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Deutschen Sporthochschule Köln
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Leistungs- und Belastungscharakteristika im leichtathletischen Weitsprung mit Unterschenkelprothese

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Köln im Oktober 2019, Johannes Funken

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INHALTSVERZEICHNIS

ABBILDUNGSVERZEICHNIS

TABELLENVERZEICHNIS

EINLEITUNG

Weitspringer*innen mit Unterschenkelamputation[A], die eine Sportprothese nutzen sind in der Lage beeindruckende Weiten zu erzielen. Der deutsche Weitspringer Markus Rehm, beispielsweise, stellte zuletzt bei den Para-Leichtathletik-Europameisterschaften 2018 in Berlin einen neuen Weltrekord (8,48 m) in der Wertungsklasse der männlichen Athleten[B] mit einseitiger transtibialer Amputation auf [1]. Bei Betrachtung der Podiumsplatzierungen der vergangenen Olympischen Spiele [2] fällt auf, dass diese Weite bei den letzten drei Olympischen Spielen ausgereicht hätte um die Goldmedaille im Weitsprung zu gewinnen und bei allen Olympischen Spielen der Neuzeit mit mindestens einer Bronzemedaille im Weitsprung ausgezeichnet worden wäre [3].

Die zu Grunde liegende Biomechanik des Weitsprungs mit Sportprothese auf dem aktuellen Leitungsniveau ist jedoch weitgehend unbekannt. Auf der Basis einer dreidimensionalen Bewegungsanalyse, vertieft die vorliegende Dissertation daher das Wissen zum Weitsprung mit Unterschenkelprothese und bearbeitet hierbei drei Leitfragen. Diese erstrecken sich über das Verstehen der Bewegung und deren Einordnung in die Biomechanik, es wird die Frage der Chancengleichheit im Vergleich zu Athleten ohne Amputation aufgegriffen und es wird eine Betrachtung der muskulo-skelettalen Belastung vorgenommen.

Neben ihrer sportwissenschaftlichen Relevanz aus Sicht der Biomechanik, können die Ergebnisse und Ausarbeitungen der vorliegenden Arbeit in Diskussionen soziokultureller, philosophischer oder sportrechtlicher Natur einfließen.

[A] Der Begriff "Unterschenkelamputation" meint im Rahmen dieser Dissertation eine transtibiale Amputation, also eine Amputation unterhalb des Kniegelenks

[B] Bei der Ausarbeitung dieser Dissertation wurde auf einen genderneutralen Sprachgebrauch geachtet. Wenn im Verlaufe dieser Arbeit das Wort "Athlet", also die männliche Form, genutzt wird ist explizit der männliche Athlet gemeint.

WEITSPRUNG MIT UNTERSCHENKELPROTHESE

In diesem Kapitel wird eine kurze Einführung in die Eigenschaften einer von transtibial amputierten Athlet*innen für das Laufen, Sprinten und Springen eingesetzten Sportprothese gegeben. Weiterhin wird der Forschungsstand zum Weitsprung mit und ohne Unterschenkelprothese[C] in komprimierter Form erarbeitet, die bestehende Wissenslücke herausgestellt und die daraus resultierenden Forschungsfragen abgeleitet. Detaillierte, fragestellung-spezifische Darstellungen der relevanten Literatur finden sich in den Einleitungsteilen der jeweiligen Studien.

Sportprothesen aus Karbon zum Laufen, Sprinten und Springen

In Laufdisziplinen nutzen Athlet*innen mit einer Amputation an den unteren Extremtäten seit etwa 30 Jahren Prothesen aus Karbon im Wettkampf [4]. Diese, für das Laufen und Sprinten optimierten, in der englisch sprachigen Fachliteratur als '*Running-Specific Prosthesis*' (RSP) bezeichneten, Prothesen wurden seitdem stetig weiterentwickelt [5] und bestehen für Athlet*innen mit einer transtibialen Amputation heute im Wesentlichen aus zwei Komponenten - dem Schaft und der Prothesenfeder, die über unterschiedliche Adapter und/oder Verbindungselemente starr miteinander verbunden werden [6]. Abbildung 1 zeigt beispielhaft die Bauteile einer für den Weitsprung eingesetzten Unterschenkelprothese. Diese unterscheidet sich lediglich hinsichtlich der, von den Athlet*innen gewählten, Steifigkeit von den Prothesen, die für das Laufen und Sprinten eingesetzt werden. Anders als bei Athlet*innen mit einer transfemoralen Amputation, haben Athlet*innen mit transtibialer Amputation noch ihr eigenes, biologisches Kniegelenk. Die Prothese,

[C] Die Formulierung "Weitsprung mit und ohne Unterschenkelprothese" soll im weiteren Verlauf dieser Dissertation äquivalent zu der Formulierung "Weitsprung von Athleten mit Unterschenkelprothese und nicht amputierten Athleten" verstanden werden.

bestehend aus Schaft und Feder, fungiert als ein starr miteinander verbundenes Bauteil. Während der Schaft die Funktion hat eine Bindung zwischen Prothese und Unterschenkelstumpf herzustellen, dient die Prothesenfeder der Interaktion mit dem Boden.

Abbildung 1: Unterschenkelprothese zum Laufen, Sprinten und Springen. Links: Schaft und Prothesenfeder als Einzelbauteile. Rechts: Gesamtprothese mit Textilüberzug und retro-reflektierenden Markern für die Bewegungsanalyse

Laut Bestimmung des International Paralympic Committee (IPC) zur Wettkampfausrüstung (IPC Policy on Sport Equipment, 3.2) [7], ist Equipment verboten, welches dazu führt, dass die sportliche Leistung nicht vornehmlich durch den Athleten bzw. die Athletin, sondern durch automatisierte, computergestützte oder roboterhafte Vorrichtungen generiert wird. Aus diesem Grund sind die bei Wettkämpfen, welche dem IPC Regelwerk folgen, eingesetzten Unterschenkelprothesen rein passiv-elastische Bauteile. Mit dem Einwirken einer Kraft (z.B. Bodenreaktionskraft) kann die Prothesenfeder mechanisch verformt werden und somit Energie speichern [8–10]. Mit nachlassender Kraft entspannt sich die Feder und die darin gespeicherte Energie wird an das mit ihr verbundene System, also den Athleten bzw. die Athletin, zurückgegeben [8–10].

Anders als ein biologisches Bein verfügen die im sportlichen Wettkampf zum Laufen, Sprinten und Springen eingesetzten Karbonprothesen nicht über die Möglichkeit eine sensorische Rückmeldung an den Athleten bzw. die Athletin zu geben [11]. Weiterhin wurden aktuelle Federmodelle nur bedingt für Bewegungen in anderen Bewegungsebenen als der Sagittalebene ausgelegt, was sich beispielhaft darin zeigt, dass sie beim Kurvensprint die Funktionen des kurveninneren Beins nicht in gleichem Maße wie ein biologisches Bein übernehmen können [12,13].

Biomechanische Aspekte des Weitsprungs mit und ohne Unterschenkelprothese

Weitsprung ohne Prothese. Eine gute Leistung im leichtathletischen Weitsprung erfordert eine hohe Anlaufgeschwindigkeit und einen effektiven Absprungschritt [14–16]. Wie von Hay (1986) [17] dargestellt, wird die Wichtigkeit beider Parameter in Relation zum Leistungsniveau in der Literatur kontrovers diskutiert. Auch in späteren Arbeiten bleiben die Ansichten verschiedener Autoren uneinheitlich. So schlussfolgern Graham-Smith und Kollegen [14], dass die Anlaufgeschwindigkeit der dominierende Parameter ist, während sich Muraki und Kollegen [18] in der Einleitung ihrer Arbeit der Argumentation von Lukin (1949 [19], zitiert in: [17]) anschließen, welche der Absprungtechnik, gerade auf einem hohen Leistungsniveau, einen besonderen Stellenwert zuschreibt. Bridgett und Kollegen [20] zeigen in einer Fallstudie, dass sich die Sprungweite im obersten Leistungsbereich nicht mehr linear zur Anlaufgeschwindigkeit weiterentwickelt.

In Vorbereitung auf den Absprung senken nicht amputierte Athleten ihren Körperschwerpunkt während der letzten Schritte vor dem Absprungschritt ab [21,22]. Für den eigentlichen Absprung nutzen sie im Anschluss eine Technik, die in der Literatur als „Pivoting“ beschrieben wird [16,23], um vertikale Abfluggeschwindigkeit zu generieren [23]. Hierbei versuchen sie ihr Bein als rigiden Hebel einzusetzen und ihren Körperschwerpunkt um den Fuß zu rotieren [23]. Um einen relativ starren Hebel zu erzeugen, ist es nötig der Flexion der beteiligten Gelenke zu widerstehen, was wiederum durch entsprechende exzentrische Kraftfähigkeiten in der beteiligten Muskulatur begünstigt wird [14,16,23,24]. Der Absprungwinkel, resultierend aus dem Verhältnis von horizontaler zu vertikaler Absprunggeschwindigkeit, wird laut einer Übersichtsarbeit von Hay (1986) [17] von verschiedenen Autoren mit Werten zwischen 18,4 und 26,6° angegeben. In anderen ausgewählten Literaturstellen werden Mittelwerte von etwa 20° angegeben [15,25] und Popov (1971 [26], zitiert in: [17]) schlägt vor einen optimalen Absprungwinkel von 20 – 22° anzustreben.

Während die Kinematik des Weitsprungs in der Sagittaleben umfassend analysiert wurde, sind entsprechende Untersuchungen für die Frontal- und Transversalebene [14,15] nicht umfassend. Informationen über kinetische Parameter, wie Bodenreaktionskräfte und Gelenkmomente, welche Aufschluss über muskulo-skelettale Belastungen geben können sind ebenfalls sehr limitiert. Lediglich in zwei Arbeiten [18,27] wurden Gelenkmomente in der Sagittalebene kalkuliert, davon nur in einer Arbeit aus dem vollen Anlauf [18]. Entsprechende Untersuchungen bzgl. Kinetik bzw. Muskel-Skelett-Belastung für die Frontal- und Transversalebene bei nicht amputierten Weitspringer*innen während des Absprungschritts fehlen gänzlich.

Der Weitsprung mit Sportprothese. Der Weitsprung mit Sportprothese ist nur bedingt erforscht. Es gibt eine Reihe von Forschungsarbeiten von Nolan und Kollegen [28–32], die Athletinnen bzw. Athleten mit transtibialer oder transfemoraler Amputation auf internationalen Wettkämpfen zwischen 1998 und 2004 untersucht haben. Hier wurde zunächst kein Unterschied in den grundlegenden Bewegungsmustern im Anlauf und im Absprung zwischen Athleten mit einseitiger, transtibialer Amputation [28] und den aus der Literatur bekannten Bewegungsmustern von nicht amputierten Athleten erkannt. Allerdings nutzte in dieser Untersuchung, die während der paralympischen Weltmeisterschaften 1998 stattfand, nur ein Athlet das prothetische Bein für den Absprung. Alle anderen Athleten sprangen von ihrem biologischen Bein ab. Bei den Paralympischen Spielen 2004 sprang die Hälfte der untersuchten Athleten mit Unterschenkelamputation von ihrem prothetischen Bein ab [31]. Nolan und Kollegen [31], stellten hier fest, dass sich die Absprungbiomechanik der Athleten, die ihre Prothese für den Absprung verwendeten, deutlich von der Technik unterschied, welche die Athleten verwendeten, die von ihrem biologischen Bein absprangen. Die mittleren Sprungweiten unterschieden sich jedoch nicht signifikant zwischen den beiden Gruppen. Die Autoren verglichen die Technik, der Athleten, die von ihrer Prothese absprangen, mit der Nutzung eines Sprungbrettes mit ‚steifem' Kniegelenk, während die Athleten, die von ihrem biologischen Bein absprangen eine ausgeprägte Knie- und Hüftextension aufwiesen [31]. Während den Finals der Paralympischen Spiele 2004 wurde in der Wertung der einseitig unterschenkelamputierten, männlichen Athleten eine Bestweite von 6,68 m erreicht (Absprung von der Prothese) [31]. Heute, anders als noch in den Jahren 2002 [29] oder 2004 [31], nutzen nahezu alle männlichen Spitzenathleten mit Unterschenkelamputation ihre Prothese für den Absprung und der Weltrekord im Weitsprung in der Wertung der einseitig unterschenkelamputierten männlichen Athleten liegt bei 8,48 m (aufgestellt: August 2018) [1]. Biomechanische Untersuchungen, die Athleten mit Unterschenkelamputation auf einem aktuellen Leistungsniveau einschließen, fehlen ebenso, wie kinematische Analysen der Frontal- oder Transversalebene. Forschungsarbeiten, welche kinetische Parameter wie Bodenreaktionskräfte erhoben, oder Gelenkmomente kalkuliert hätten, sind weder für die Sagittalebene noch für die Frontal- oder die Transversalebene bekannt. Ebenso wenig sind energetische Betrachtungen bekannt, wie sie zum Sprint mit Sportprothesen [9] oder anderen Disziplinen, wie dem Stabhochsprung [33], gemacht wurden, bei denen elastische, federartige Hilfsmittel verwendet werden.

Problemstellung und Leitfragen

Bedingt durch die deutliche Leistungsentwicklung der Weitspringer mit Unterschenkelprothese in den letzten 10 bis 15 Jahren entsteht nun die Frage, ob Athleten mit Unterschenkelprothese[D] und nicht amputierte Athleten im sportlichen Wettkampf, innerhalb derselben Wertung, gegeneinander antreten sollten. Ähnlich der Debatte um den beidseitig transtibial amputierten Sprinter Oscar Pistorius [34,35], drängt sich sogleich die Frage auf, ob die Nutzung von Prothesen, deren Funktion der einer Sprungfeder gleicht, dem amputierten Weitspringer einen Vorteil im Wettkampf gegenüber nicht amputierten Weitspringern verschafft oder ob sich das Fehlen eines Teils des Unterschenkels sowie des Fuße insgesamt nachteilig auf die Wettkampfleistung auswirkt. Es steht also wieder, oder immer noch, die Frage der Fairness bzw. der Chancengleichheit im Raum, deren Aufarbeitung nicht nur aus sportwissenschaftlicher Sicht, sondern auch aus einer soziokulturellen, philosophischen oder sportrechtlichen Perspektive interessant und relevant sein kann. Die o.g. Frage kann jedoch aus biomechanischer Sicht auf Grundlage der vorhandenen Informationen nicht angemessen und umfassend beantwortet werden.

Es ist nicht bekannt, ob sich die grundlegenden Bewegungsmechanismen, ebenso wie die Sprungweiten, trotz Nutzung einer Prothese, zwischen Weitspringern mit und ohne Unterschenkelprothese angeglichen haben. Es ist jedoch unabdingbar, zunächst die zu Grunde liegenden Bewegungsmechanismen zu verstehen und allgemeingültige Ableitungen zu schaffen, um im Nachgang eine individualisierte Leistungsdiagnostik sowie eine erfolgreiche Bewegungsvermittlung bzw. -optimierung gewährleisten zu können.

Neben der Leistungsoptimierung ist es im (Spitzen-) Sport wichtig, Verletzungen und Überlastungsschäden frühzeitig zu diagnostizieren oder diesen idealerweise vorzubeugen. Hierzu ist es unabdingbar für Trainer und Athleten, sowie für das betreuende medizinische Personal, Kenntnisse über das muskulo-skelettale System betreffende

[D] Im weiteren Verlauf dieser Dissertation wird, sofern nicht anders kenntlich gemacht, davon ausgegangen, dass Weitspringer mit Unterschenkelprothese diese für den Absprung nutzen.

Belastungsparameter zu haben. Hierbei sollten jedoch nicht nur die Belastungen in der Hauptbewegungsebene, beim Weitsprung die Sagittalebene, sondern auch mögliche Stütz- und Ausgleichsfunktionen in anderen Bewegungsebenen berücksichtigt werden. Entsprechende Informationen sind für Athleten mit Unterschenkelprothese nicht vorhanden und für nicht amputierte Athleten stark limitiert.

Aus den herausgearbeiteten Forschungslücken sowie den erörterten Problemstellungen ergeben sich folgende Leitfragen[E]:

1. Führt die Nutzung einer Sportprothese, durch einen Athleten mit Unterschenkelamputation, im leichtathletischen Weitsprung möglicherweise zu einem Vorteil oder Nachteil hinsichtlich der Wettkampfleistung im Vergleich zu nicht amputierten Athleten?

2. Basiert der Absprung im leichtathletischen Weitsprung von Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung nutzen, und nicht amputierten Athleten auf den gleichen physikalisch-biomechanischen Mechanismen?

3. Welche Belastungen wirken während des Absprungs im leichtathletischen Weitsprung auf das muskulo-skelettale System von nicht amputierten Athleten und Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung nutzen?

Die Erkenntnisse, die aus der Beantwortung dieser drei Leitfragen hervorgehen, können dazu genutzt werden die sportliche Leistung von Athleten mit und ohne Sportprothese weiter zu steigern und wichtige Ableitungen für Verletzungsprävention und Rehabilitationsmaßnahmen zu treffen. Weiterhin können Entscheidungsträger*innen in Gremien von Dachverbänden die Erkenntnisse nutzen, um zukünftige Wettkampfregularien anzupassen.

[E] Im Diskussionsteil dieser Dissertation wird die Diskussion der zweiten Leitfrage aus inhaltlichen Gründen vorgezogen.

ÜBERSICHT DES PROMOTIONSPROJEKTES

Im folgenden Kapitel wird eine kurze Übersicht über das, in dieser Arbeit vorgestellte, Promotionsprojekt geben. Neben dem allgemeinen methodischen Vorgehen wird auch die Chronologie der Bearbeitung und Beantwortung der Leitfragen dargestellt.

Das Promotionsprojekt umfasst insgesamt vier Forschungsarbeiten. Hiervon sind zum Zeitpunkt der Abgabe der kumulativen Dissertation drei Arbeiten in internationalen Fachzeitschriften mit *Peer-Review*-Verfahren publiziert. Eine Arbeit befindet sich zu o.g. Zeitpunkt in Vorbereitung.

Erste Studie (Seite 17-40)

Willwacher S, Funken J, Heinrich K, Müller R, Hobara H, Grabowski AM, Brüggemann G-P, Potthast W. 2017 Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes. *Scientific Reports* 7, 16058.

Zweite Studie (Seite 41-55)

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation: *Medicine & Science in Sports & Exercise* 51, 716–725.

Dritte Studie (Seite 56-73)

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics. *Royal Society Open Science* 6, 190107.

