. The combination of different but complementary functional tests can be useful to objectively assess performance development and inter-limb symmetries. In this case report, a time from surgery of eight to ten months was needed for the restoration of inter-limb symmetries within RTS criteria (LSI≥90%). Consequently, the RTS readiness was detected at ten months PO. Nevertheless, the restoration of LSI did not consider the decreases of unilateral performance in the SHT and YBT tests at twelve months PO. Lastly, regular baseline screenings in competitive and uninjured athletes are advisable in order to provide data for comparison in case of injury and to support the RTS decision-making process.

Conflict of interest: There is no conflict of interest.

7.7. References

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8. General discussion

The present chapter contains the overarching discussion of the results (Chapter 8.1) and methods (Chapter 8.2) of the doctoral thesis, following on from the four scientific publications (Chapters 4, 5, 6 and 7).

This doctoral thesis contributed to knowledge on the use of functional performance test battery for the detection of injury risk factors in youth football players, as well as a support for rehabilitation in order to safely RTC after ACL-I in competitive gymnastics.

The rationale behind this doctoral thesis concerned: 1) the high rates of lower extremity injuries and, in particular, ACL injuries in high impact sports such as football or gymnastics [26,109,110]; 2) the lack of a reliable and standardized tool for testing injury risk factors, such as interlimb asymmetry or single-leg functional performance [3,26]; 3) the lack of sport- and gender-specific benchmarks for the functional performance tests selected, in order to allow better comparison of the results [26,115]; 4) the importance of pre-injury performance screening for the implementation of individual programs to decrease injury risk factors, as primary and secondary prevention strategies [4,26].

This doctoral thesis aimed to achieve the following objectives:

1) To select from the recent literature a reliable and standardized battery of functional tests for the lower limbs, making it available for amateur and professional sports, as it is easy to use and interpret the results, quick to perform and is not too expensive in terms of time and finances (Study No. 1).

2) To analyze balance, jump and speed performance trends in uninjured youth football players, to detect interlimb symmetry and to provide age-specific normative values (Studies No. 2 and 3). To examine whether there are associations between chronological age and functional performance in uninjured youth football players (Studies No. 2 and 3).

4) To assist the rehabilitation protocol of a competitive female gymnast after an ACL-R, to observe how long interlimb symmetry and single-leg performance need to return to their pre-injury level. Besides, to determine the right time to RTC (Study No. 4).

This research contributed to select a high reliable test battery for the lower limbs with a standardized testing procedure. In addition, functional performance benchmarks for healthy sport students have been provided. The selected test battery was then used to perform a functional performance screening of non-injured players from the youth sector of a professional football club. In order to detect injury risk factors at an early age, to analyze the associations between age and functional performance and to provide football - and age-specific normative values. Finally, the test battery was applied in a preventive-rehabilitative protocol, to monitor the rehabilitation process of a competitive gymnast athlete through periodic testing sessions. Based on pre-injury performance levels, it was possible to determine the right time for RTC after an ACL-R.

8.1. Discussion of the results

In this chapter, the overall significance of the results of the four studies (Chapters 4, 5, 6 and 7) is discussed with regard to the research aims of the doctoral thesis (Chapter 3).

8.1.1. Functional testing for the lower extremities

To draw valid results from sports injury research, functional performance must be evaluated with reliable and objective measures. A proper reliable assessment in clinical sports practice is crucial in order to carry out pre-injury tests and assist the rehabilitation process. The first aim of this doctoral thesis was to assess test–retest reliability within a seven-day interval of an experimental test battery for the measurements of functional performance of the lower extremities. Our results demonstrated on average a good-to-excellent test–retest reliability (0.89 < ICC < 0.97; 0.80 < α < 0.98) for the proposed functional test battery (Study No. 1).

The ”9+” functional movement test battery demonstrated high intraindividual variability and was able to identify movement patterns limitations predisposing professional male football players to lower extremities injury [8]. A high reliable and simple to perform test battery composed by functional stability, jump and plyometric measurements has been proposed by Hildebrandt et al. for healthy athletes [69]. Furthermore, the above-mentioned test battery demonstrates high capacity to detect neuromuscular limitations in ACL-R patients compared to healthy controls and to detect the inability for a safe RTS at 8 months PO [66,69]. A good to excellent test-retest reliability was demonstrated by Kockum et al., with a test battery composed by hop performance and leg muscle power tests [77]. They recommend this measurement tool for determining lower extremities functional limitations in healthy athletes or in ACL-R athletes during the rehabilitation process [77]. However, in order to obtain valuable and comparable results, the importance of the standardization procedure during functional testing has been already pointed out [77]. Therefore, it can be said that the results of the first study of this doctoral thesis agree with the reliability of the other test batteries in literature, but it cannot be overlooked that they differ in the application, measurements and included subjects, so that a proper comparison has not been possible (Study No. 1).

Test batteries are widely used in rehabilitation in order to enhance safe RTS after ACL-R and to enable longitudinal monitoring during rehabilitation [47,48,146]. In order to optimize the RTS decision-making process after ACL-R and to reduce the incidence of re-injuries, test batteries are not only restricted to functional performance measurements, but are also composed by isokinetic strength measurements and psychological readiness questionnaires, in order to implement multivariate models’ analysis [47,48]. Hop test batteries, besides to have high test-retest reliability, are able to discriminate between the performance of the injured/uninjured leg in both patients with ACL-I and ACL-R [56]. When composed by hop and balance functional tasks, test batteries show good interpretability, internal consistency and interrater reliability for the assessment of postural orientation during the rehabilitation of ACL-R patients [116]. A test battery for the postural orientation can detect altered patterns for both the injured/uninjured leg in ACL-R patients [158]. Additionally, if strength tests and evaluation of muscle power are included, test batteries could positively contribute for the decision-making process of athletes after ACL-I and ACL-R, in order to safely return to strenuous physical activities [120]. Thus, if test batteries are composed by numerous variables related to lower extremity function (e.g. isokinetic strength, muscle power, balance and hop tests), they allow a feasible evaluation of knee function after ACL-I [146]. The “Back-in-Action” test battery proposed by Ebert et al., for example, includes more physically demanding measurements, which are then reflected in lower LSI values following ACL-R and lower rate of athletes meeting the RTS required criteria [35]. The “Return-to-Activity Algorithm” proposed by Keller et al. is a test battery composed by several functional parameters (e.g. stability, balance, hop and sprint tests) and it has been used for rehabilitation purposes after ACL-R in professional football players, in order to detect performance deficits or asymmetries and to decide the right point in time to RTC [75]. Therefore, a test battery should be complex enough to appropriately test functional performance by reproducing sport-specific movements, but at the same time it should be affordable enough to allow a successful RTS. Thus, a specification regarding sport, gender and level of competition is crucial for the successful rehabilitation of individual athletes and is urgently needed.

Although the above-mentioned test batteries have already proven to be highly reliable, they have been majorly used in the context of rehabilitation for injured patients or athletes. However, performing functional performance tests is essential for healthy athletes as well, in order to recognize performance deficits and asymmetries at an early stage and to be able to plan individual training programs in order to reduce the risk of lower extremity injuries [69]. By establishing normative data from healthy individuals, it could be possible to set an important basis for clinical practice and rehabilitation strategies [69].

The results of the first study of this doctoral thesis showed an LSI ≥ 95% for the single-legged tests performed in healthy sport students, revealing no major interlimb functional asymmetries (LSI ≤ 90%) in uninjured population (Study Nr. 1). Normally, healthy sports students do not present interlimb asymmetries and show a perfect LSI ≥ 100% when performing single-leg hop tests [108]. Greenberg et al. showed similar results in uninjured youth athlete, proposing an LSI > 95% for each of the hop test performed [53]. Then, the absence of interlimb asymmetries in balance and hop tests could be normalized in healthy adult populations.

However, uninjured healthy athletes may show functional deficits. This is why the importance of pre-injury screening for prevention strategies is gaining ground in scientific practice. In fact, two thirds of healthy judo and taekwondo athletes presented side differences in jump tests and did not reach the interlimb symmetry threshold value (LSI ≥ 90%) [82]. In case of an injury, Lambert et al. suggested to refer to individual jump performance for each limb by performing pre-season screening in professional uninjured alpine ski athletes: while young adult athletes displayed optimal interlimb symmetries (LSI ≥ 100%) in strength-related tests, adolescent athletes displayed sub-optimal interlimb symmetries (LSI ≤ 90%) in hop tests and therefore were not able to safely RTS after injuries [154].