Vierte Studie (Seite 74-94)

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Leg stiffness during the long jump take-off step of athletes with and without a below the knee prosthesis. *In Vorbereitung*

Allgemeine Methodik

Studiendesign. Die in der vorliegenden Arbeit vorgestellten Studien sind Teil eines multinationalen Forschungsprojektes. Das Ziel dieser Querschnittsuntersuchung war es, anhand von zwei Gruppen, den Weitsprung von Athleten mit und ohne Sportprothese bewegungs- und belastungsanalytisch abzubilden und zu vergleichen. Die Datenerfassung fand im April 2016 an der Deutschen Sporthochschule Köln (DSHS) und dem Japan Institute of Sport Sciences (JISS) statt. Das im Verlauf dieser Arbeit vorgestellte und angewandte methodische Vorgehen steht im Einklang mit der *„Declaration of Helsinki“* und wurde durch die Ethikkommission der DSHS im Vorfeld der Untersuchung positiv begutachtet (Ethikantrag Nr. 040/2016). Um einen angemessenen Umfang der Arbeit zu wahren, werden lediglich die Untersuchungen und Teile der Methodik besprochen, die für die hier vorgestellten vier Studien relevant sind. In dem vorliegenden Kapitel werden dem Leser allgemeine Informationen vermittelt; Details zur jeweiligen Messmethodik und Parameterkalkulation finden sich im Methodenteil der entsprechenden Studie.

Probandenkollektiv. An der Studie haben elf männliche Probanden freiwillig teilgenommen - drei Athleten mit rechtsseitiger transtibialer Amputation und acht nicht amputierte Athleten. Alle Athleten wurden über den Ablauf der Untersuchung aufgeklärt und haben der freiwilligen Teilnahme zugestimmt. Zu Beginn der Untersuchung waren alle Teilnehmer gesund und beschwerdefrei. Ein nicht amputierter Proband hat die Untersuchung wegen muskulärer Probleme frühzeitig abgebrochen. Dieser wird im Weiteren nicht berücksichtigt. Es ergab sich demnach das in Tabelle 1 dargestellte Probandenkollektiv. Alle Athleten mit Sportprothese haben diese für den Absprung verwendet. Vier der nicht amputierten Athleten nutzten ihr rechtes Bein und drei ihr linkes Bein für den Absprung.

Tabelle 1: Persönlicher Rekord (PR) im Weitsprung zum Zeitpunkt der Studie, allgemeine anthropometrische Daten und das Alter der Athleten mit Unterschenkelamputation (BKA, übernommen aus dem Englischen: below the knee amputation) und der nicht amputierten Athleten (nAMP) als Mittelwerte mit Standardabweichung.

Gruppe	PR (m)	Masse (kg)	Größe (m)	Alter (Jahre)
BKA (n=3)	7,43 ± 0,99	78,7 ± 9,8*	1,83 ± 0,04	26,0 ± 1,7
nAMP (n=7)	7,65 ± 0,65	80,1 ± 6,2	1,82 ± 0,07	24,6 ± 2,5

** Beinhaltet die Masse der Prothese*

Datenerfassung. Die individuellen Längen und Umfänge der Körpersegmente aller Athleten wurden mit einem Anthropometer und einem Maßband vermessen. Im Anschluss bekamen die Athleten Zeit sich individuell aufzuwärmen. Um sowohl den Anlauf als auch den Absprung angemessen bewegungsanalytisch untersuchen zu können, erfolgten zwei separate Messungen. Zunächst wurde der Absprung aus vollem wettkampfspezifischem Anlauf erfasst. In einer zweiten Messung wurde der Sprint mit maximaler Geschwindigkeit aufgezeichnet.

Die Aufzeichnung der Kinematik erfolgte mit einem markerbasierten 3D-Bewegungsanalysesystem (Vicon, Oxford, Großbritannien). Die Kinetik wurde mit in den Boden eingelassenen Kraftmessplatten (Kistler Instrumente AG, Winterthur, Schweiz) erfasst. Zusätzlich wurde der Geschwindigkeitsverlauf beim Weitsprung und bei den maximalen Sprints mit einem Lasermessgerät (LAVEG, Jenoptik, Jena, Deutschland) aufgezeichnet. Weiterhin wurde sowohl an der DSHS als auch am JISS ein Optojumpsystem (OPTOJUMP, Microgate, Bolzano, Italien) genutzt um ergänzende Aussagen über Schrittlängen, Kontakt- und Flugzeiten treffen zu können.

Retroreflektierende Marker (10 mm; Twist, ILUMARK GmbH, Feldkirchen, Deutschland) wurden mit doppelseitigem Toupetklebeband (Kryolan, Berlin) an anatomischen Referenzpunkten der nicht amputierten Athleten bzw. der Athleten mit Unterschenkelamputation und deren Prothese fixiert.

Modelberechnungen. Die vom 3D-Bewegungsanalysesystem erfassten Daten der Kinematik sowie die synchron aufgezeichnete Kinetik und die probandenspezifische Anthropometrie fungierten als Eingangsdaten für ein modifiziertes mathematisches Mehrkörpermodel (Dynamicus, alaska, Institut für Mechatronik e.V., Chemnitz, Deutschland). Dieses diente zur invers-kinematischen und invers-dynamischen Analyse. Für die Athleten mit Unterschenkelamputation wurde im Model der fehlende Teil des Unterschenkels durch ein Prothesenmodel ersetzt. Jeweils eine Aufnahme in aufrechtstehender Haltung diente dazu, die Koordinatensysteme der Körpersegmente im Model festzulegen. Bei den Athleten mit Sportprothese wurde hierzu während der Referenzposition die Beinlänge des biologischen Beines an die des prothetischen Beines angepasst. Gelenkwinkel bilden die Rotation des distalen Segments in Relation zum proximalen Segment des jeweiligen Gelenks ab. Drehmomente werden als externe Momente im Koordinatensystem des distalen Segments dargestellt. Die Vorbereitung der Rohdaten für die Modelberechnungen sowie die fragestellung-spezifische Auswertung und Kalkulation einzelner Parameter wurde mit Hilfe von selbst erstellten Analyseskripten (MATLAB, The MathWorks, Natick, USA) durchgeführt.

Limitationen. Es wurde eine relativ geringe Zahl von Athleten mit Unterschenkelamputation rekrutieren. Diese umfassten jedoch drei der vier besten Weitspringer der Paralympischen Spiele 2016. Auf Grund der großen Leistungsvarianz im paralympischen Weitsprung würde eine deutlich größere Probandenzahl ein erhöhtes Risiko bergen, für Top-Athleten übliche, Bewegungsmuster zu übersehen.

3D-Bewegungsanalysesysteme haben Vorteile, müssen aber auch kritisch betrachtet werden. Speziell bei schnellen Bewegungen mit einer hohen Krafteinwirkung oder einem großen Bewegungsausmaß in den beteiligten Gelenken kann es zu Verschiebungen der verwendeten Marker in Relation zu den anatomischen Referenzpunkten kommen. Dies kann die Kalkulation von Gelenkwinkeln beeinflussen. Weiterhin kann nicht ausgeschlossen werden, dass die Athleten durch das Tragen der Marker und die für sie ungewohnte Umgebung im Labor beeinflusst wurden. Es ist jedoch zu erwarten, dass die durch o.g. Limitationen potentiell verursachten Variationen im Verhältnis zum Bewegungsausmaß der zu erwartenden Bewegung klein sind. Aus diesem Grund kann mit großer Sicherheit davon ausgegangen werden, dass weder die Ergebnisse der vorliegenden Arbeit noch die hieraus abgeleiteten Schlussfolgerungen in relevanter Weise durch o.g. Limitationen beeinflusst werden. Darüber hinaus, hat die für die Datenerfassung und Modelkalkulation verantwortliche Forschungsgruppe des Instituts für Biomechanik und Orthopädie der DSHS langjährige Erfahrung mit Analysen von hochdynamischen Bewegungen wie dem Sprint mit und ohne Sportprothese [9,13,36–38]. Basierend auf dem hieraus resultierenden methodischen und inhaltlichen Fachwissen, wurden methodische Vorkehrungen getroffen, um mögliche Fehlerquellen zu minimieren. Studienspezifische Limitationen können den Diskussionen der einzelnen Manuskripte entnommen werden.

Kurzübersicht der Studien

Erste Studie. *Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes* (S. 17-40)

Willwacher et al., 2017, Sci. Rep. 7(1), 16058.

In der ersten Studie sollte zunächst die Frage erörtert werden, ob Weitspringer mit einseitiger Amputation unterhalb des Kniegelenks, die ihre Sportprothese für den Absprungschritt verwenden, einen Vorteil oder einen Nachteil gegenüber Athleten ohne Amputation haben. Es konnte gezeigt werden, dass Weitspringer mit Unterschenkelprothese im Vergleich zu nicht amputierten Athleten langsamer anlaufen, aber einen effizienteren Absprungschritt haben. Ein, den gesamten Bewegungsablauf berücksichtigen, Vor- oder Nachteil, konnte weder bestätigt noch ausgeschlossen werden. Weiterhin wurde herausgearbeitet, dass sich die zugrundeliegende Bewegungsmechanik bezogen auf den Energieumsatz am Körperschwerpunkt und den Gelenken der unteren Extremität zwischen den beiden Athletengruppen elementar unterscheidet.

In diesem ersten Analyseansatz fand keine Differenzierung zwischen Bewegungsebenen statt und Belastungsparameter wie Drehmomente wurde nicht berücksichtigt.

Zweite Studie. *Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation* (S. 41-55)

Funken et al., 2019, Med. Sci. Sports Exercise. 51(4), 716–725.

In der zweiten Studie wurde ein besonderes Augenmerk auf die differenzierte Darstellung von Belastungsgrößen wie Drehmomente und Bodenreaktionskräfte in allen drei Raumrichtungen und Bewegungsebenen während des Absprungs gelegt. Es konnte gezeigt werden, dass die Drehmomente und die Absorption/Generation von Energie an Hüfte und Knie sowie einzelne Komponenten der Bodenreaktionskraft im Allgemeinen geringer sind bei Athleten, die eine Unterschenkelprothese für den Absprung verwenden im Vergleich zu nicht amputierten Athleten. Hieraus lässt sich eine ebenfalls verringerte muskulo-skelettale Beanspruchung ableiten. Weiterhin scheint sich die Bewegungsausführung des Absprungs von Athleten mit Prothese fast ausschließlich auf die Sagittalebene zu beschränken, während bei Weitspringern ohne Amputation ein nicht zu vernachlässigender Anteil an kompensatorischen Stützfunktionen speziell in der Frontalebene wirkt.

Dritte Studie. *Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics* (S. 56-73)

Funken et al., 2019, R. Soc. Open Sci. 6(4), 190107

In der ersten Studie fiel auf, dass sich wichtige, die Sprungweite determinierende, Parameter zum Zeitpunkt des Abflugs (Abfluggeschwindigkeit, - Winkel, und Körperschwerpunkthöhe), nicht unterschieden zwischen dem besten nicht amputierten und dem besten amputierten Weitspringer. In den ersten beiden Studien wurden jedoch fundamentale Unterschiede zwischen den beiden Gruppen hinsichtlich der Körperschwerpunk- und Gelenkkinetik im Verlauf des Absprungschrittes gezeigt. Um die mechanische Ursache für diese Unterschiede zu ergründen, wurde daher in der dritten Studie ein besonderes Augenmerk auf die dreidimensionale Körperschwerpunkt- und Gelenkkinematik während des Absprungschrittes gelegt. Athleten mit Sportprothese platzieren diese während des Absprungs anders in Relation zum eigenen Körperschwerpunkt als dies Athleten ohne Amputation tun. Athleten ohne Amputation nutzen den, in der Literatur beschriebenen, Hebelmechanismus (Pivot) [23] um vertikale Abfluggeschwindigkeit zu generieren. Athleten mit Amputation hingegen können, basierend auf den Ergebnissen der dritten Studie, ihre Prothese nicht als rigiden Hebel zum Umlenken der Bewegungsrichtung nutzen, sondern nutzen diese als effiziente Feder, ähnlich einem Sprungbrett. Dieser Effekt wurde bereits vorher für Athleten mit Unterschenkelprothese bei Sprungweiten um ca. 6 m beschrieben [31] und konnte hier für Athleten mit Unterschenkelprothese auf dem aktuellen Leistungsniveau bestätigt werden. Die Körperschwerpunkt und Gelenkbewegung unterschied sich grundlegend, über die Sagittalebene hinaus, zwischen den beiden Athletengruppen.

Vierte Studie. *Leg stiffness during the long jump take-off step of athletes with and without a below the knee prosthesis* (S. 74-94)

Funken et al., in Vorbereitung

Die in Studie 3 getroffenen Schlussfolgerungen zur Beinsteifigkeit und Bewegungscharakteristik während des Absprungschritts basierten auf der Bewegung des Körperschwerpunktes, der Gelenkkinematik sowie der Deformierung des Beines – eine Kalkulation der Beinsteifigkeit bzw. der vertikalen Steifigkeit an sich fand nicht statt. Aus diesem Grund lag in Studie 4 der Fokus auf der Kalkulation der Beinsteifigkeit und der vertikalen Steifigkeit sowie der Darstellung der unterschiedlichen Bewegungsmuster zwischen Athleten mit und ohne Unterschenkelprothese. Es konnte gezeigt, werden, dass sich die Beinsteifigkeit zwischen den beiden Gruppen nicht signifikant unterschied, wenn ein lineares Verhältnis zwischen wirkender Bodenreaktionskraft und Beinlängenverkürzung angenommen wurde. Die vertikale Steifigkeit war jedoch bei nicht amputierten Athleten signifikant höher als bei Athleten mit Unterschenkelprothese. Weiterhin wurde auch herausgearbeitet, dass die Annahme eines linearen Verhältnisses zwischen Bodenreaktionskraft und Beinlängenverkürzung während des Absprungs beim Weitsprung nur für Athleten mit Unterschenkelprothese zulässig zu sein scheint, und einen direkten Vergleich bzgl. der Beinsteifigkeit zwischen Athleten mit und ohne Unterschenkelprothese nur bedingt zulässt.

ERSTE STUDIE

Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes

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Abstract

The use of technological aids to improve sport performance (‘techno doping’) and inclusion of Paralympic athletes in Olympic events are matters of ongoing debate. Recently, a long jumper with a below the knee amputation (BKA) achieved jump distances similar to world-class athletes without amputations, using a carbon fibre running-specific prosthesis (RSP). We show that athletes with BKA utilize a different, more effective take off technique in the long jump, which provided the best athlete with BKA a performance advantage of at least 0.13 m compared to non-amputee athletes. A maximum speed constraint imposed by the use of RSPs would indicate a performance disadvantage for the long jump. We found slower maximum sprinting speeds in athletes with BKA, but did not find a difference in the overall vertical force from both legs of athletes with BKA compared to non-amputees. Slower speeds might originate from intrinsically lower sprinting abilities of athletes with BKA or from more complex adaptions in sprinting mechanics due to the biomechanical and morphological differences induced by RSPs. Our results suggest that due to different movement strategies, athletes with and without BKA should likely compete in separate categories for the long jump.

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Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes

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The use of technological aids to improve sport performance ('techno doping') and inclusion of Paralympic athletes in Olympic events are matters of ongoing debate. Recently, a long jumper with a below the knee amputation (BKA) achieved jump distances similar to world-class athletes without amputations, using a carbon fibre running-specific prosthesis (RSP). We show that athletes with BKA utilize a different, more effective take-off technique in the long jump, which provided the best athlete with BKA a performance advantage of at least 0.13 m compared to non-amputee athletes. A maximum speed constraint imposed by the use of RSPs would indicate a performance disadvantage for the long jump. We found slower maximum sprinting speeds in athletes with BKA, but did not find a difference in the overall vertical force from both legs of athletes with BKA compared to non-amputees. Slower speeds might originate from intrinsically lower sprinting abilities of athletes with BKA or from more complex adaptions in sprinting mechanics due to the biomechanical and morphological differences induced by RSPs. Our results suggest that due to different movement strategies, athletes with and without BKA should likely compete in separate categories for the long jump.

Jumping for distance may be one of the most traditional competitive events in sports, with potentially the earliest use of performance enhancing technical aids (handheld weights); first performed during the Ancient Greek Olympic Games[1]. Following current competition rules, the long jump is performed after a preceding approach run of self-selected distance. A successful long jump requires the maximization of controllable run-up speed followed by an efficient redirection of the centre-of-mass (CoM) velocity during the take-off step[2]. Today, long jumping is also an essential part of the competition program for Paralympic athletes with amputations using running specific prostheses (RSPs) that are made from carbon fibre. RSPs are attached to a rigid socket that encompasses the residual limb and are thus in series with, or beneath, the residual limb. Unlike biological legs and feet, RSPs provide no sensory feedback and no control, cannot flex for ground clearance, and do not have the ability to change stiffness dynamically. RSPs allow for elastic energy storage and return, similar to tendons and ligaments of biological legs; but do not simulate the action of muscle fibres because RSPs cannot generate mechanical energy by conversion of metabolic energy.

Elastic mechanisms play an important role in animals specialized for jumping tasks[3–5], because the power returned from elastic elements is nearly independent of speed[4,6], as opposed to the power developed by muscle fascicles[7]. Therefore, it is reasonable to suppose that artificial limb designs featuring greater quantities of

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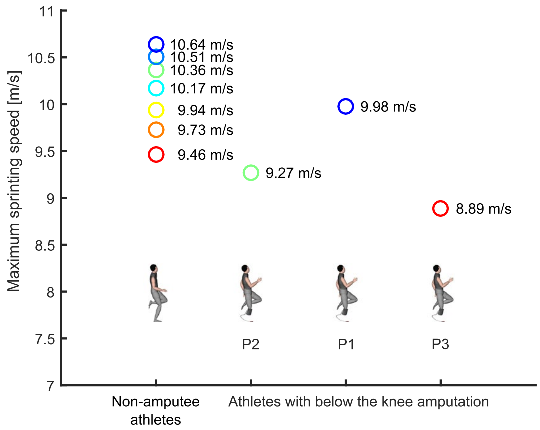

Figure 1. Maximum sprinting speeds observed in non-amputee athletes and athletes with below the knee amputation. Each data point represents the fastest speed obtained for each individual athlete. We use the same colors for individual athletes with BKA and non-amputee athletes throughout the entire article.

highly elastic components would perform better than their biological counterparts would during the take-off step in the long jump[8]. Indeed, the record distance of male athletes with below the knee amputation (BKA) using RSPs (8.40 m) has improved by 2.60 m (45%) since 1996; a resulting jump distance similar to those of current world-class non-amputee athletes, whose records have not changed during the same period. (Note: For the purposes of this article, it is assumed that athletes with BKA have a unilateral amputation and use a running-specific prosthesis below the site of amputation. It is also assumed that non-amputee athletes are not using any form of leg prosthesis or similar device.) The improved performances of athletes with BKA were observed after the introduction of carbon-fibre prostheses that are designed to mimic the spring-like behaviour of the biological lower extremities during running and sprinting[9]. Today, the best long jumpers with BKA take off from their affected leg using a prosthesis. All ten of the finalists in the 2016 Paralympic Games with BKA (class T44) took off from their affected leg using an RSP. The improved performance of long jumpers with BKA has led to speculation about a potential performance advantage compared to non-amputee athletes.

Athletes with BKA elicit lower anterior ground reaction forces and have longer contact times during the push-off from the starting blocks and the first step of the acceleration phase compared to non-amputees[10–12]. This indicates a performance disadvantage during maximum acceleration tasks compared to non-amputees; potentially due to the missing muscles and reduced capacity for positive power generation and other constraints imposed by the use of RSPs[10–13]. Still, no published data of athletes with BKA for subsequent steps of the acceleration phase exist at the moment. Furthermore, long jumpers do not accelerate maximally because the length of the run-up allows athletes to achieve maximum run-up speed over a longer period of time and distance. Thus, theoretical limits on force and power needed to accelerate maximally are likely to have little effect on long jump performance. Correspondingly, the limits on maximum constant sprinting speed appear to be more important for long jump performance[2].

Previous studies suggest that maximum constant sprinting speed is primarily limited by the ability to apply high vertical forces to the ground during progressively shorter periods of ground contact with increasing speed[14,15]. Vertical impulse during the stance phase, the integral of force with respect to time, must be sufficiently high so that it yields aerial phases long enough for repositioning of the swing legs[14]. As running speed increases and consequently ground contact times decrease, higher average vertical support forces (ASFs) are required in order to create sufficient vertical impulse. Therefore, maximizing ASFs during short contact times is crucial for attaining fast maximum sprinting speed.

Athletes with BKA using RSPs have asymmetrical biomechanics between their affected and unaffected legs during constant speed running. For example, athletes with BKA exhibit 9% lower ASFs in their affected compared to unaffected leg across a wide range of speeds from 3 m/s up to top speed, and exhibit 18% lower leg stiffness in their affected compared to unaffected leg at 10 m/s[16,17]. Nonetheless, between-leg asymmetries in force application of 4.1% on average have also been reported during constant maximum speed treadmill sprinting of non-amputee sprinters[18]. The way that between-leg asymmetry affects overall ASF application demands on sprinters measured during several consecutive steps at maximum constant speed is currently unknown. Qualitative observation of representative waveform data provided e.g. in the work of Rabita *et al.*[13] (page 5, Fig. 1) or Clark and Weyand[19] (page 608, Fig. 2b), suggest that the ASF requirement is satisfied by considerable amounts of between-leg and step to step asymmetries. It is conceivable that lower ASF application in one leg can be compensated for by higher ASF application in the other leg. Still, the capacities for contralateral leg force application compensation at maximum sprinting speed are limited by biological constraints. Vertical forces averaged over both legs during consecutive steps would therefore be reduced if the use of an RSP during maximum speed sprinting induces an above threshold force impairment on the affected leg, which cannot be compensated for by the unaffected leg. This would imply a maximum speed limitation, based on the assumption that no additional compensations (i.e. higher step frequency or a longer distance travelled by the CoM during the contact phase) were present[14].

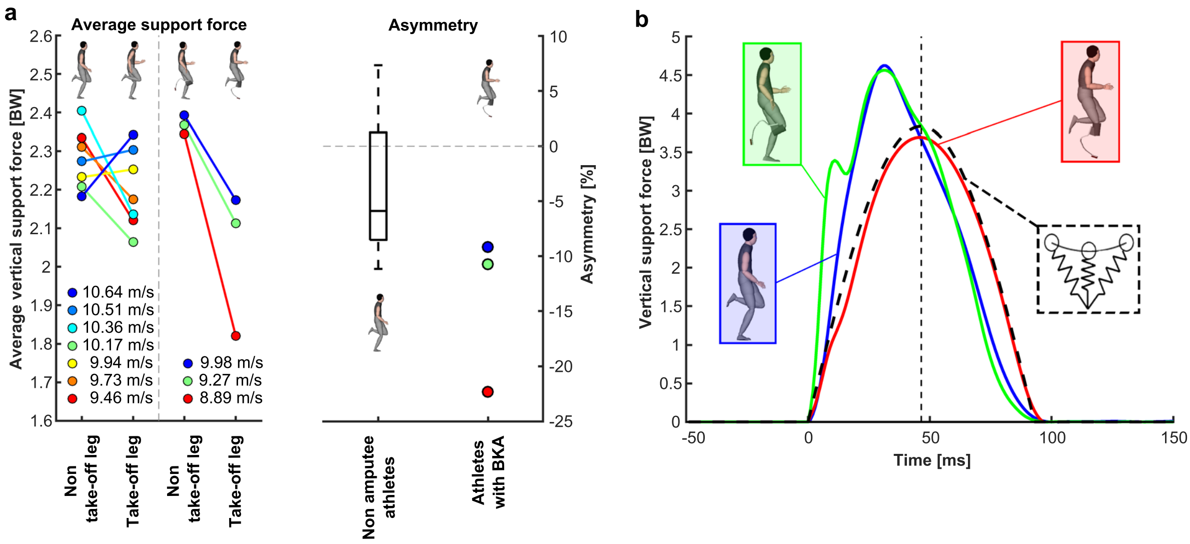

Figure 2. Maximum sprinting speed mechanics. (**a**) Stance average vertical support force (left) and average support force asymmetry (right) for take-off and non-take-off legs of all subjects during maximum sprinting speed trials in units of bodyweight (BW). Values are provided as the average over all trials for the respective leg. Negative asymmetry values indicate greater force applied by the non-take-off leg. (**b**) Representative vertical ground reaction force patterns of the fastest athlete with a below the knee amputation (BKA) and the fastest non-amputee athlete, compared to the pattern of an ideal spring-mass model calculated using the equations provided by Clark *et al.*[19]. The fastest athletes were also the athletes who achieved the longest distances during the long jump trials. For the spring-mass model, step, contact and aerial times from measurements of the same trial of the affected leg of the fastest athlete with BKA were used.

We addressed the components that affect long jump performance by comparing the biomechanics of the world's three best long jumpers with BKA from 2015 (personal record [PR], 7.43 ± 0.99 m), including the 2016 Paralympic champion (class T44), to a group of non-amputee long jumpers at a similar average performance level (n = 7; PR, 7.65 ± 0.65 m), including the 2016 Olympic champion, during maximum constant speed sprinting and maximum-distance long jumping. Our analyses were focused on factors previously associated with performance in sprinting and jumping, including ground reaction force production and the efficiency of CoM energy conversion during the take-off step. We hypothesized that athletes with BKA would have slower speeds during the approach run compared to non-amputees, due to force constraints imposed by their prostheses during maximum constant speed sprinting. In addition, we hypothesized that athletes with BKA would have more efficient energy conversion during the take-off step of the long jump compared to non-amputees, due to the elastic energy storage and return capabilities of their carbon fibre prostheses. Furthermore, we aimed to identify the motor solutions used by each group of jumpers by comparing the mechanical energy, both of the CoM and lower extremity joints.

Results

Maximum sprinting. During the sprinting trials, the best athlete with BKA had a 0.66 m/s (6.2%) slower maximum running speed compared to the fastest non-amputee athlete (Fig. 1). These athletes had very similar long jumping performance (7.96 m vs. 7.92 m, respectively). On average, athletes with BKA achieved a jump distance of 7.26 m ± 0.77 m, while athletes without BKA achieved 7.27 m ± 0.45 m. Athletes with BKA had 7.6% slower maximal sprinting speeds of 8.89–9.98 m/s (mean: 9.38 m/s), compared to non-amputee athletes, who achieved top sprinting speeds of 9.46–10.64 m/s (mean: 10.15 m/s) ($p = 0.11$, Fig. 1). We measured all maximum sprinting speeds using a laser gun.

Athletes with BKA applied 9.0% lower ($p = 0.03$) stance average vertical support forces (ASFs) to the ground with their affected leg compared to the average of left and right legs of non-amputees, while their unaffected legs applied 5.7% higher ($p = 0.02$) ASFs compared to the average of both legs of non-amputees (Fig. 2a, Table 1).

Directional asymmetries in ASF application between take-off and non-take-off legs were observed both in athletes with and without BKA (Fig. 2). The fastest athlete with BKA was 13% more symmetric than the slowest athlete with BKA (−9.2% vs. −22.2% asymmetry, respectively, Fig. 2a). Take-off leg vs. non-take-off leg (directional) asymmetry was calculated using the following formula:

$$Asymmetry\ (\%) = \left(\frac{F_{Avg\_Take\_off\_leg} - F_{Avg\_Non\_Take\_off\_leg}}{F_{Avg\_Non\_Take\_off\_leg}}\right) \cdot 100 \tag{1}$$

Here $F_{Avg\_Take\_off\_leg}$ and $F_{Avg\_Non\_Take\_off\_leg}$ refer to the ASF created during the stance phase by the take-off and non-take-off leg, respectively. Negative values indicate a greater ASF application by the non-take-off leg while

	Long jumpers without amputations				Long jumpers with BKA								
					P1 (7.96 m)			P2 (7.38 m)			P3 (6.43 m)		
	Mean	SD	Min	Max	UL	AL	Mean	UL	AL	Mean	UL	AL	Mean
Maximum speed (m/s)	10.15	(0.42)	9.46	10.64	—	—	9.98	—	—	9.27	—	—	8.89
Stance averaged vertical GRF (BW)	2.24	(0.05)	2.14	2.29	2.39	2.17	2.28	2.37	2.11	2.24	2.34	1.82	2.08
Vertical impulse (BWs)	0.22	(0.01)	0.21	0.24	0.23	0.21	0.22	0.29	0.22	0.25	0.25	0.22	0.23
Step frequency (Hz)	4.45	(0.24)	4.10	4.72	—	—	4.34	—	—	3.85	—	—	—
Contact time (ms)	99	(7)	93	112	98	98	98	124	102	113	105	121	113
Contact length (m)	0.89	(0.07)	0.81	1.03	0.86	0.80	0.83	0.83	0.81	0.82	—	—	—
Swing time (s)	349	(18)	330	374	358	363	360	391	396	393	—	—	—
Negative work hip joint (J/kg)	0.87	(0.12)	0.73	1.02	1.32	0.25	0.79	1.03	0.10	0.57	—	—	—
Positive work hip joint (J/kg)	0.85	(0.24)	0.69	1.32	2.19	1.20	1.70	1.47	1.30	1.39	—	—	—
Negative work knee joint (J/kg)	0.56	(0.17)	0.35	0.87	1.24	0.19	0.72	1.00	0.14	0.57	—	—	—
Positive work knee joint (J/kg)	0.25	(0.11)	0.13	0.44	0.16	0.10	0.13	0.20	0.05	0.13	—	—	—
Negative work below knee joints (J/kg)	2.17	(0.23)	1.94	2.54	1.94	1.54	1.74	2.42	1.60	2.01	—	—	—
Positive work below knee joints (J/kg)	1.79	(0.16)	1.56	1.98	1.55	1.48	1.52	1.65	1.41	1.53	—	—	—

Table 1. Discrete parameters for the analysis of maximum speed sprinting. Stride frequency in athletes with BKA was calculated from complete stride cycles (including steps with the affected and unaffected legs). Stride frequency was then multiplied by two in order to calculate average step frequency. Kinematic data during sprinting could not be obtained from one non-amputee athlete and from one athlete with BKA. UL - unaffected leg of athletes with BKA. AL - affected leg of athletes with BKA. Mean - average value of affected and unaffcted legs of athletes with BKA. For non-amputee athletes averages of the left and right legs are presented. P1-P3: Long jumpers with BKA; their best jump distance achieved is provided in parentheses.

positive values indicate a greater ASF application by the take-off leg. Directional asymmetry between take-off and non-take-off legs tended to be higher in athletes with BKA compared to non-amputees (Fig. 2a).

When considering absolute values of between-leg asymmetry (fluctuating asymmetry, ignoring which leg was take-off and non-take-off leg), athletes with BKA displayed greater asymmetry than non-amputee athletes (14.1 ± 7.2% vs. 6.1 ± 3.8%, respectively), even though the level of significance was not reached ($p = 0.12$). Lower vertical force application in athletes with BKA appeared to be qualitatively closer to the behaviour of a spring-mass model, as indicated by the half- sinusoidal shape of the vertical ground-reaction force (GRF) curve (Fig. 2b). Recently, Clark *et al.* found that running speeds in elite sprinters are maximized by a vertical ground reaction force pattern that differs from the behaviour of classical spring-mass models[19]; this phenomenon was qualitatively observed during maximum speed sprinting for all of our non-amputee subjects, but not for the affected legs of athletes with BKA (Figs 2b; S1).

Nonetheless, when averaged across unaffected and affected legs, ASF in athletes with BKA was not different from non-amputee athletes (2.15 ± 0.13 BW vs. 2.24 ± 0.05 BW, respectively; $p = 0.41$; Table 1). The best athlete with BKA elicited 0.9% higher average ASF from both legs compared to the fastest non-amputee athlete and 2.0% higher between leg averaged ASF compared to the mean of all non-amputee athletes (Fig. 3, Table 1). Therefore, when averaging ASF from both legs during consecutive steps, there was not a general force reduction in athletes with unilateral BKA compared to non-amputees.

An explanation for the slower maximum speed observed in the best athlete with BKA despite similar average ASF application over consecutive steps might be found in the relatively low values of step frequency and contact length compared to non-amputee athletes with similar sprinting speed (Fig. 3, Table 1).

Take-off step. The slower maximum sprinting speeds of athletes with BKA were also reflected in slower horizontal CoM velocities immediately before the take-off step (Table 2; Fig. S2). However, the best athlete with BKA and the best non-amputee athlete achieved very similar maximum jumping distances (7.96 m vs. 7.92 m). Jumping distance was calculated from the intersection of the parabolic flight curve of the CoM and the horizontal landing surface for all athletes, thereby ignoring any effects of the landing technique of the athletes (see methods section for details).

During the take-off step, all athletes with BKA lacked the initial impact-force peak in both the vertical and horizontal (braking) directions, so that the curves representing these forces closely resembled those produced by an ideal spring-mass-model[20,21] (Fig. 4a,b). An effective take-off mechanism is characterized by the ability to create a large vertical impulse that launches the athlete into a parabolic flight curve, while at the same time avoiding a large horizontal braking impulse and the corresponding loss of CoM velocity and energy[2,8] (Fig. 4). Athletes with BKA showed similar values for vertical impulses ($p = 0.27$, Table 1), but had lower net horizontal braking impulses ($p = 0.02$) and a corresponding lower horizontal velocity loss compared to non-amputees. This resulted in 93% higher values for the ratio of vertical to net horizontal braking impulse, indicating a more effective take-off mechanism for athletes with BKA compared to non-amputees (Table 2; Figs 4; S2). During the take-off step, athletes with BKA created similar ASFs compared to non-amputee athletes ($p = 0.83$, Table 2). The best athlete with BKA generated 3.3% lower ASF during the take-off step compared to the best non-amputee athlete (Table 2).

The change in direction of the CoM trajectory during the take-off step involves conversion of some of the CoM energy into mechanically usable (i.e. elastic strain energy) and unusable forms of energy such as heat and

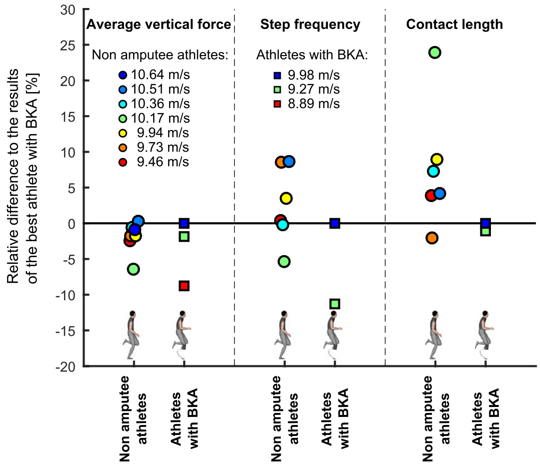

Figure 3. Individual results for average vertical force application from both legs, step frequency and contact length. Constant running speed equals the product of these three variables; thereby they indicate three potential mechanical approaches by which sprinters might achieve faster maximum speeds[14]. The graph shows the relative individual differences (in percent) compared to the results of the best athlete with below the knee amputation (BKA).

sound[8,22]. During the first half of the take-off phase, non-amputee athletes reduced their CoM energy, and this energy was not fully regenerated during the second half of the take-off step (Fig. 5a).

The CoM energy generation of jumpers with BKA was 13.5 ± 13.1% greater than the energy absorbed during the first part of the contact phase (Fig. 5b; Table 2). Whereas, the CoM energy generation of non-amputee athletes was only 56.7 ± 15.9% of the energy absorbed during the first part of the contact phase. This corresponds to a net CoM energy gain of 0.57 ± 0.65 J/kg for athletes with BKA and a net loss of 3.07 ± 1.27 J/kg for the non-amputee athletes. CoM energy losses during the take-off phase were strongly correlated with reductions in horizontal kinetic energy (Pearson correlation, $r = 0.96$, $p < 0.01$), while vertical kinetic energy ($r = -0.50$, $p = 0.14$) and potential energy ($r = -0.62$, $p = 0.06$) were higher at the end of the take-off step than at the beginning (Fig. S3).

To better understand the sources of these differences in CoM energy absorption and generation, we analysed the work patterns of the major joints of the lower extremities[23,24]. Athletes with BKA utilized a distinctively different motor control strategy, which relied on storing and returning a larger amount of mechanical energy within the carbon-fibre prosthesis (Table 3; Figs 5h,j; S4). Comparatively small absolute portions of energy were absorbed at the knee and generated at the hip in athletes with BKA compared to non-amputees (Tables 2 and 3; Figs 5d,f,j; S4).

The net CoM energy increase during the take-off step of athletes with BKA could therefore be explained by the additional positive muscular work at the hip, which added to the energy returned from the prosthesis. Energy absorption and generation were more evenly distributed between joints in non-amputee jumpers compared to athletes with BKA during the take-off step (Tables 2 and 3; Figs 5c,e,g,i; S4).