In this context, several authors already pointed out that youngest age groups may have a higher risk of lower extremities muscle and joint injury due to their higher limb asymmetries [47,48,63,114,155,156]. On the other hand, a longitudinal study shows no significant correlations between functional capacities and suffered injuries in football players [49]. In addition, some authors reported that the application of screening tools to identify players at risk of injury do not provide confident results in literature [135,136,137,138,139,140,141].

However, in professional football, besides previous injury, among the most perceived risk factors for a non-contact lower extremity injury are muscular fatigue, muscle imbalances, functional performance deficits or asymmetries and scarce movement efficiency [102]. Additionally, among the most utilized criteria for the identification of pertinent injury risk factors, the following are included: reduced lower limb symmetry in functional tests (e.g. balance and hop tasks), muscle imbalances in strength and power, proprioceptive and neuromuscular control deficits [135,136,137,138,139,140,141].

Sports injury prevention strategies are considered to be worth and cost-effective for sports clubs [93,175]. It has been demonstrated that young athletes can improve balance ability and vertical jump height after completing an injury prevention training program [152]. However, in order to determine an adequate injury prevention training program, it is necessary to proper recognize injury risk factors. Functional performance screening tests seem to be the most advantageous solution for team sports like football, given their quick and easy application, together with their reduced time for analysis and minimal financial cost [75,111].

The utility and use of functional performance screening tests have already been discussed in literature. For example, measurements of lower extremities static and dynamic postural control as well as muscle strength seem to enable the detection of injury risk profiles in elite youth football players [78]. Also, dynamic balance performance deficits (e.g. YBT) could place football players at four times higher risk to sustain a lower extremity injury [50].

To sum up, the first research question of this doctoral thesis can be positively answered, since the combination of different functional tests for the lower extremities resulted in a standardized, objective and high reliable test battery (Study No. 1).

In general, the most common prevention practices of premier league football clubs concern: 1) the utilisation of functional testing, 2) the identification of risk factors and 3) the implementation of preventive measures [102]. Based on this assumption and on the results of the Study No. 1, the second and third studies of this doctoral thesis were planned to explore the potentials of functional testing for risk factors identification in youth and uninjured football players (Studies No. 2 and 3).

8.1.2. Performance screening in youth football players

The secondary aim of this doctoral thesis was to detect functional performance deficits and asymmetries in youth and uninjured football players. Additionally, to explore the associations between functional performance and chronological age (Studies No. 2 and 3). Functional performance was intended as single-leg dynamic balance (DBP), single-leg jump in various directions and multidirectional speed (MDS). Furthermore, normative values were provided (Studies No. 2 and 3).

The main findings of the third and second studies of this doctoral thesis show a perfect interlimb symmetry (LSI ≥ 100%), both for jump and balance performance in uninjured youth football players. Therefore, perfect interlimb symmetries (LSI ≥ 100%) in functional tests could be assumed in young football players (Studies Nr. 2 and 3). In addition, it was found chronological age to be positively associated with single-leg DBP (dominant leg), single-leg hop performance in various directions (dominant, non-dominant leg) and MDS performance but not with LSI in uninjured youth football players (Studies Nr. 2 and 3).

Concerning the LSI, Premier League (English) football players exhibit their major interlimb asymmetries (LSI ≤ 90%) in jump tests [121]. Generally, while interlimb asymmetries in isokinetic strength tests have been already shown to be able to differentiate between academy and professional football players [14,15], LSI scores are not able to differ significantly between age-groups [14,15]. In addition, regardless of age and level of competition, non-injured football players do not tend to exhibit interlimb asymmetries (LSI ≤ 90%) in balance tests (e.g. YBT) [51]. Nevertheless, when strength tests are used, interlimb asymmetries could be more evident in players with lower training experience and professional training age [43]. Therefore, it seems appropriate to establish which measurement methods are necessary for the different objectives, because differences between the various tests have already been demonstrated in terms of ability to detect interlimb asymmetries. In this context, Madruga-Parera et al. encouraged practitioners to use multiple tests according to the sport-specific requirements profile, in order to detect existing interlimb differences in uninjured athletes [94].