Discussion

The purpose of the present study was to identify the key biomechanical differences in maximum effort long jumps between athletes with BKA and non-amputee athletes. This was necessary as the existing research[25–27] does not include performances at the level recently observed for the best athletes with BKA and/or only includes kinematic analyses, which are not able to distinguish kinetic differences at the joint level. Nonetheless, these analyses are needed to justify any conclusions regarding motor control solution similarity between athletes with BKA and non-amputees.

A strength of the present study is that it potentially includes the best athlete with BKA and one of the best non-amputee athletes at the time of data collection. This can be observed from their personal records (8.40 m vs. 8.52 m, respectively) and from their long jump results during the experiment (7.96 m vs. 7.92 m, respectively). Therefore, a direct comparison of the maximum performances currently observed in humans with and without BKA was possible, although no inferential statistics could be applied when comparing the results of these two athletes directly. Furthermore, the biomechanical differences in motor solution strategies could be compared in jumps with very similar performance outcomes (i.e. jump distance).

In the present study, athletes with BKA demonstrated slower maximum speeds during the sprinting trials (Fig. 1), as well as slower horizontal speeds immediately before the take-off step compared to non-amputee athletes, while the ratio between the two speeds was not different between groups (Table 2). A constraint on maximum running speed induced by the use of RSPs would indicate a performance disadvantage for the long jump. Maximum constant running speed is among other factors related to the ability to apply high vertical GRFs in short periods of time, which results in high ASF application on the ground[14]. This is necessary to facilitate sufficient aerial times in order to reposition the swing leg for the next step. Furthermore, when accelerating up to maximum speed, high forward directed ground reaction force and power are needed to increase the horizontal velocity of the athlete. Better sprinters keep the GRF vector oriented forward for a longer period of time[28], thereby reaching higher maximum constant speed.

	Long jumpers without amputations				Long jumpers with BKA		
					P1	P2	P3
	Mean	SD	Min	Max	AL	AL	AL
Theoretical distance (m)	7.27	(0.45)	6.51	7.92	7.96	7.38	6.43
Horizontal velocity at touchdown (m/s)	9.39	(0.36)	8.86	9.86	9.32	8.61	8.22
Ratio touchdown/maximum velocity (%)	92.85	(2.31)	89.80	95.65	93.37	92.87	92.43
Vertical velocity at touchdown (m/s)	−0.37	(0.11)	−0.54	−0.23	−0.68	−0.52	−0.36
Contact time (ms)	125	(10)	108	141	118	127	147
Horizontal velocity loss (m/s)	−1.09	(0.23)	−1.49	−0.84	−0.64	−0.59	−0.57
Take-off angle (°)	17.98	(1.98)	16.41	20.91	18.25	20.10	16.94
CoM take-off height (m)	1.18	(0.06)	1.08	1.26	1.18	1.24	1.18
Horizontal CoM take-off position (m)	0.29	(0.06)	0.19	0.38	0.30	0.26	0.39
Vertical velocity at toe-off (m/s)	3.01	(0.26)	2.76	3.47	3.00	3.08	2.55
Vertical impulse (BWs)	0.41	(0.08)	0.30	0.52	0.48	0.49	0.43
Peak vertical force (BW)	8.05	(2.40)	5.26	12.21	6.35	6.03	4.44
Stance averaged vertical GRF (BW)	3.33	(0.60)	2.49	4.21	4.07	3.83	2.93
Net horizontal impulse (BWs)	−0.11	(0.03)	−0.17	−0.09	−0.07	−0.07	−0.05
Stance averaged resultant GRF (BW)	4.27	(0.81)	3.46	5.24	4.76	4.83	4.27
Ratio vertical/horizontal impulse	3.82	(0.54)	3.13	4.51	6.74	7.33	8.04
Total CoM energy at touchdown (J/kg)	53.71	(3.59)	48.73	57.78	53.72	47.72	43.64
Negative CoM work (J/kg)	−7.06	(1.13)	−9.14	−5.99	−5.33	−4.89	−2.96
Positive CoM work (J/kg)	3.99	(1.17)	2.21	5.50	5.33	6.18	3.38
Ratio positve/negative CoM work (%)	57	(16)	35	77	100	126	114
Negative work hip joint (J/kg)	2.66	(0.50)	2.07	3.56	0.16	0.17	0.35
Positive work hip joint (J/kg)	2.28	(0.76)	1.51	3.78	1.17	1.23	0.85
Negative work knee joint (J/kg)	2.56	(1.23)	1.62	5.21	0.91	0.64	0.74
Positive work knee joint (J/kg)	1.45	(0.50)	0.60	2.12	0.26	0.28	0.31
Negative work below knee joints (J/kg)	2.55	(0.81)	1.70	4.06	5.69	4.72	2.65
Positive work below knee joints (J/kg)	1.96	(0.28)	1.51	2.34	4.41	3.79	2.48

Table 2. Discrete parameters for the analysis of the long jump take-off step. The result of the best jump (based on distance achieved) of each athlete was taken into consideration for the analysis. Center of mass is abbreviated with CoM throughout the table. AL - affected legs of athletes with BKA. P1-P3: Long jumpers with BKA.

We found that athletes with BKA had lower ASFs elicited by their affected compared to unaffected leg during maximum constant speed sprinting, which led to higher ASF asymmetry compared to their non-amputee counterparts. The 9% reduction in ASF during sprinting for the affected compared to unaffected leg of the best athlete with BKA in this study matches nicely with the average ASF reductions in the affected compared to unaffected leg reported previously for elite athletes with BKA[16]. These lower ASFs may be related to differences in the limb posture required to run using a prosthesis and a reduced ability to create high leg stiffness when using a prosthesis[17]. Theoretically, a number of additional reasons for the identified ASF asymmetry exist, which could include the minimization of overall biomechanical asymmetries, improvement of balance and limb-socket comfort, and/or the differences in the decelerated effective mass below the knee during impact[29]. These influences on ASF symmetry need to be investigated in future studies in greater detail.

Inferring a general reduction of ASF application due to the use of RSPs is not possible, as the average ASFs during the take-off step (3.61 ± 0.60 BW) clearly exceeded the average ASFs during sprinting (2.16 ± 0.22 BW). This indicates that athletes with BKA are capable of creating higher ASFs in tasks different from maximum speed sprinting. On the other hand, during sprinting and jumping, the constraining conditions under which forces are generated are dissimilar. Maximum, constant speed sprinting requires a sufficient vertical impulse, which allows an aerial time long enough to reposition the leg for the next step. The major demands of maximum speed sprinting are to generate high vertical forces during progressively shorter contact times and to generate slightly higher propulsive than braking impulse in order to keep a constant running speed while overcoming air resistance. The take-off step requires a high vertical impulse while keeping the net horizontal impulse as low as possible. Accordingly, the conditions for force application are different in the two conditions, which is reflected in the longer contact times and greater collision angles observed during the take-off step for all athletes (Table 2, Fig. 6). Furthermore, differences with respect to the external GRF lever arms at the lower extremity joints between sprinting and the take-off step are conceivable[15]. Consequently, higher stance average forces were measured during the take-off step in all athletes taking part in the study, including non-amputee athletes (Table 2, Figs 2 and 3). Future studies should explore the conditions that affect the application of force on the ground in different situations.

Fluctuating morphologic asymmetry is negatively correlated with sprint speed and racing ability in cursorial animals like lizards[30], racehorses[31] and humans[32]. Between-leg asymmetry resulting from impaired ASFs on the affected side might be related to functional and morphological differences introduced by the RSP and has been attributed to

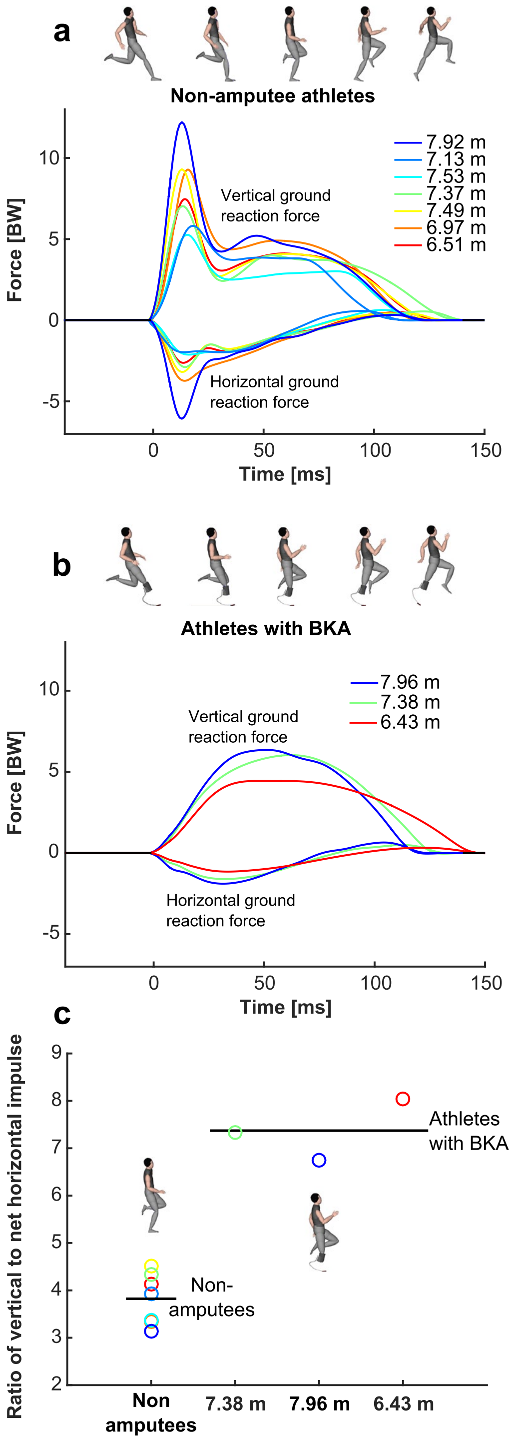

Figure 4. Take-off step mechanics. Vertical and horizontal ground-reaction forces (GRFs) for non-amputee athletes (**a**) and athletes with below the knee amputation (BKA) (**b**) in units of bodyweight (BW) for the take-off step of the long jump. Athletes with BKA lacked the initial vertical and horizontal (braking) peaks in their GRF curves. Note the simultaneous presence of the vertical and braking force peaks in non-amputee athletes. In athletes with BKA, GRF dynamics are qualitatively similar to the dynamics of an ideal spring-mass model[20,21]. Athletes with BKA generate a similarly large vertical impulse while generating a reduced net horizontal braking impulse compared to non-amputees, which results in higher ratios of vertical to net horizontal impulse (**c**), and a more effective take-off mechanism.

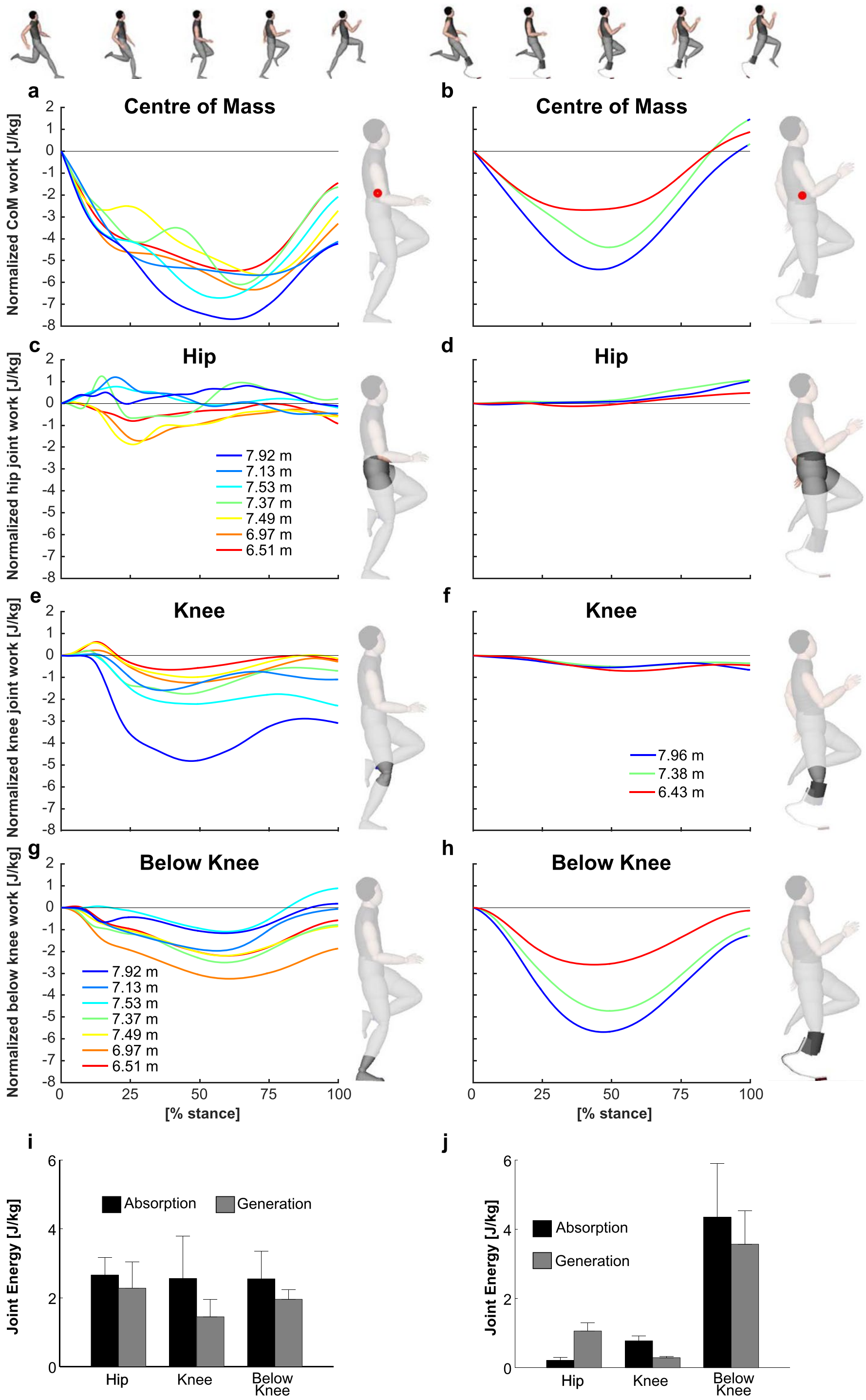

Figure 5. Stance-phase normalized work performed on the center of mass in non-amputee athletes (**a**) and athletes with below the knee amputation (BKA) (**b**). Joint work performed at the hip, knee and below the knee (ankle and metatarsal phalangeal joint) in non-amputees (**c**,**e**,**g**) and athletes with BKA (**d**,**f**,**h**). Below-knee work in athletes with BKA is the work performed by the prosthesis. Note the similarity between the centre of mass and below-the-knee work in athletes with BKA and the relatively low amounts of work performed at the hip and knee in athletes with BKA. Energy absorption and generation (mean + standard deviation) within the joints are summarized in the bottom part of the figure for non-amputees (**i**) and athletes with BKA (**j**).

be a limiting factor in achieving top speeds compared with non-amputee sprinters[16]. The results of the present study suggest that athletes with BKA can compensate for reduced ASF on their affected side by generating higher ASF on their unaffected side during maximum speed sprinting. This was clearly the case in the best athlete with BKA, whose between leg averaged ASF was higher compared to the best non-amputee long jumper and the mean value

	Relative work (% CoM work)	Long jumpers without amputations				Long jumpers with BKA		
						P1 (7.96 m)	P2 (7.38 m)	P3 (6.43 m)
		Mean	SD	Min	Max	AL	AL	AL
Neg. work	Hip	38.44	(9.20)	28.50	51.46	3.00	3.48	10.47
	Knee	35.04	(10.26)	26.42	56.99	17.09	13.09	26.35
	Below knee	37.28	(13.31)	19.91	58.72	106.85	96.51	89.18
Pos. work	Hip	59.43	(16.83)	32.59	79.28	21.96	19.92	23.36
	Knee	39.42	(16.33)	11.83	56.02	4.88	4.53	9.76
	Below knee	53.26	(20.87)	36.42	98.73	82.77	61.38	74.23

Table 3. Negative (neg.) and positive (pos.) work at the individual joints as a % of CoM negative work and positive work, respectively. AL - affected legs of athletes with BKA. P1-P3: Long jumpers with BKA.

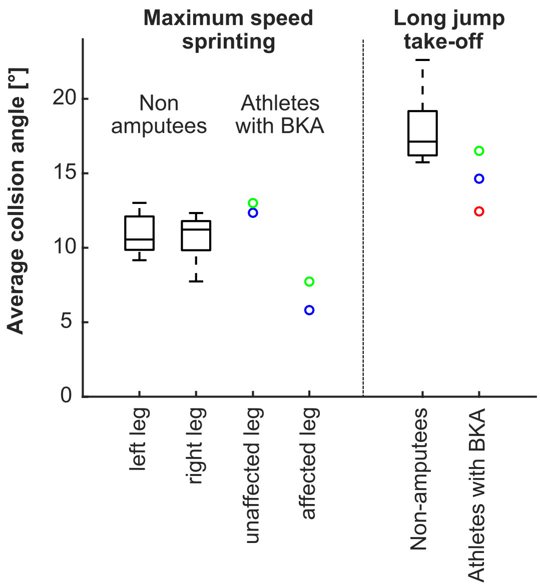

Figure 6. Average collision angles determined through the energy absorption phase of ground contact during maximum-speed sprinting and the long jump take-off step. As motion capture data were not available for the sprinting trials of the third best athlete with below the knee amputation (BKA), sprinting data from only two subjects with BKA are shown. In general, the greatest collision angle occurred during the take-off step for the long jump, in both sets of athletes. The best long jump performance coincided with the greatest collision angle.

of non-amputees during maximum speed sprinting (Table 1). Furthermore, the between-leg averaged ASFs of all athletes with BKA fell nicely within the relationship between running speed and ASF application provided in the literature[14]. We also observed asymmetries of 6% on average in our non-amputee athletes, which was slightly higher than the 4.1% ASF asymmetry reported in a recent study of non-amputee treadmill sprinting[18]. Therefore, it is likely that non-amputee athletes use similar compensation strategies to meet the ASF demands at their top running speeds. From an average ASF application point of view, the use of RSPs seems to induce no general performance limitation during maximum speed sprinting. As mentioned above, this is in disagreement with the interpretation of a previous study[16]. Their experimental design did not have a non-amputee control group, thus they did not compare ASF from both legs of athletes with BKA to those of non-amputees. Our results show clear differences in ASF asymmetry between athletes with BKA of different performance levels. Higher between-leg ASF asymmetries were found in slower compared to faster athletes with BKA. If the use of an RSP in an individual athlete results in between leg ASF asymmetry above a certain threshold which cannot be compensated for by the unaffected leg, then this might result in a slower run-up speed. Therefore, improving biological force application capacities and utilizing a running technique that minimizes between leg asymmetries and the necessity for ASF compensation appear to be two key strategies to improve maximum sprinting speed in long jumpers with BKA. Nonetheless, the specific threshold of between leg asymmetry, above which a compensation by higher contralateral ASF application becomes impossible, is currently unknown and should be determined in future studies.

During the take-off step, we found that athletes with BKA utilized a technique that allowed them to store and return more energy in their RSPs compared to the legs of non-amputees. Beneficial conditions for power generation by means of energy storage and return within the tendons and ligaments of biological limbs play an important role in jumping[3–6,8,33]. In this context, beneficial conditions for power generation refer to a higher power output from elastic structures as compared to power developed by muscle fascicles alone, because power developed from elastic structures is not constrained by the muscle fascicle's power-velocity relationship. The human Achilles tendon can store 0.51 J/kg during running at 3.9 m/s[34,35], while in full-effort sprinting, 0.70 J/kg of positive work is performed by reutilizing the strain energy in the Achilles tendon[36]. In addition, the human foot is capable of storing about 17 J of strain energy (around 0.21 J/kg for someone weighing 80 kg) when forces similar to running at 4.5 m/s are applied[35]. Other tissues like the long tendons of extrinsic foot muscles and the ankle-joint ligaments are capable of storing additional energy, though the quantities of elastic energy are lower than for the Achilles tendon and the foot. No measured energy storage values have been reported for the maximal dynamic motions of elite long jumpers, so direct comparison of passive elastic strain energy storage capacities between biological and prosthetic legs may not be applicable. The theoretical upper limit to energy return from elastic structures within the leg can be calculated by assuming that all positive work performed at and below the knee is the result of passive energy return[37]. The best athlete with BKA generated 37% (1.27 J/kg) and 12% (0.50 J/kg) more positive work at and below the knee than the non-amputee average and the best non-amputee long jumper (PR: 8.52 m), respectively (Table 1), during the take-off step. This indicates that the amount of elastic energy storage and return from prosthetic limbs may not be achievable for non-amputee athletes taking off from their biological limbs and therefore, use of a prosthesis as the take-off leg results in more efficient energy conversion for athletes with BKA compared to non-amputees during the take-off step. Due to this improved energy conversion efficiency, athletes with BKA lost less horizontal kinetic energy and consequently lost less horizontal velocity during the take-off step. Our results indicate that greater amounts of passive energy storage within the leg might be beneficial for tasks involving high collision energies like the long jump take-off step as opposed to dynamic tasks involving relatively smaller collisions, like sprinting. In fact, lower collision angles were measured during sprinting (~11°) versus jumping (~17°), in athletes with and without BKA (Fig. 4). Sprinting performance may be more closely related to generation of high leg stiffness[16,17], high stance average vertical support forces[14,15,19] and horizontal forces and power[13,28]. Nonetheless, the amount of passive elastic energy storage was not an independently controlled variable in this study. Therefore, the observed differences may be also related to different motor behaviours, inertial properties, or other factors.

Quantifying the potential performance advantage resulting from the use of an RSP during the take-off step and the potential performance disadvantage resulting from the use of an RSP during maximum speed sprinting is difficult and deals with a substantial amount of uncertainty. A performance advantage might result from reduced horizontal velocity losses when using an RSP for the take-off step compared to non-amputees. Whereas a performance disadvantage might result from differences in sprint mechanics forced by the use of RSPs and corresponding slower run-up and maximum sprinting speeds.

The best athlete with BKA in this study left the ground after take-off with essentially the same CoM conditions (vertical take-off velocity, horizontal and vertical take-off position) as the mean of the non-amputee sample (Table 2). Therefore, differences in the jump distances achieved between the best athlete with BKA and the average non-amputee athlete were almost entirely the result of a different horizontal take-off velocity. In this case, a performance advantage results from a lower horizontal velocity loss during the take-off step of athletes with BKA compared to non-amputee athletes. Given the initial take-off CoM conditions provided in Table 2, one can calculate the resulting flight time between take-off and landing to be 0.884 s, based on the laws of ballistic flight. The theoretical advantage ($\text{Advantage}_{\text{take-off}}$) provided by the use of the RSP could be calculated as:

$$\text{Advantage}_{\text{take-off}} = 0.884\,\text{s} \cdot \Delta V_{\text{loss\_hor}} \tag{2}$$

Here, $\Delta V_{\text{loss\_hor}}$ refers to the difference in horizontal velocity loss between an athlete with BKA and a non-amputee reference value. When taking the mean value of the non-amputee athletes from our study as the reference, $\Delta V_{\text{loss\_hor}}$ equals 0.55 m/s (95% confidence interval: [0.38, 0.72], Table 2), which results in a theoretical advantage of 0.49 m (95% confidence interval: [0.34, 0.64]) during the take-off step for the best athlete with BKA.

A problem with this approach is that it compares the data from the best athlete with BKA to a reference data set of limited size ($n = 7$) and that it is only valid if the take-off conditions between the athlete under consideration and the non-amputee reference data are very similar, like for the best athlete with BKA (Table 2). Nonetheless, it is well accepted that horizontal velocity losses during the take-off also increase as a function of run-up speed and take-off angles in non-amputee athletes[1,38]. In an attempt to develop a more general method to estimate a potential take-off advantage due to the use of RSPs for athletes using different approach speeds and take-off angles, we fitted a linear multiple regression model using horizontal velocity at touchdown and take-off angle as input variables to predict the horizontal velocity loss during the take-off step ($R^2 = 0.94$, Fig. 7). In this analysis, we used our non-amputee data, and data from world class athletes[39] and from some of the best long jump performances in history from the literature[40] (Fig. 7). Subsequently, we calculated the residuals of non-amputee athletes and athletes with BKA from the non-amputee regression plane (Fig. 7). These residuals represent the difference in horizontal velocity loss of an individual athlete compared to an average world class long jump take-off. The best athlete with BKA displayed a residual more than 4 standard deviations away from the average residual of world class non-amputee performances, which highlights that the take-off technique utilized due to low horizontal velocity loss provides an artificial performance advantage compared to non-amputee jumpers. From basic probabilistic theory, 99.7% of the data following a normal distribution are found within a range of the mean ± three standard deviations. Therefore, it seems plausible to use these values as very conservative boundaries for naturally occurring horizontal velocity losses in non-amputee athletes. The difference of the residual of the best athlete with BKA and the upper limit of these boundaries is 0.15 m/s (Fig. 7B). Implementing this value for $\Delta V_{\text{loss\_hor}}$ into equation (2), a performance advantage of at least 0.13 m is a conservative estimate of the advantage during the take-off step compared to non-amputee long jumpers.

Nonetheless, this estimation is only valid for the run-up speed used by the best athlete with BKA in the present study. There is no scientific evidence that athletes with BKA follow the same relationship between approach speed,

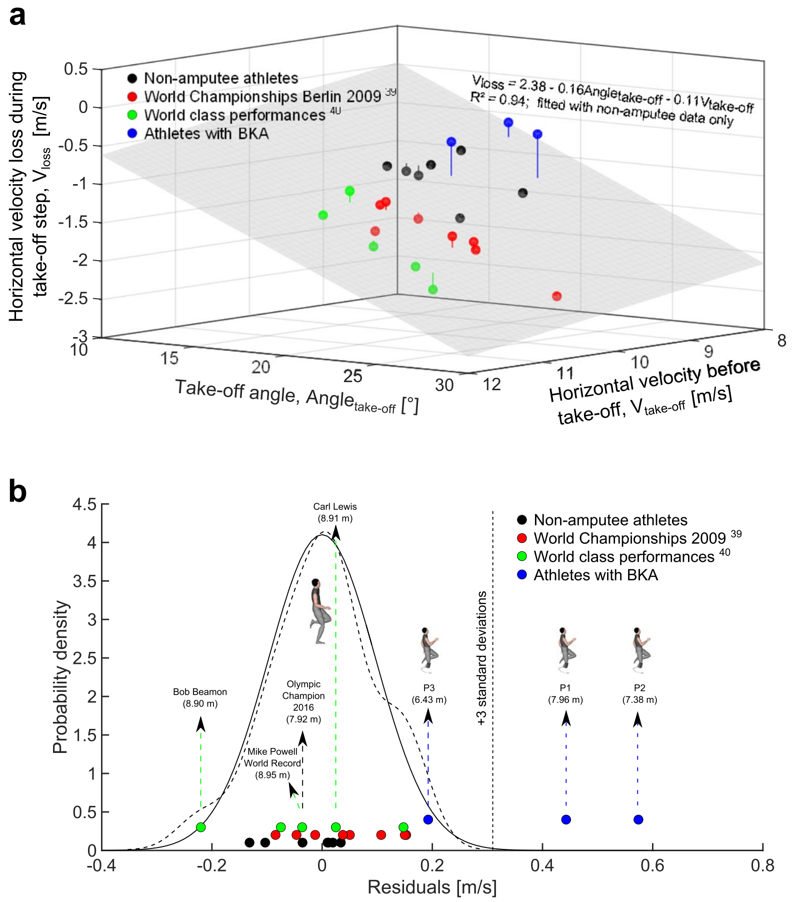

Figure 7. Visualization of the multiple regression analysis performed in order to provide a more general framework for the determination of the potential advantage due to the use of RSPs during the take-off step. (**a**) 3D representation of the performed multiple regression analysis using only non-amputee data as input. Different colours represent individual performance from different athletes/sources in the literature[39,40]. Vertical lines indicate residuals. The frequency distribution of these residuals is shown in (**b**). A normal distribution using the mean and standard deviation of the non-amputee residuals is plotted, next to a kernel density function calculated using the same input. The similarity between these two frequency distributions shows how well the residual data follows a normal distribution. Vertical arrows indicate individual performances of selected athletes, providing the jump distances achieved in brackets.

take-off angle and horizontal velocity loss as determined by us (Fig. 7) or others[2]. Therefore, future studies need to investigate in detail the relationship between horizontal velocities prior to take-off, take-off angles and horizontal velocity losses during the take-off step in athletes with BKA taking off from an RSP.

Calculating a potential performance disadvantage due to the use of RSPs is more difficult in sprinting than for the take-off step. In this study, the best athlete with and without BKA achieved very similar long jump performances (7.96 m vs. 7.92 m, respectively) with differences of 0.54 m/s in horizontal velocity immediately before the take-off step and 0.66 m/s in maximum speed sprinting. The critical question is how much of this difference was due to an intrinsically lower sprinting ability of the athlete with BKA and how much was caused by a potential disadvantage induced by the use of an RSP?

The best athlete with BKA was able to compensate for his impaired ASF application ability on his affected leg with higher ASF application on his unaffected leg; thereby, when considering both legs, overall ASF application was not reduced compared to non-amputee athletes. Nonetheless, it is conceivable that adjustments in his sprinting mechanics were necessary to realize this compensation, which might have led to negative effects on his sprinting speed. On the other hand, these adjustments might also be necessary in non-amputee athletes with ASF application asymmetry. The 9% fluctuating asymmetry found for the best athlete with BKA is inside the range of the mean ± one standard deviation (6.1% ± 3.8%) for non-amputee long jumpers reported in the present study and within two standard deviations (4.1% ± 5.2%) of the mean of a study on non-amputee treadmill sprinting[18]. This indicates that the difference in ASF application asymmetry of the best athlete with BKA is less pronounced and may be within normal ranges for non-amputees. Future studies are needed to examine the contribution of ASF asymmetry on maximum sprinting speed.

Apart from ASF asymmetry, other factors can affect sprinting performance. A study on athletes with BKA found that the dynamics of their affected legs display less dynamic stability compared to their unaffected legs and to the biological legs of non-amputee runners[41]. Furthermore, except for the first steps of a sprint, little is known about the horizontal force and power abilities and the influence of RSPs during the acceleration phase. Due to the importance of horizontal force and power application in order to reach maximum sprinting speed[13,28], there is a clear need for further fundamental research in this area, before a valid estimation of maximum sprinting speed performance differences due to the use of RSPs can be determined. This should also address other details of the sprinting technique related to the morphological differences between legs, which might affect running performance[30–32].

To conclude, we provide an integrated kinematic and kinetic framework for evaluating differences in performance between Olympic and Paralympic long jumpers; and as such, our results may prove useful for researchers, regulators and decision-makers in this field. We found that athletes with BKA use a slower approach speed and have slower maximum sprinting speeds compared to non-amputee long jumpers. Because of the different factors that affect maximum speed, it is not possible to estimate a potential performance disadvantage due to the use of RSPs in approach speed and maximum sprinting. Nonetheless, when taking both legs into account, the sprint mechanics of athletes with BKA were more similar to their non-amputee counterparts compared to their mechanics during the take-off step. During the take-off step, we found a different and mechanically more effective motor solution in athletes with BKA. We conservatively estimate a minimum take-off step performance advantage of 0.13 m for the best athlete with a BKA compared to non-amputees. Taking-off from an RSP allows the storage and return of a large amount of energy within the prosthesis. The energy storage and return capacities of RSPs used by athletes with BKA may exceed the biological energy storage and return capacities within the take-off legs of non-amputees, making this technique unachievable for non-amputee long jumpers. Based on our findings, future technical regulations regarding inclusion of Paralympic athletes in the Olympics should consider both the biomechanics of the final movement and the potential for preceding trade-offs, as they are identified by future research. In addition, rules committees need to take into account the comparability of biologically and technologically generated motor control solutions. Our results show that the motor solution strategy adopted by athletes with BKA during the take-off step is more effective and different from that of non-amputee athletes. Therefore, our results suggest that due to different movement strategies, athletes with and without BKA should likely compete in separate categories for the long jump.

Methods

Data acquisition took place at the German Sport University Cologne (GSU) and the Japanese Institute of Sport Sciences (JISS). Ethical approval was obtained from the ethical committee of the German Sport University (approval number: 040/2016). The protocol was performed in accordance with the relevant ethical guidelines and regulations, based on the Declaration of Helsinki.

Subjects. Two groups of subjects were included. Group 1 comprised three of the world's best long jumpers with a unilateral below the knee amputation (BKA; age: 26 ± 1.7 years; body mass (including socket and prosthesis): 78.7 ± 9.76 kg; standing height: 1.83 ± 0.04 m; long-jump personal record [PR]: 7.43 ± 0.99 m), and included the world-record holder (International Paralympic Committee T44 classification, unilateral BKA). Group 2 comprised seven non-amputee long jumpers (age: 24.6 ± 2.5 years; body mass: 80.1 ± 6.22 kg; standing height: 1.82 ± 0.07 m; PR: 7.65 ± 0.65 m), who were competitive at international, national and regional levels. All subjects participated voluntarily and gave written informed consent. Consent to publish subject photos was obtained from each subject.

Treatments. Prior to data collection, the anthropometrics of each athlete were recorded according to the reference handbook of the ALASKA modelling system[42]. Furthermore, detailed measurements of different portions of the prosthesis of each subject with a BKA were taken. These included weight and geometry measurements (lengths, circumferences, curvatures, etc.). After an individual, competition-specific warm-up, all athletes performed long jumps and maximum speed sprints aimed at achieving their best performance. Athletes were asked to use their individual competition-specific approach run for the long jump, and to use an approach run that enabled them to reach a constant maximum velocity in the measuring volume for the maximum speed sprints. Two athletes completed both movement trials on the same day, but all others performed the jumping and sprinting trials on different days to avoid any potential effects of fatigue.

Kinematics. Retro-reflective spherical markers (10 mm; Twist, ILUMARK GmbH, Feldkirchen, Germany) were fixed to anatomical landmarks on the athlete's body and prosthesis using ph-neutral double-sided tape. In total, 55 (non-amputee) or 83 (BKA) markers were used (Figure S5).

Marker trajectories for the long jump and sprinting were captured by means of an infrared camera system (250 Hz; Vicon, Oxford, UK; long jump: 20 cameras (MX40); sprinting: 14 cameras (T-Series)). One static trial in upright standing position was captured and used to define the neutral position for all joints. Athletes with BKA placed their unaffected leg on a wooden block during the static trial so that there were no differences in hip height between legs and to ensure comparability with the non-amputees. Approach-run and sprinting velocities were recorded using a laser gun (100 Hz, LAVEG, Jenoptik, Jena, Germany). Step frequency and flight time during sprinting were recorded using an optical measurement system (1000 Hz, OPTOJUMP, Microgate, Bolzano, Italy) with a length of 13 m. Additionally, three high speed video cameras (100 Hz; Basler, Ahrensburg, Germany) were used to take qualitative videos of the take-off phase of the jump in order to ensure that each athlete landed on the force plate(s).

For two subjects (one non-amputee and one with BKA), motion-capture data was only obtained from the jumping trial, but not from the maximum sprinting trial. Therefore, in sprinting trials, only the running speed and ground reaction force (GRF) measurements are included in the analysis of these athletes.

Kinetics. GRFs were captured simultaneously with kinematic data using piezo-based force plates (1000 Hz; Kistler Instrumente AG, Winterthur, Switzerland). For the long jump, GRFs were captured during the take-off step. Therefore, a force plate (40 × 60 cm) covered with a wooden take-off board (GSU) or a force plate (90 × 60 cm) covered with the same tartan surface as the run-up (JISS) were used. For the sprinting trials, four (GSU) or six (JISS) force plates (90 × 60 cm) were used that were mounted flush with the floor and covered with the same tartan surface as the run-up.

Post-processing. All motion capture data were visually checked for valid force plate contacts using the high-speed video. Three dimensional marker coordinates were reconstructed and labelled within the same software (Nexus 2.3, Vicon Motion Systems, Oxford, UK). Small gaps (<10 frames) within the marker trajectories were filled using implemented algorithms. Marker coordinates and GRFs were both filtered using the same filter (4^{th} order recursive digital Butterworth filter; 50 Hz cut-off frequency) in order to avoid artefacts within the model-based inverse dynamics calculations[43,44].

Ground reaction forces. Bodyweight normalized stance average vertical support force (ASF) was calculated by taking the average of the filtered vertical GRF over the entire stance phase. Bodyweight was measured from the static standing reference measurement. Stance phases were defined using a 20 N threshold of the resultant GRF. Vertical and net horizontal impulses were determined for each stance period by numerical integration of vertical and horizontal GRF curves with respect to time. Impulses were also normalized by bodyweight (BW).