Generally, in elite academy football players, asymmetries in jump tests may be present and be indicative for reduced athletic performance, such as change-of-direction speed [14,15]. In elite academy football players, it is therefore important to monitor functional performance asymmetries (e.g. balance, jump and speed), in order to define proper training and prevention strategies to reduce the risk of injuries [14,15]. However, this doctoral thesis did not investigate whether the absence of interlimb asymmetries could have been related to lower injury incidence during the season, due to the lack of longitudinal observation and injury documentation (Studies No. 2 and 3).

Normally, numerous factors contribute to the risk of injury in young footballers, such as performance deficits, interlimb asymmetries or biomechanical factors [79,101]. In addition, chronological and biological age represent important risk factors for lower extremity injuries in male youth football players [19,20,71,135,136,137,138,139,140,141,157]. In fact, high injury rates, risk and burden are related to the youngest age groups in youth male football players [22]. Thus, it seems clear that improvements on injury risk factors identification and preventive measures in younger athletes (e.g. children and adolescent), are urgently needed in sports science and research [22]. Age-related considerations may play a central role in football academies, not only for talent identification and injury prevention strategies, but also for the planification of performance-oriented strategies, such as the differentiation of training programs and testing procedures to be carried out. However, despite good prevention strategies or rehabilitation protocols, non-modifiable factors such as chronological age of athletes, could interact with the measurement, outcome and interpretation of functional performance tests (Studies No. 2 and 3).

The high incidence rate place football as one of the top five sports in which players are more prone to injury [143]. Injury susceptibility increases with advances in chronological age in youth male football players, and the implementation of targeted injury-risk prevention strategies is urgently needed in football academies [143].

In this context, Huertas et al. already pointed out that the selection and scouting processes in youth football academies may offsets age-related differences, which could be anticipated in functional performance due to growth and maturation [70]. In order to not disregard later maturation athletes and to decrease premature drop-out rates in youth football, talent sectors should consider not only motor function and maturation status assessments, but also chronological and biological age of athletes, which should be included for the development and interpretation of testing procedures and training programs [70,92].

In this doctoral thesis, chronological age was found to be positively associated with single-leg hop, balance (dominant leg) and multidirectional speed performance in uninjured youth football players (Studies Nr. 2 and 3). Concerning speed performance, also maturity status has revealed a great association with sprint performance in English male academy football players [133]. Previous authors also demonstrated that anaerobic performance and sprint ability improves during maturation in amateur male adolescent football players [74]. Concerning balance performance, it has been showed that dynamic balance capacity (e.g. YBT) may vary depending on the level of competition [24,25]. Contrarily, when performing the YBT in young male football players, age-related interactions were not found [112]. Concerning jump/hop performance, a recent study has shown that higher ages correspond to better jump performance children, adolescent and adult football players. [124]. This assumption was confirmed from a comparison study across age-categories in football players, which confirmed the higher jump performance for the older age groups [91]. However, the findings of this doctoral thesis partially adhere to what the literature offers, so further research is required on this topic (Studies No. 2 and 3). In particular, athletes' movement strategies may differ depending on age and level of competition, so normative values need to be established according to each age-group and competition level [24,25].

Concerning interlimb asymmetries, the LSI and its relationship with age have been already extensively investigated in sports science, bringing contrasting outcomes. In fact, chronological age and stage of maturation age could have a profound effect on interlimb asymmetries in young football players [135,136,137,138,139,140,141]. Interlimb asymmetries (LSI ≤ 90%) may start as early as childhood and remain stable in adolescence [135,136,137,138,139,140,141]. Furthermore, maturity status was found to be negatively correlated to interlimb asymmetries during clinical measurements in elite youth tennis players, therefore it has to be certainly considered during functional performance testing [90]. The results of the second and third articles of this doctoral thesis, however, could have not demonstrated the presence of any association between LSI and chronological age in uninjured youth football players, whereby further studies are required on this argument (Studies No. 2 and 3).

Another finding of this doctoral thesis was the dominant-leg dynamic balance performance (DBP) to be positively associated with multidirectional speed performance (MDS) in uninjured youth football players (Study No. 3). DBP and chronological age, in addition, explained the variation of MDS by 44% (Study No. 3).

Medium-sized associations were already discovered between speed, dynamic balance, and change-of-direction in prepubescent football players [61]. Additionally, linear and short distance sprinting, jumping and dynamic balance performance were showed to explain the variations of change-of-direction speed in young football players [37]. The main evidence from this doctoral thesis and the current literature suggests that a greater emphasis on DBP and MDS training might be a solution and an advantage for youth players, in order to increase neuromuscular capabilities and decrease injury risk factors [61].