Model calculations. Inverse dynamics calculations were executed using a modified version of the full-body model, Dynamicus (ALASKA, Advanced Lagrangian Solver in Kinetic Analysis, Institute of Mechatronics, Chemnitz, Germany[42]). The prosthesis was modelled as two rigid bodies with a ball joint connection. The prosthetic joint was defined by two markers placed at the medial and lateral edge of the prosthesis and positioned with respect to the most posterior point of the prosthesis, which coincided with the point of highest curvature of the prosthesis[45]. While this approach has been utilized in previous publications[45,46], other approaches for modelling the total power of prosthetic below-knee structures exist. For example, a unified deformable segment model has been used for quantifying the total power of the entire prosthesis[47]. It is possible that some degree of error in below knee energy computations resulted from the chosen method[47]. All body markers were rigidly attached to the corresponding segments of the full-body model using their 3D coordinates, which were obtained from the standing reference measurement.

The motion of the model was calculated using a standard inverse kinematics procedure. Within these calculations, the (measured) tracking markers were mathematically optimized using a weighted square deviation of the position of the body mounted (model) markers from their corresponding tracking markers. The anthropometric segmental parameters were taken from previously established equations[48–50].

The segmental coordinate systems were defined using the standing reference measurement and were attached to each segment. The hip joint centres (HJC) were estimated using a regression equation provided by the software. The knee (KJC) and ankle joint centres (AJC) were defined as the central points between the medial and lateral femoral condyles and the medial and lateral malleoli markers, respectively. The joint centre of the metatarsophalangeal joints (MJC) were defined as the midpoint between the 5^{th} and 1^{st} metatarsal head markers. The external joint moments were calculated using the inverse dynamics method and are described in the distal segmental coordinate system.

The inertia parameters of the prosthesis were calculated by dividing it into 9 cuboids. The geometric dimension of each cuboid was obtained by measuring the width, length and thickness of the corresponding region of the prosthesis. The geometrical model of the prosthesis was designed in a way that prosthetic joints were positioned between two cuboid segments of the prosthesis. The volume of the whole prosthesis was calculated by summing the volumes of individual cuboid segments. The density of the prosthesis was assumed to be homogenous and was estimated by dividing the mass of the prosthesis by its volume. Consequently, each cuboid was assigned a definite mass. The moment of inertia of each cuboid segment was estimated using standard equations[51].

The centre of mass (CoM) of the whole modified full-body model was estimated via the anthropometric dimensions of the biological parts of the model combined with the properties and dimensions of the prosthesis. Joint power was calculated using the following equation[23]:

$$P_j = M_j \times \omega_j \tag{3}$$

P is the power of joint j, M_j represents the resultant internal moment of joint j and ω_j represents the angular velocity of the joint j. Negative joint power was defined as energy absorption, while positive joint power was defined as energy generation. Joint work was calculated by numerically integrating joint power over time. Joint work was the sum of the work of all three planes of motion.

CoM velocity in sprint trials was calculated by numerical differentiation of the raw position data obtained from the laser gun system. CoM velocity was smoothed using a recursive digital Butterworth low-pass filter (4^{th} order, 1 Hz cut-off). From the filtered CoM velocity, peak velocities were obtained during the sprinting and jumping trials.

Potential CoM energy (E_{pot}) was calculated as follows:

$$E_{pot} = mgh \tag{4}$$

m is the body mass, g is gravitational acceleration and h is the CoM height with respect to the global laboratory reference frame, originating at the surface of the running track. Horizontal and vertical kinetic CoM energy (E_{kin_hor}, E_{kin_vert}) were calculated according to the following equations, respectively:

$$E_{kin\_hor} = \frac{mv_{hor}^2}{2} \quad (5)$$

$$E_{kin\_vert} = \frac{mv_{vert}^2}{2} \quad (6)$$

v_{hor} and v_{vert} represent the horizontal and vertical CoM velocities, respectively. Total CoM energy was calculated as the sum of the potential CoM energy and the two components of kinetic CoM energy.

Averaged weighted collision angles, determined by the angle between the GRF and CoM velocity vectors, were calculated for the energy absorption phases during maximum sprinting and for the jump take-off using the formulae provided in reference[22].

For both athletes with and without an amputation, three joints contributing to the energy exchange of the system were defined: hip, knee and 'below knee'. For athletes with BKA, the below knee joint represents the energy exchange of the prosthesis, whereas for the non-amputees, the below knee joint combines the energy exchange of the ankle and metatarsophalangeal joints. Joint energy was calculated by numerically integrating the power-time curve and summing all three planes of motion. However, in accordance with common practice[23], the energy of the metatarsophalangeal joint only represents the energy exchange within the sagittal plane for time periods in which the point of GRF application is anterior to the metatarsophalangeal-joint centre.

Spatiotemporal parameters. Step frequency ($Freq_{step}$) was calculated as

$$Freq_{step} = 2 \cdot Freq_{stride} \quad (7)$$

Stride frequency ($Freq_{stride}$) was calculated as:

$$Freq_{stride} = \frac{1}{t_{stride}} \quad (8)$$

Stride time (t_{stride}) was defined as the time interval from touchdown of one foot on the ground to the next ipsilateral touchdown. This time interval included a left and right contact phase and two aerial phases, from the left leg to the right leg and vice versa.

Jump distance calculations. For all jump trials, we assumed a parabolic flight curve of the CoM after take-off; that drag forces due to air resistance were negligible, and we did not consider landing technique.

$$CoM_{flight\_AP}(t) = CoM_{0\_AP} + v_{com0\_AP} \cdot t \quad (9)$$

$$CoM_{flight\_Vert}(t) = CoM_{0\_Vert} + \frac{gt^2}{2} + v_{com0\_Vert} \cdot t \quad (10)$$

The starting point of the flight path was defined by the vertical (CoM_{0_vert}) and horizontal (CoM_{0_AP}) CoM positions at final contact with the ground, while the resulting CoM velocity (v_{com0_res}) and take-off angle (α) were calculated from the initial flight phase vector of the CoM, which was determined by subtracting the initial CoM position from the CoM position 25 ms after the last contact with the ground. Jump distance was defined as the distance from the most anterior point of the foot or prosthesis during take-off ground contact to the intersection between the CoM flight path and the ground[52]. We used this approach to avoid taking into account the effects of landing technique on long jump performance. There was a strong correlation between the jump distances determined as described above and the jump distances measured with a tape measure ($r = 0.99$, $p < 0.001$; average difference: -0.36 m).

Take-off performance advantage calculations. The analysis of a potential performance advantage was focussed on the horizontal velocity loss of the CoM during the take-off step. More specifically, we assessed the differences between the horizontal velocity losses of the best athlete with BKA compared to reference data of non-amputee athletes. Horizontal velocity losses during the take-off step are strongly related to run-up speed and take-off angle in non-amputee athletes[1,38]. Therefore, we fitted a multiple regression model using horizontal velocity immediately prior to the take-off step and take-off angle as input variables to predict the horizontal velocity loss during the take-off step (Fig. 7). The model shared 94% of the variance with the measured values of horizontal velocity losses. Only data from non-amputee athletes were used for the statistical modelling. In order to improve the inferential conclusions drawn from the model, we added previously published data from the literature using 16 mm high-speed cine cameras and high-speed video cameras to calculate CoM velocity and take-off parameters[39,40]. The data from the literature represent some of the best long jump performances in the history of the sport obtained during World Championships and Olympic competitions. In general, the approach speeds are faster compared to data from the present study, which were captured in a laboratory setting. Nonetheless, the corresponding horizontal velocity losses during take-off are higher indicating that these data sets, collected when athletes were at their peak athletic ability and peak motivation, have the same underlying relationship between run-up speed, take-off angle and horizontal velocity loss. This is also indicated by the high R^2 value obtained for the multiple regression model.

In the second step of the analysis we fitted a normal distribution to the residuals of the multiple regression model. To confirm the correspondence of the residual data with this normal distribution we used a kernel fitting technique (Fig. 7b). The resultant fit qualitatively corresponded well with the fitted normal distribution (Fig. 7b). Subsequently, we used a threshold value of three standard deviations from the mean as a conservative estimate of typically occurring deviations from the predicted horizontal velocity losses in non-amputee athletes. Any value outside of this range was considered an artificially induced difference. From this, we calculated the artificially induced horizontal velocity loss reduction of the best athlete with BKA, which was subsequently used in equation (2) to calculate the performance in distance jumped.

Statistics. Due to low sample sizes, we used a non-parametric test (Wilcoxon rank sum test) in order to compare the results of non-amputee athletes to athletes with BKA. While taking this low sample size into account, we set the level of significance to 0.10.

Furthermore, the absolute and relative differences (in % of the non-amputee value) between the best non-amputee athlete and the best athlete with BKA are described in order to gain insight into differences at the very top level of performance.

Pearson correlation analyses and a multiple linear regression analysis were performed after checking for the respective assumptions made by these tests.

Data and code availability. All raw data and custom written code for the analysis of the data is available from https://dshs-koeln.sciebo.de/index.php/s/K8wY40iRvJyhqnH. All code was created using Matlab (R2015b, The Mathworks, Natick, MA, USA).

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Author Contributions

The study was designed by W.P., H.H., A.M.G., S.W., J.F. and R.M. S.W. wrote the paper with substantial contribution from J.F., W.P., H.H., A.M.G., K.H. and G.P.B. Experimental data were collected by J.F., S.W., R.M., H.H., A.M.G. and W.P. Model calculations were performed by K.H. Analyses were performed by S.W., J.F. and R.M.

Additional Information

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Competing Interests: The authors declare that they have no competing interests.

Tabelle 2.

Zentrale Erkenntnisse Studie 1

Leistungs- und Belastungscharakteristika im leichtathletischen Weitsprung mit Unterschenkelprothese			
Studie 1 *Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes* *Willwacher et al., 2017, Sci. Rep.*	Studie 2 *Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation* *Funken et al., 2019, Med. Sci. Sports Exercise*	Studie 3 *Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics* *Funken et al., 2019, R. Soc. Open Sci.*	Studie 4 *Leg stiffness during the long jump take-off step of athletes with and without a transtibial amputation* *Funken et al., nicht publiziert*
Athleten mit BKA*, die ihre Prothese für den Absprung nutzen**, haben im Vergleich zu nicht amputierten Athleten einen Vorteil im Absprung. Athleten mit BKA laufen im Vergleich zu nicht amputierten Athleten langsamer an, was zu einem Nachteil führt. Der Absprung im Weitsprung unterscheidet sich grundlegend zwischen Athleten mit und ohne BKA hinsichtlich der, bezogen auf den Körperschwerpunkt, gespeicherten und zurückgegebenen Energie. Die Prothese der Athleten mit BKA verfügt über größere Energiespeicherkapazität als der Muskel-Sehnen-Band-Apparat der unteren Extremität bei nicht amputierten Athleten.			

* BKA: Unterschenkelamputation (abgeleitet aus dem Englischen: Below the Knee Amputation
** Es wird im Folgenden vorausgesetzt, dass Athleten mit BKA ihre Unterschenkelprothese für den Absprungschritt nutzen

Appendix Studie 1

Supplementary Information

Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes

Steffen Willwacher, Johannes Funken, Kai Heinrich, Ralf Müller, Hiroaki Hobara, Alena M. Grabowski, Gert-Peter Brüggemann, Wolfgang Potthast

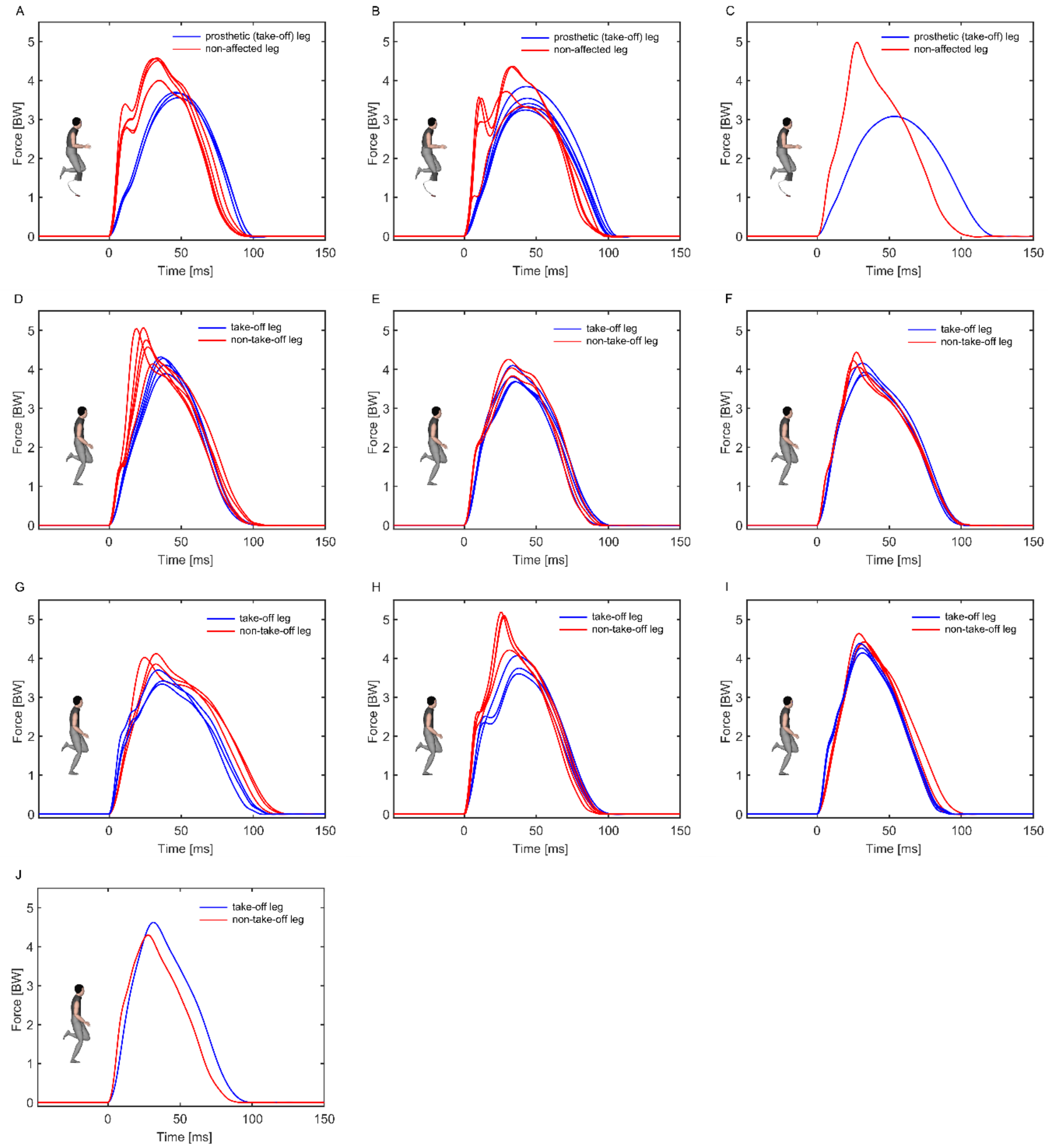

Fig. S1: Individual athlete's vertical ground-reaction force (GRF) curves during maximum-speed sprinting in units of bodyweight (BW). A-C, Athletes with below-the-knee amputation (BKA). D-J, Non-amputee athletes. The take-off leg is represented in blue and the non-take-off leg in red. In athletes with BKA, the take-off leg is also the affected leg. For biological legs in both sets of athletes, the GRF curve is skewed left towards the earlier period of the stance phase (ground contact). In contrast, the affected legs of athletes with BKA exhibit a more temporally symmetrical, near half-sinusoidal, curve that is typical of classical spring-mass behaviour.

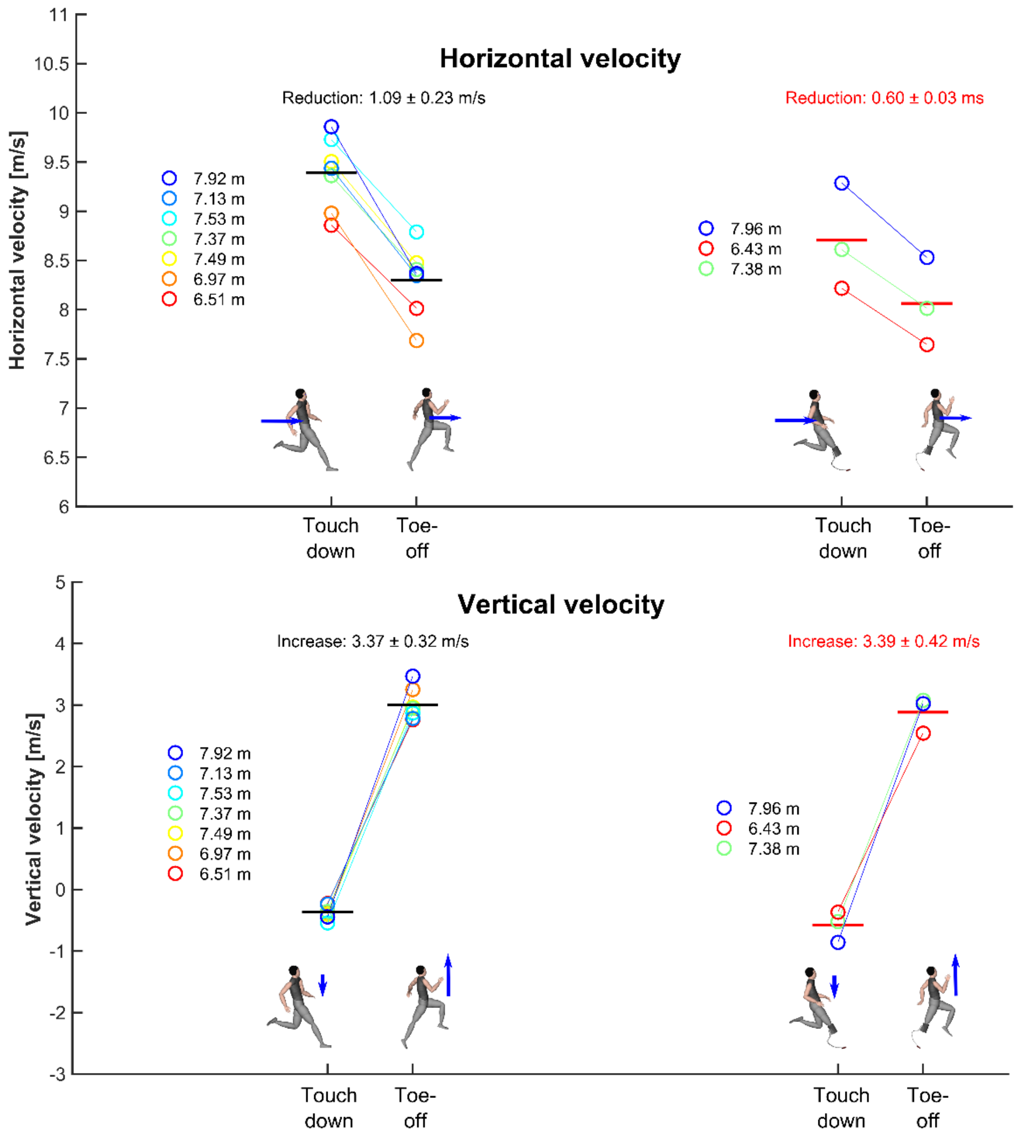

Fig. S2: Centre-of-mass velocity changes during the take-off step in the horizontal (top) and vertical (bottom) directions. Athletes with below-the-knee amputation (BKA) have a slower horizontal run-up velocity, but they lose less horizontal velocity during the take-off. No differences with respect to vertical velocity were identified. Blue arrows represent the vertical and horizontal velocity vectors during touch-down and toe-off.

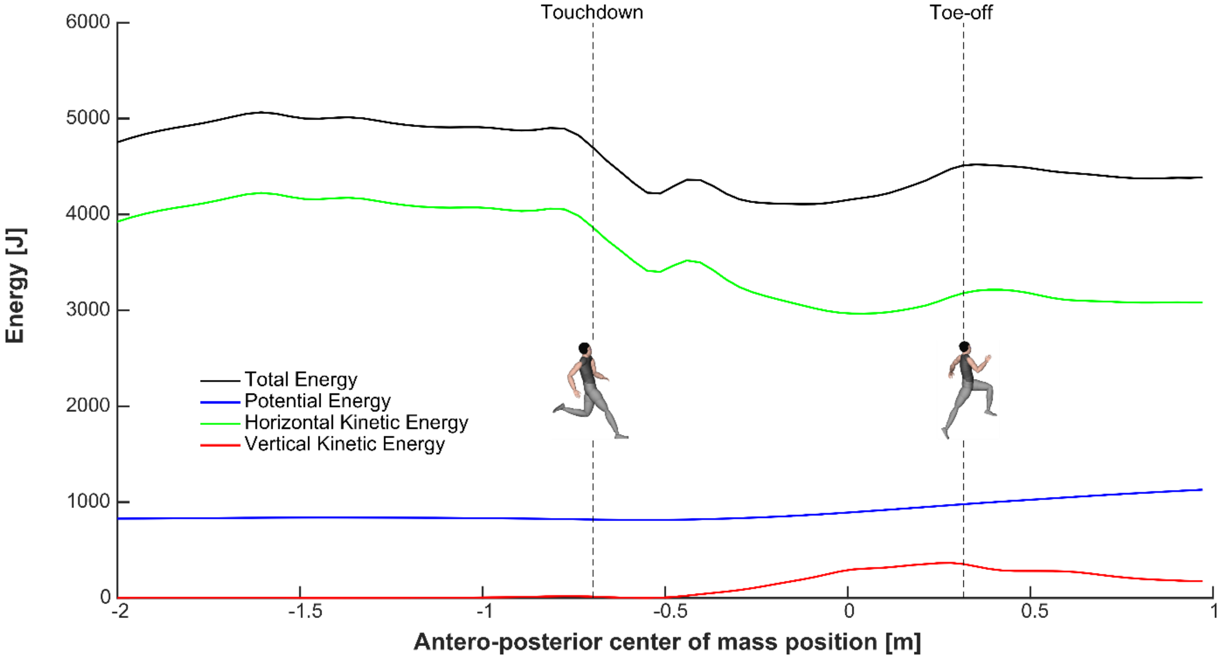

Fig. S3: Total, potential, horizontal kinetic and vertical kinetic centre of mass (CoM) energy from a representative non-amputee during the take-off step. Total CoM energy is the sum of the potential and kinetic energies within the sagittal plane of motion. Horizontal kinetic energy was the dominant component of the total CoM energy. While horizontal CoM energy decreased during the take-off step (from touchdown to toe-off), potential and vertical kinetic energy increased until the end of the take-off.

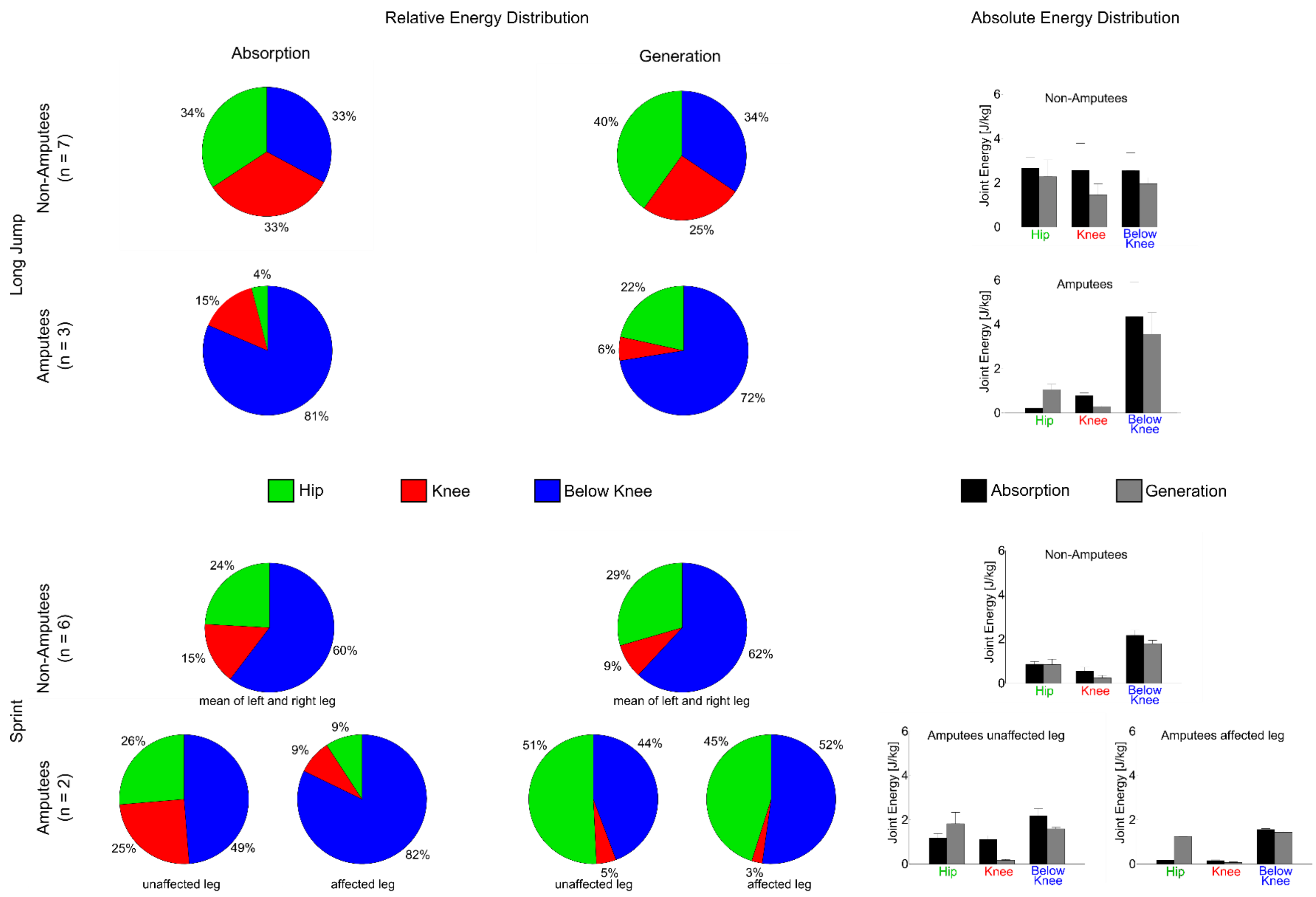

Fig. S4: Pie charts showing the energy distribution of the hip, knee, and 'below knee' (ankle and the metatarsophalangeal) joints relative to the total amount of joint energy generated (left) and absorbed (right). Bar graphs show the total energy distribution of the joints normalized to body mass. Top rows show energy distribution during the take-off step of the long jump. Bottom rows show the energy distribution during the stance (ground contact) phase of sprinting.

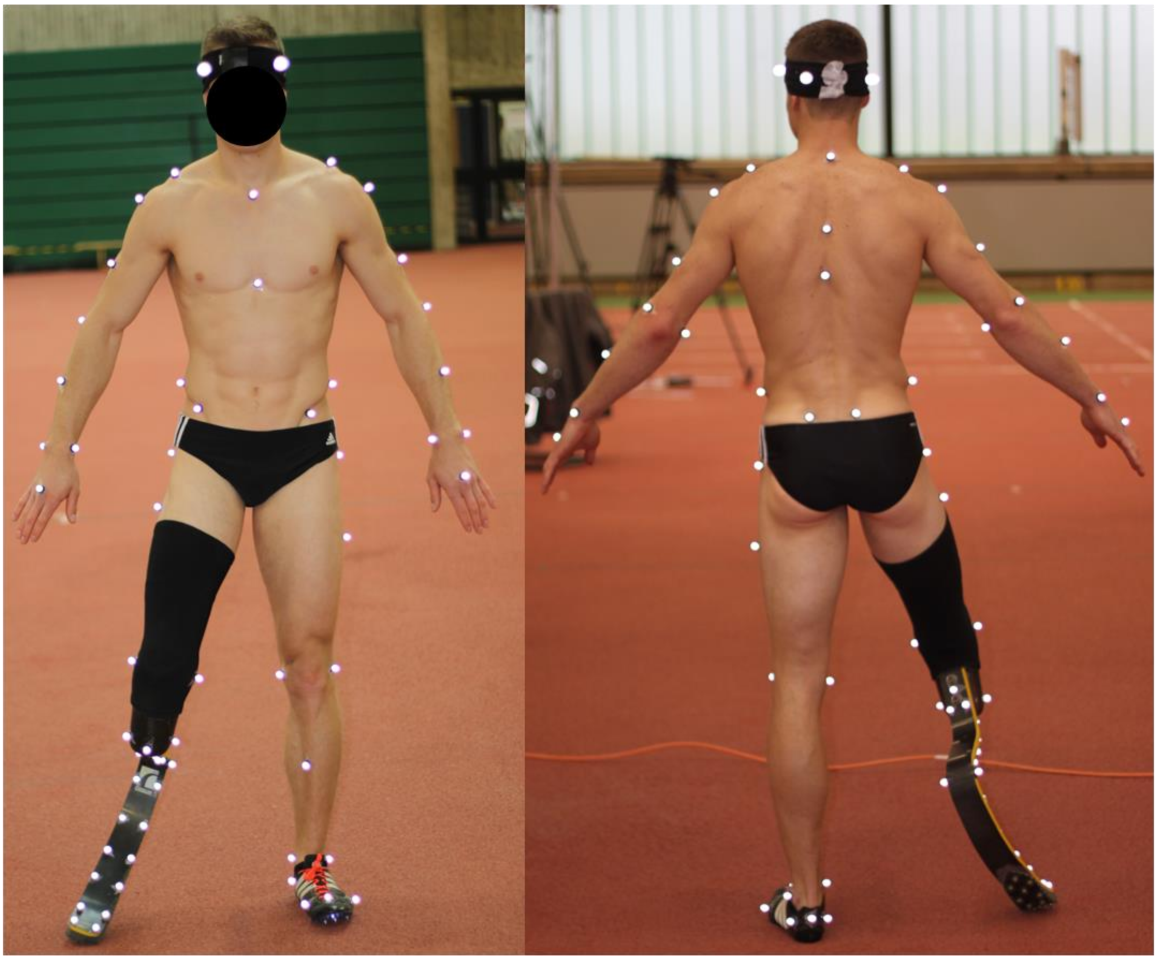

Fig. S5: Marker set used in the study. The marker set of the athletes with BKA was the same as for non-amputees, except for in the area below the knee of the affected leg. Marker arrangement was bilaterally symmetrical across the legs of non-amputees.

ZWEITE STUDIE

Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation

Johannes Funken[1], Steffen Willwacher[1,2], Kai Heinrich[1], Ralf Müller[1], Hiroaki Hobara[3], Alena M. Grabowski[4,5] & Wolfgang Potthast[1,6]

Medicine & Science in Sports & Exercise, 2019, 51(4):716–725

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Abstract

Purpose: The loads applied on the musculoskeletal system during the long jump takeoff step are not well established for nonamputee athletes or athletes with a lower extremity amputation. Information on joint loading and potential injury mechanisms is important for improving training or rehabilitation protocols, prosthetic design, and the general understanding of the long jump. *Methods:* Three-dimensional takeoff step kinematics and kinetics were used for inverse dynamic model calculations on three male athletes with and seven male athletes without a below the knee amputation (BKA). Athletes with BKA used their affected leg as their takeoff leg. *Results:* Despite equivalent long jump performance, ground reaction force application characteristics were widely different, and calculated joint loads were significantly lower in athletes with BKA compared with nonamputee athletes during the takeoff step. The takeoff step of the long jump for athletes with BKA seems to be dominated by sagittal plane movements, whereas it involves sagittal plane movement and compensatory joint work in the frontal plane for nonamputee athletes. *Conclusions:* Coaches and athletes should adapt training protocols to the unique musculoskeletal loading patterns of long jumpers with or without a BKA. Specifically, nonamputee athletes should strengthen the muscles responsible for hip and knee extension, as well as for frontal plane stabilization, early in the season to avoid injuries. The presented data enable clinicians to identify potential causes of pain or injury more differentially in both groups of athletes and might stimulate future research in the field of robotics and prosthetic components. Furthermore, the altered joint mechanics of athletes with BKA versus nonamputees serves as an explanation for their previously described more effective takeoff step.

https://journals.lww.com/acsm-msse

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation: *Medicine & Science in Sports & Exercise* 51(4), 716–725. (doi:10.1249/MSS.0000000000001853)

Aus Gründen des Urheberrechts wurden die Seiten 42 - 51 entnommen und sind in der publizierten Version dieser Dissertation nicht enthalten.

Der Artikel

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation: *Medicine & Science in Sports & Exercise* 51(4), 716–725.
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ist online erhältlich unter:

https://journals.lww.com/acsm-msse/Abstract/2019/04000/Three_Dimensional_Takeoff_Step_Kinetics_of_Long.14.aspx

Tabelle 3. **Zentrale Erkenntnisse Studien 1 und 2**

Leistungs- und Belastungscharakteristika im leichtathletischen Weitsprung mit Unterschenkelprothese			
Studie 1 *Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes* *Willwacher et al., 2017, Sci. Rep.*	Studie 2 *Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation* *Funken et al., 2019, Med. Sci. Sports Exercise*	Studie 3 *Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics* *Funken et al., 2019, R. Soc. Open Sci.*	Studie 4 *Leg stiffness during the long jump take-off step of athletes with and without a transtibial amputation* *Funken et al., nicht publiziert*
Athleten mit BKA*, die ihre Prothese für den Absprung nutzen**, haben im Vergleich zu nicht amputierten Athleten einen Vorteil im Absprung. Athleten mit BKA laufen im Vergleich zu nicht amputierten Athleten langsamer an, was zu einem Nachteil führt. Der Absprung im Weitsprung unterscheidet sich grundlegend zwischen Athleten mit und ohne BKA hinsichtlich der, bezogen auf den Körperschwerpunkt, gespeicherten und zurückgegebenen Energie. Die Prothese der Athleten mit BKA verfügt über größere Energiespeicherkapazität als der Muskel-Sehnen-Band-Apparat der unteren Extremität bei nicht amputierten Athleten.	Die Hebelarme zwischen dem Vektor der Bodenreaktionskraft und dem Knie- bzw. Hüftgelenk sind bei Athleten mit BKA während des Absprungs kürzer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung am Knie und an der Hüfte während des Absprungs ist bei Athleten mit BKA geringer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung während des Absprungs von Athleten mit BKA konzentriert sich, speziell an der Hüfte, nahezu ausschließlich auf die Sagittal-ebene, während bei nicht amputierten Athleten die Strukturen in der Frontalebene in erheblicher Weise mitbelastet werden.		

* BKA: Unterschenkelamputation (abgeleitet aus dem Englischen: Below the Knee Amputation
** Es wird im Folgenden vorausgesetzt, dass Athleten mit BKA ihre Unterschenkelprothese für den Absprungschritt nutzen

Appendix Studie 2

Aus Gründen des Urheberrechts wurden die Seiten 54 - 55 entnommen und sind in der publizierten Version dieser Dissertation nicht enthalten.

Der Artikel

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation: *Medicine & Science in Sports & Exercise* 51(4), 716–725. (doi:10.1249/MSS.0000000000001853)

ist online erhältlich unter:

https://journals.lww.com/acsm-msse/Abstract/2019/04000/Three_Dimensional_Takeoff_Step_Kinetics_of_Long.14.aspx

DRITTE STUDIE

Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics

Johannes Funken[1], Steffen Willwacher[1,2], Kai Heinrich[1], Ralf Müller[1], Hiroaki Hobara[3], Alena M. Grabowski[4,5] & Wolfgang Potthast[1,6]

Royal Society Open Science, 2019, 6(4):190107

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Abstract

Long jumpers with below the knee amputation (BKA) have achieved remarkable performances, yet the underlying biomechanics resulting in these jump distances are unknown. We measured three-dimensional motion and used multisegment modelling to quantify and compare the centre of mass (COM) and joint kinematics of three long jumpers with BKA and seven non-amputee long jumpers during the take-off step of the long jump. Despite having the same jump distances, athletes with BKA, who used their affected leg for the take-off step, had lower sagittal plane hip and knee joint range of motion and positioned their affected leg more laterally relative to the COM compared to non-amputee athletes. Athletes with BKA had a longer compression phase and greater downward movement of their COM, suggesting that their affected leg (lever) was less rigid compared to the biological leg of nonamputees. Thus, athletes with BKA used a different kinematic mechanism to redirect horizontal to vertical velocity compared to non-amputee athletes. The specific movement patterns of athletes with BKA during the take-off step were constrained by the mechanical properties of the prosthesis. These results provide a basis for coaches and athletes to develop training protocols that improve performance and inform the design of future prostheses.