This doctoral thesis, even though no follow-up nor longitudinal observations for injury documentation were performed, provides valuable normative values which can be useful for the comparison with existing literature or future studies. Pre-injury data are not only useful to monitor uninjured athletes' performance, but also to assist the rehabilitation process in case of an injury occur.

Finally, since the test battery was not capable of detecting interlimb asymmetries (LSI ≤ 90%) during single-leg balance and jump tests in young and uninjured footballers, the first half of the second research question of this doctoral thesis cannot be positively answered. Nevertheless, since the test battery was capable to detect age-related associations during single-leg functional performance tests (balance and jump) in young and uninjured footballers, the second half of the second research question of this doctoral thesis can be positively answered.

8.1.3. Rehabilitation and return to competition after ACL injury in female gymnastics

The final aim of this doctoral thesis was to monitor the rehabilitation process of a competitive female gymnastics' athlete by the use of the functional test battery during the first year after ACL-R (Study No. 4). The test battery was carried out during rehabilitation with two-month interval. In addition, data from 10 months before the injury were also available, which allowed a comprehensive comparison with the previous performance level of the athlete (Study No. 4).

The results of the Study No. 4 demonstrated that LSI values in functional performance tests can be restored at 10 months post-operation (PO) and maintained stable at 12 months PO after ACL-R (Study No. 4).

When aggressive quadriceps training is performed during rehabilitation, normal LSI can be restored to pre-injury level even at 6 months PO in sports athletes [88]. Contrarily, some authors showed that interlimb asymmetries (LSI ≤ 90%) and deficits in isokinetic strength tests may still persist at 9 months PO in ACL-R patients [17]. Other authors suggest that functional performance deficits and interlimb asymmetries (LSI ≤ 90%) may persist even up to 12 months PO in pre-adolescent athletes after ACL-R [54]. Thus, different restoration times for the LSI have been reported in the literature to date. These differences could be due to numerous factors, such as the age and practised sport of the ACL-R athlete, as well as the threshold values in clinical tests used for the clearance to RTC. Therefore, in order to decrease these discrepancies, a multidimensional and multifactorial approach is recommended in the RTC decision-making process. Additionally, the decision-making process should be based on the individual level of the injured athletes.

The LSI ≥ 90% is commonly reported as one of the most used criteria regarding the RTC decision-making process after ACL-I [152]. Study Nr. 4 demonstrated that RTC after ACL-R can be allowed not earlier than 10 months PO, when interlimb symmetries (LSI ≥ 90%) in functional performance tests are properly restored (Study No. 4). Some authors suggested that RTC clearance should be considered at least 6-12 months PO, when hop tests and psychological readiness are considered for the decision-making process [5,6]. Other authors advocated that RTC should be delayed until 24 months PO to avoid the risk of an ACL re-injury [118]. Most elite athletes, however, took less time than non-elite athletes (between 6- and 13-months PO) to RTS after ACL-R [81]. Thus, the findings of this doctoral thesis partially agree on what the literature states (Study No. 4). However, the combination of multiple factors may play a decisive role in order to optimize the RTC decision-making process after ACL-I. In fact, the Study No. 4 did not include other parameters (e.g. biomechanical measures, isokinetic strength tests or psychological readiness), which are commonly used in rehabilitation practice and which could have influenced the RTC decision-making process of the athlete in question. Therefore, a more comprehensive test battery including all these aspects is desirable for future research.

The findings of this doctoral thesis revealed another interesting aspect. Study Nr. 4 demonstrated that at 12 months after RTC, no re-injury was recorded if 3 out of 4 functional tests (performed for the clearance to RTC) have returned to their pre-injury level at 12 months PO (Study No. 4). In young athletes, there is a high overall rate (33%) of subsequent ACL injury for those who RTC before 12 months PO. However, a similar overall rate (32%) was also detected for those who RTC after 12 months PO [168,169]. Therefore, time from surgery seems to be not the only factor that can influence the recurrence of ACL injury and the pre-injury level of performance could be also considered for an optimized decision-making process. In fact, Study No. 4 showed that at the one-year follow-up after RTC, the athlete had not experienced any re-injury.

It was previously reported in literature that LSI can overestimate knee function after ACL-I [171]. In addition, previous authors demonstrated that bilateral deficits on hop tests could still be present in ACL-R athletes when compared to healthy controls [47,48]. Therefore, in rehabilitation it seems advisable to consider not only when ACL-R athletes can return to the desired performance level, but also if ACL-R athletes can restore their functional capacities with respect to the pre-injury level. This approach could support research on injury risk management and mitigation.

Finally, Study No. 4 demonstrated that pre-injury level of performance was not restored at 12 months PO for the single-leg hop for distance test (SLH) (Study No. 4). Nevertheless, the single hop for distance test (SLH) is considered one of the strongest objective predictive parameters for a successful RTC [113]. Additionally, interlimb asymmetries (LSI ≤ 90%) in the SLH at 6 months PO could be considered as an effective screening tool to identify athletes with future limitations in returning to sports at 12 months after ACL-R [119]. Also, hop tests can provide significantly higher LSI values with respect to isokinetic testing following ACL-R [117]. Therefore, based on the results of this doctoral thesis and current literature, it can be stated that LSI may overestimate single-leg performance and its values should be interpreted with caution when used as a criterion for RTS after ACL-R [47,48].

In most RTC protocols, it is almost never considered the pre-injury level of the athlete. Therefore, the execution of pre-injury performance screening on athletes is rare. During the rehabilitation process after ACL-R of a female competitive gymnast, the Study No. 4 demonstrated the importance of using pre-injury screening tests, in order to establish baseline data for the different performance levels and according to the individual athlete’s profile. Therefore, it is advisable to introduce pre-injury screening tests in the normal practice for optimizing injury prevention and rehabilitation strategies in youth sports athletes.

Finally, the answers to the third research question of this doctoral thesis can be summarised as follows:

a) The interlimb symmetry (LSI ≥ 90%) in functional tests restores at least 10 months after ACL-R for a competitive female gymnast.

b) The single-leg functional performance restores to pre-injury level at least 12 months after ACL-R for a competitive female gymnast. However, functional performance for the SLH test has not been restored.

c) Based on the restoration of interlimb symmetries, the RTC can be allowed from 10 months after ACL-R for a competitive female gymnast.

8.2. Discussion of the methods

Since the strengths and weaknesses of the four published studies have already been discussed within the scientific articles (Chapters 4, 5, 6 and 7), the following section will highlight the methodological limitations.

In this doctoral thesis, the influence of growth and maturation status (Study No. 2 and 3), practiced sport and gender of the participants (Study No. 1) were not considered. Biological maturity status significantly influences the functional capacity of adolescent football players [97]. Age and maturation positively influence also hop performance [135,136,137,138,139,140,141]. Biological maturation influences the selection strategies in youth football players [161]. Gender and practised sport are indicated as influencing factors for the performance and functional capabilities of young athletes [23]. Therefore, future research should also consider the influences of these factors in longitudinal and association studies.

Intrarater and interrater reliability are fundamental aspects for the efficient utilization of functional tests. Previous authors already advocated for more reliability analysis studies [72]. Generally, for excellent reliability in functional assessments, patients should be scored by one test leader [80]. In the Study No. 1, the tests were carried out by one test leader accordingly. Furthermore, for acceptable reliability between multiple test leaders, the first landing of hop tests (e.g. drop vertical jump) should be taken for the score [80]. In the Study No. 1, it was considered the absolute best hop performance for the score, because the tests were carried out by only one rater. In addition, to be properly used and interpreted, a test must also be valid. Validity refers to the accuracy of a measurement instrument and assesses whether the characteristic being measured and the characteristic it has to be measured are the same [80]. However, intrarater and interrater reliability, as well as validity of the tests were not analysed in this doctoral thesis (Study Nr. 1). Therefore, further studies are required to deeply investigate these aspects. Furthermore, for optimal test-retest reliability results, a large number of participants is required for reaching sound conclusions [80]. However, this aspect was not considered in this doctoral thesis (Studies Nr. 1, 2, 3 and 4) and therefore is suggested for future researches.

In this doctoral thesis, the influence of field position and activity level of uninjured youth football players was not considered (Studies Nr. 2 and 3). In previous research it has been shown that single-leg strength and functional performance outcomes, but not interlimb symmetry, may differ based on activity level in healthy participants [86] Also, maximal functional performance (e.g. maximal jump height) can extensively be influenced by different activity levels in children and adolescents [41]. In addition, differences in functional balance test (e.g. YBT) can be influenced by activity level and field position in football players [86]. These differences are important for a clinician's understanding of normative values and for the interpretation of the RTC outcomes. Therefore, these influencing factors should be included in future studies.

Follow-ups are important in football not only to monitor training progress, but also to document injuries. In this way, it is possible to uncover any injury correlation with possible deficits and asymmetries of the lower limbs during functional tests [11,46]. However, no follow-up or longitudinal observation for injury documentation were executed in this doctoral thesis (Studies No. 2 and 3). A recent research stated that performance limitations should be used as part of injury definitions in injury surveillance strategies. The clinicians and sport therapists involved should have an active role to guide this process [165]. Thus, longitudinal observations and follow-ups for injury documentation are urgently required for further studies.

In this doctoral thesis, a longitudinal observation was applied during the ACL-I rehabilitation of a female gymnast (Study No. 4). However, the study design was a case report, so that it was not possible to provide statistical significance of the results. Therefore, a larger cohort of participants for longitudinal studies in ACL-R athletes is strictly required. Finally, gold standard measurements such as movement quality analysis for the identification of primary/secondary ACL risk factors, isokinetic tests for the hamstrings/quadriceps strength ratio and psychological readiness of the athlete were not considered during the RTC decision-making process of this doctoral thesis (Study No. 4). Therefore, an optimized, criterion-based approach for the rehabilitation after ACL injury is suggested for future studies.

8.3. Practical implications and future directions

Functional performance tests are fundamental in the return to sport decision-making process, but are also important for injury prevention, to identify risk factors and intervene accordingly with individual training programs, aimed at reducing injury incidence. Unfortunately, there is a lack of functional tests in the literature that have demonstrated high reliability, making their application and interpretation questionable. However, the first study of this doctoral thesis found that selected functional tests, when properly organized and standardized, produce high statistical reliability and bode well for their future use in clinical practice (Study No. 1).

Additionally, healthy sport students showed a mean interlimb symmetry index of 95% in all functional tests, thus not calculable as a risk factor for lower limb injuries (Study No. 1). In healthy sport athletes, a lower limb symmetry index of 90% in functional tests is usually considered normal and out of the risk of injury. Additionally, during rehabilitation after anterior cruciate ligament injury, a lower limb symmetry index of 90% is the cut-off point for restored functional performance and to return to sport. Based on the findings of the first study of this doctoral thesis, an LSI of at least 95% in uninjured sport athletes could be considered instead (Study No. 1).

Lower limb functional test batteries are widely used in the scientific literature, especially to monitor and assist the rehabilitation of injured athletes and patients. Thanks to this, it is possible to refer to a large amount of sport-, age- and gender-specific benchmarks of injured athletes, enabling high-quality clinical comparisons. In contrast, from an injury prevention perspective, test batteries are not so widely used and there is a lack of sport-, age- and gender-specific benchmarks for uninjured sport athletes. In the absence of these benchmarks, it is difficult to adequately interpret the results from the pre-injury screening procedures. Furthermore, in sports research and practice, the use of preventive training programmes largely prevails over systematic screening of functional performance. This brings numerous advantages such as a drastic decrease in the incidence of injuries [130]. Nonetheless, good success in reducing ACL injuries through pre-injury screening followed by preventive training of players at risk could also be a solution [106]. However, in order to plan optimal preventive training plans, it is essential to recognise the risk factors present individually in each athlete. This doctoral thesis offers the scientific community a clear example of performance screening in uninjured athletes, demonstrating that an LSI ≥ 100% should be normalized for football players at young age (Studies No. 2 and 3). Furthermore, it is worth to look more at the associations that chronological age may have with functional performance parameters, rather than lower limb asymmetries (LSI), to be able to plan effective individual prevention programs (Studies No. 2 and 3).

In general, functional test-assisted rehabilitation relies on comparing the injured leg with the uninjured leg for obtaining the limb symmetry index, which does not always lead to the desired results. In fact, after an ACL injury, for example, the performance of the uninjured leg also decreases, making these comparisons not so valid. This is why an effort is needed from the entire sports science community, in order to apply periodic and systematic pre-injury screening measurements, so that the pre-injury level of functional performance of athletes can be considered at the moment of injury. In this doctoral thesis, a female competitive gymnast who suffered an ACL-R was returned to sport within the first year of rehabilitation, thanks to the systematic use of functional tests to monitor the rehabilitation and to support the decision-making process (Study No. 4). The LSI values of the injured athlete were restored 10 months PO (LSI ≥ 90%) and remained stable at 12 months PO (Study No. 4). Therefore, RTC was allowed at 10 months PO (Study No. 4). However, the pre-injury performance level in the single-leg hop for distance (SLH) test was not restored at 12 months PO (Study No. 4). Nevertheless, the athlete did not suffer any re-injury at one-year follow-up after RTC (Study No. 4). Thus, the importance of baseline data from uninjured athletes is underlined here. This doctoral thesis showed how and why pre-injury data can be useful in the event of an injury, in order to guide the rehabilitation process for a successful RTC after ACL injuries.

To summarize the methodological considerations and practical implications for future research, this doctoral thesis provided a reliable, objective and standardized test battery for the assessment of functional performance of the lower extremities (Study No. 1). The test battery consists of an easy-to-use, fast-to-execute and not expensive measurement tool for the implementation of injury prevention and rehabilitation strategies in football academies and sports clinical practice (Studies No. 1, 2, 3 and 4). Sport- and age- specific normative values were provided for healthy sports students, uninjured youth football players and a competitive female gymnastic athlete after ACL-R (Studies No. 1, 2, 3 and 4). Positive associations between chronological age and functional performance, but no associations between chronological age and interlimb symmetry (LSI) were found in uninjured youth football players (Studies No. 2 and 3). Healthy sport students as well as uninjured youth football players do not display interlimb asymmetries (LSI ≤ 90%) in single-leg functional performance tests (Studies No. 1, 2 and 3). During the rehabilitation after ACL-I, the LSI restores after 10 months post ACL-R in a competitive female gymnast, but the pre-injury level in jumping performance (SLH, dominant and non-dominant) does not restore at 12 months post-surgery (Study No. 4). The RTC is allowed 12 months post-surgery, if LSI values (restored at 10 months) are kept stable at 12 months post-surgery (LSI ≥ 90%). At one-year follow-up after RTC, the competition level was the same as before the injury and no re-injuries were recorded (Study No. 4). Thus, the rehabilitation was successful and this finding could provide new perspectives that can support sports therapist, physiotherapists, and physical therapists in injury prevention strategies and RTC decision-making processes after ACL-R.

9. Conclusion

This doctoral thesis can be summarised as a scientific research with three-fold aim. In fact, the first study (Study No. 1) sought to understand how best to measure functional performance in healthy athletes, by providing a high reliable and standardized testing measurements for injury prevention and rehabilitation strategies. The second and third studies (Studies No. 2 and 3) contributed to deeply understand functional performance trends and their association with chronological age in uninjured youth football players. In fact, uninjured youth football players do not exhibit interlimb asymmetries during balance and jump tests, and an LSI ≥ 100% could be expected for this population. In addition, older players executed with better dynamic balance (dominant), jumping (dominant, non-dominant) and multidirectional speed performance. Thus, in football academies, age is an important factor with significant influence on functional performance and must therefore always be considered when performing individual tests and planning training programmes. Furthermore, studies No. 2-3 provided sport- and age-specific benchmarks for functional performance to allow better comparison in future research. Finally, the fourth study (Study No. 4) applied the test battery during the rehabilitation protocol after ACL-I of a female competitive gymnast. The test battery was used at two-month intervals to observe how long it takes to restore interlimb symmetries and pre-injury level of the lower extremities. Pre-injury data were also recorded and could better orientate the RTC decision-making process. The LSI of the lower limbs restores at 10 months PO and remains stable at 12 months PO. However, while the pre-injury level in the SLH was not restored at 12 months PO, RTC was allowed at 12 months PO, based on LSI data. To conclude, this doctoral thesis could contribute to improve individual and comparative analysis for future research. The proposed test battery could be useful in collecting pre-injury data, providing a baseline for the planification of corrective training programs and for the optimization of rehabilitation monitoring. Follow-up for injury documentation is necessary and as much important as pre-injury screening assessments for uninjured young athletes, in order to establish performance trends and guidelines. Standardized, reliable and objective testing procedures are necessary for the transferability of the methods and the comparability of the results.

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