Funken J, Willwacher S, Heinrich K, Müller R, Hobara H, Grabowski AM, Potthast W. 2019 Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics. *Royal Society Open Science* 6(4), 190107. (doi:10.1098/rsos.190107)

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Research

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THE ROYAL SOCIETY PUBLISHING

Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics

Johannes Funken[1], Steffen Willwacher[1,2], Kai Heinrich[1], Ralf Müller[1], Hiroaki Hobara[3], Alena M. Grabowski[4,5] and Wolfgang Potthast[1,6]

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Long jumpers with below the knee amputation (BKA) have achieved remarkable performances, yet the underlying biomechanics resulting in these jump distances are unknown. We measured three-dimensional motion and used multi-segment modelling to quantify and compare the centre of mass (COM) and joint kinematics of three long jumpers with BKA and seven non-amputee long jumpers during the take-off step of the long jump. Despite having the same jump distances, athletes with BKA, who used their affected leg for the take-off step, had lower sagittal plane hip and knee joint range of motion and positioned their affected leg more laterally relative to the COM compared to non-amputee athletes. Athletes with BKA had a longer compression phase and greater downward movement of their COM, suggesting that their affected leg (lever) was less rigid compared to the biological leg of non-amputees. Thus, athletes with BKA used a different kinematic mechanism to redirect horizontal to vertical velocity compared to non-amputee athletes. The specific movement patterns of athletes with BKA during the take-off step were constrained by the mechanical properties of the prosthesis. These results provide a basis for coaches and athletes to develop training protocols that improve performance and inform the design of future prostheses.

1. Background

Humans are capable of adapting the way they move to accomplish a wide range of bipedal movement tasks [1–4]. These adaptations also include those made by athletes with leg amputations using sport-specific prostheses to run, sprint and jump [5–7]. Long jumpers with a unilateral below the knee amputation (BKA) who use a carbon fibre running-specific prosthesis (RSP), for example, have achieved remarkable jump distances [7]. The current long jump world record for male athletes with BKA (8.48 m) would have resulted in a gold medal in the previous three Olympic Games and at least a bronze medal in all Olympic Games ever [8], where the world record for non-amputees is 8.95 m. However, the underlying biomechanics of such elite long jumpers with BKA are not known but are important for understanding how these athletes adapt the way that they move to perform the long jump and may also be used by coaches and athletes to enhance training and performance.

A previous study reported that male athletes with BKA ($n = 8$) showed the same basic long jump technique as male non-amputee long jumpers [9]. However, this study measured data from athletes with BKA competing in the 1998 World Disabled Athletics Championship where the average actual jump distance was 6.00 m, and only one athlete used his affected leg as his take-off leg. During the long jump final of the 2002 World Disabled Athletics Championships, a new world record (6.79 m) was achieved by a male athlete with unilateral BKA using his unaffected leg as his take-off leg [10]. There were no significant differences in jump distance during the 2004 Paralympic Games due to the take-off leg, but take-off technique differed between male athletes with BKA who used their affected leg as their take-off leg ($n = 5$, 6.04 ± 0.66 m) compared to those who used their unaffected leg ($n = 5$, 5.22 ± 0.73 m) as their take-off leg [11]. Athletes who used their affected leg for the take-off step had less sagittal plane hip joint range of motion (ROM) and a stiffer knee joint compared to athletes who used their unaffected leg for the take-off step [11]. Since 2002, the long jump world record of male athletes with BKA has improved by about 1.7 m, and today almost all elite long jumpers with BKA use their affected leg as their take-off leg. In line with Nolan *et al*. [11], we found that the underlying centre of mass (COM) [7] and joint kinetics [7,12] were fundamentally different throughout the take-off step between three male long jumpers with BKA who used their affected leg as their take-off leg compared to male non-amputee long jumpers. However, specific take-off parameters, which directly determine jump distance, such as take-off angle, COM height and velocity, were similar at the end of the take-off step for the best long jumper with BKA (personal record (PR) at the time of the study: 8.40 m) and the best non-amputee long jumper (PR: 8.52 m) [7]. In order to identify the underlying reasons for the kinetic differences during the take-off step [7,12], it is necessary to determine COM and joint kinematics not only for the end of the take-off step but throughout the entire stance phase. Furthermore, it is important to understand the adaptations and constraints that are potentially induced by using RSPs. Numerous studies have determined the two-dimensional kinematics [13–16] and the three-dimensional kinematics [17–20] of non-amputee athletes during the long jump take-off step. To our knowledge, no previous studies have determined the three-dimensional kinematics of long jumpers with BKA who use RSPs and compete on a recent performance level. Since the use of an RSP results in different biomechanics for athletes with BKA during running and sprinting compared to non-amputees [21–23], the sagittal, as well as frontal and transverse plane kinematics during the long jump take-off step, may also differ between athletes with and without a BKA. Determining the three-dimensional kinematics of athletes with BKA using an RSP and their affected leg as their take-off leg during the long jump compared to non-amputees will provide information that can be used to improve training techniques and prosthetic design. A comprehensive three-dimensional analysis of the biomechanical movement patterns elicited by athletes with BKA will, furthermore, generate valuable insight about the long jump and jumping locomotion in general.

Therefore, the aim of the present study was to quantify the three-dimensional long jump take-off step COM and joint kinematics of athletes with BKA and compare them to those elicited by non-amputee athletes.

Table 1. PR for the long jump and anthropometrics for athletes with BKA and non-amputee athletes (non-AMP).

group	PR (m)	mass[a] (kg)	height (m)	age (years)
BKA ($n = 3$)	7.43 ± 0.99	78.7 ± 9.8	1.83 ± 0.04	26.0 ± 1.7
non-AMP ($n = 7$)	7.65 ± 0.65	80.1 ± 6.2	1.82 ± 0.07	24.6 ± 2.5

[a]Body mass of the athletes with BKA includes the prosthesis.

2. Methods

2.1. Participants and study design

Ten male athletes gave voluntary informed consent to participate in the study and were divided into two groups (table 1). The first group (BKA) comprised three athletes with a BKA on their right side and the second group (non-AMP) included seven non-amputee athletes. All athletes with BKA used the same type of RSP (Cheetah Xtreme; Össur, Reykjavik, Iceland) with their individual alignment. Data collection was conducted at the German Sport University Cologne (GSU, two athletes with and six without BKA) and the Japan Institute of Sport Sciences (JISS, one athlete with and one without BKA). The study design was in line with the declaration of Helsinki and was approved by the GSU ethical committee board (approval number: 040/2016).

2.2. Data collection

We measured each athlete's lower and upper body segment lengths and circumferences with a tape measure and an anthropometer. Body height was measured while athletes stood upright with both legs loaded. We attached retroreflective markers to anatomic reference points on the athlete's body and prosthesis using double-sided tape [7]. Before testing, each athlete performed an individual competition specific warm-up and completed practice long jumps to get used to the measurement set-up. The athletes were asked to perform three to six maximum distance long jumps with their individual, competition specific maximum run-up. A three-dimensional motion capture system (Vicon, Oxford, UK) operating at 250 Hz (GSU) or 500 Hz (JISS), respectively, was used to collect kinematic data during the take-off step. One force plate mounted flush with the floor (1000 Hz, Kistler Instrumente Corporation, Winterthur, Switzerland) captured kinetic data of the take-off step. Three high-speed video cameras (100 Hz, Basler, Ahrensburg, Germany) with different points of view were used for capturing qualitative videos and to ensure valid force plate strikes between touchdown (TD) and toe-off (TO). All athletes with BKA used their affected right leg as their take-off leg. Four non-amputee athletes used their right leg and three used their left leg for the take-off step.

2.3. Data analysis

Kinematic and kinetic data were both filtered with the same cut-off frequency [24] of 50 Hz using a fourth-order recursive Butterworth filter [25]. Ground contact (from first (TD) to last (TO) frame with the foot on the ground) was determined using the vertical component of the ground reaction force with a threshold of 10 N [12]. The compression phase was defined as the time interval from TD to maximum knee flexion (MKF) and the extension phase was defined as the time interval from MKF to TO [9,15]. A mathematical rigid full body model (Dynamicus, Alaska, Institute of Mechatronics, Chemnitz, Germany) consisting of 16 main segments was used for kinematic calculations for the non-amputee athletes. The segments comprised: head, trunk, as well as left and right: upper arm, lower arm, hand, thigh, shank, rear foot and forefoot. The trunk consisted of several subsegments. For athletes with BKA, the same model was used, but modified by replacing the foot and lower shank of the right leg with a prosthesis (figure 1). To detect frontal, transverse and sagittal plane motion, we chose to reconstruct the prosthesis as a two-segment rigid body connected with a ball joint. The prosthetic 'ankle joint' refers to the point on the prosthesis with the highest curvature [21,26], which coincides with its most posterior point. The 'ankle joint' axis was determined from two markers attached to the medial and lateral edge of the RSP [7,26]. The anthropometric data, as well as mass and dimensions of the prosthesis, were used to adapt each model to the individual body dimensions

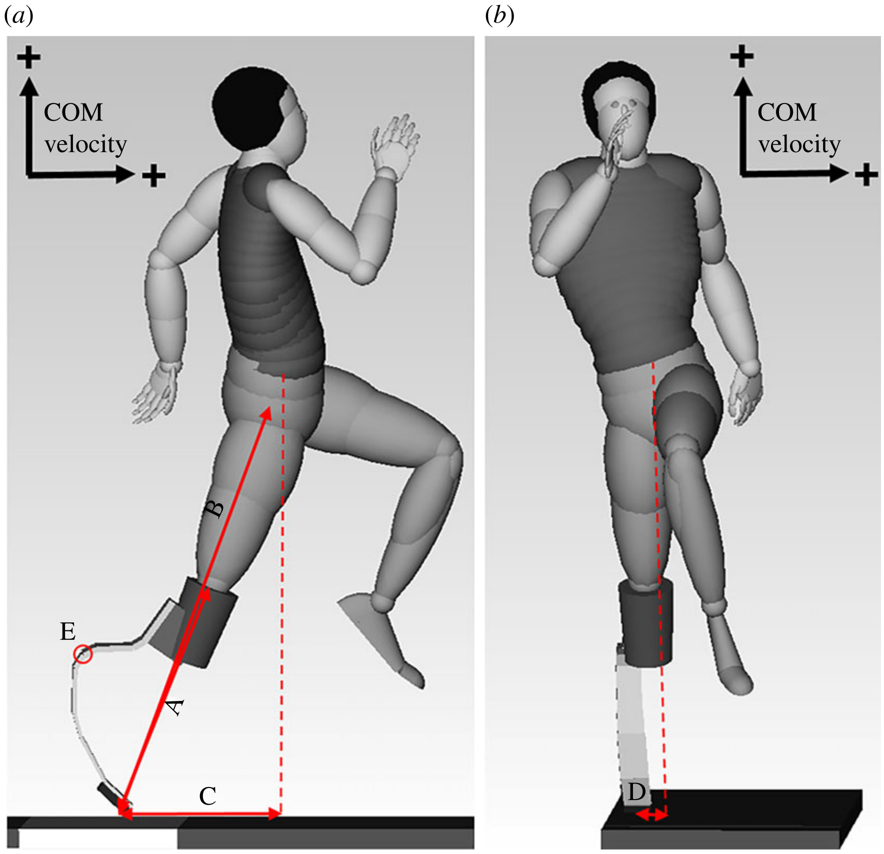

Figure 1. Model sagittal (*a*) and frontal (*b*) plane views including COM velocity orientation. Red arrows indicate (A) the lower leg length, (B) the whole leg length, (C) the antero-posterior distance of the COM to the centre of pressure (COP) and (D) the medio-lateral distance of the COM to the COP. The red circle indicates the position of the prosthetic ankle joint (E).

and RSP of each athlete. One reference trial was captured with athletes in a static erect position to define the segmental coordinate systems.

COM displacement during the take-off step was calculated in the global laboratory coordinate system for all three axes as the distance of the COM coordinate to the respective COM coordinate at the instant of TD. COM velocity was calculated by mathematical differentiation of the COM position throughout the entire stance phase. To account for the take-off foot laterality, COM velocity and displacement are expressed in the global coordinate system with respect to the take-off foot. A velocity described as 'lateral', therefore, represents COM velocity in the lateral direction relative to the take-off foot (e.g. to the right for an athlete using the right leg for the take-off step).

In order to identify differences in foot position, the antero-posterior and medio-lateral distances from the COM to the centre of pressure (COP) of the take-off foot were determined. Additionally, lengths of the whole leg and lower leg were calculated as the linear distance from the COP to the hip joint centre or the linear distance from the COP to the knee joint centre, respectively (figure 1). All joint angles represent the rotation of the coordinate system attached to the distal segment with respect to the coordinate system attached to the proximal segment of the respective joint. To ensure a reasonable comparison of jump distances between the two groups, the influence of landing technique was eliminated by calculating the theoretical jump distance as in our previous publication [7]. The best jump with respect to the theoretical jump distance of each athlete was used for analysis of the take-off step. Since we analysed the same jumps as in our previous publication [7], we also adopted the previously calculated theoretical jump distances. Further details on the mathematical model (e.g. joint centre definition) and calculation of jump distance are in Willwacher *et al.* [7].

2.4. Statistics

Due to the small sample size, a non-parametric Wilcoxon ranked-sum test was used to identify differences between the two groups and the margin of error was set to 10% [7]. We assumed that the null hypothesis was indicated as no difference between groups. We also present the percentage difference for athletes with BKA relative to the non-amputee athletes.

3. Results

The average long jump distance for athletes with BKA (7.26 ± 0.77 m) was not different compared to non-amputee athletes (7.27 ± 0.45 m) ($p = 1.000$). Athletes with BKA reached MKF in their take-off leg later during the take-off step compared to the non-amputee athletes (non-AMP: 43.8 ± 4.9%, BKA: 52.7 ± 2.5%, $p = 0.017$).

3.1. COM kinematics

COM displacement in the antero-posterior (jumping) direction was not different between groups during the take-off step—neither with regard to total displacement ($p = 1.000$) nor the distance of the COM relative to the COP at TO ($p = 0.517$) (table 2 and figures 2 and 3). At the instant of TD, the COM of the non-amputee athletes was approximately 10 cm closer to the COP compared to athletes with BKA ($p = 0.067$). At MKF, both groups had their COM posterior relative to their COP, but athletes with BKA had their COM approximately 13 cm closer to their COP compared to non-amputees ($p = 0.017$).

Medio-lateral COM displacement during stance was different between groups ($p = 0.033$). Non-amputees had a lateral (relative to their take-off foot) COM displacement (2.6 cm), while athletes with BKA did not have relevant medio-lateral movement during the take-off step (figure 2 and table 2). The COM position was approximately 5 cm medial to the COP in athletes with BKA during most of the stance phase, while for the non-amputee athletes, the COM was above the COP for most of stance, and was 1.4 cm lateral to the COP at TO (table 2 and figure 3).

In athletes with BKA, the vertical COM position was below their vertical COM position at TD for a longer relative duration of ground contact compared with non-amputee athletes (non-AMP: 17.2 ± 3.9%, BKA: 42.2 ± 5.8%, $p = 0.017$).

The downward vertical COM displacement in the athletes with BKA was 0.9 cm greater ($p = 0.017$), but total vertical COM displacement was 18.7% lower ($p = 0.017$) compared to non-amputee athletes (table 2 and figure 2).

Athletes with BKA had 7.5% slower horizontal velocity at TD ($p = 0.067$), lost 46.0% less horizontal velocity during stance ($p = 0.017$) and their horizontal velocity at TO was not different ($p = 0.667$) compared to non-amputee athletes (figure 2 and table 2). Vertical velocity at TD and TO was not different between groups ($p = 0.383$, $p = 1.000$). Medio-lateral COM velocity was close to zero at TD for both groups. During ground contact, medio-lateral COM velocity was near constant for athletes with BKA, but increased by 0.35 m s^{-1} in the lateral direction for non-amputee athletes and was different at TO between groups ($p = 0.033$).

During the take-off step, total change in whole leg length (non-AMP: 18.7 ± 5.6 cm, BKA: 17.9 ± 1.9 cm) and in lower leg length (non-AMP: 16.9 ± 6.0 cm, BKA: 16.9 ± 2.4 cm) of the take-off leg were not different in athletes with BKA compared to non-amputee athletes ($p = 0.833$ and 0.383, respectively) (figure 3 and table 2).

During the compression phase of the take-off step (TD–MKF), shortening of the whole leg (non-AMP: 6.5 ± 4.7 cm, BKA: 16.8 ± 3.2 cm) and shortening of the lower leg (non-AMP: 5.4 ± 3.4 cm, BKA: 16.0 ± 3.6 cm) were 159.8% and 194.3% greater, respectively, in athletes with BKA compared to non-amputee athletes (both: $p = 0.017$). During the extension phase of the take-off step (MKF–TO), lengthening of the whole leg (non-AMP: 18.1 ± 5.7 cm, BKA: 17.0 ± 1.6 cm) and lengthening of the lower leg (non-AMP: 15.7 ± 6.2 cm, BKA: 15.8 ± 1.9 cm) were not different between both groups ($p = 1.000$ and 0.267, respectively).

3.2. Joint angles

Athletes with BKA had smaller sagittal plane ROM for all joints compared to non-amputee athletes (all $p = 0.017$) (figure 4). The passive-elastic RSP used by athletes with BKA displayed peak dorsiflexion of 27.9 ± 3.7° and only minimal plantarflexion during stance, while the biological ankle joint of non-amputee athletes displayed both dorsiflexion and plantarflexion with peak values of 17.6 ± 4.1° and 31.5 ± 5.5, respectively. The peak knee and hip flexion, but not extension, were lower in athletes with BKA compared to non-amputee athletes (both $p = 0.017$) (figure 4; electronic supplementary material, table S1).

Non-amputee athletes had discontinuous hip extension with a flexion angle at TD of 24.8 ± 4.8° and peak hip flexion of 34.4 ± 5.1° at approximately 25% of ground contact during the take-off step. Their hip

Table 2. COM kinematics. The mean values with standard deviations (s.d.), at the instances of TD, MKF and TO for athletes with BKA ($n = 3$) and non-amputee athletes (non-AMP, $n = 7$) during the take-off step of the long jump. Bold values indicate significant differences between groups.

measures	athletes with BKA			non-amputee athletes		
	TD	MKF	TO	TD	MKF	TO
COM displacement during stance (cm)						
anterior	0	54.2 (5.8)	100.9 (6.2)	0	47.2 (7.8)	102.8 (8.9)
medio(+)/lateral(−)	0	0.3 (0.7)	**0.2 (1.3)**	0	−0.5 (0.7)	**−2.6 (1.5)**
vertical	0	1.8 (1.6)	**16.7 (1.6)**	0	4.0 (1.9)	**21.8 (3.1)**
distances (cm)						
anterior (+)/posterior (−) COM to COP	**−63.2 (2.1)**	**−7.3 (4.7)**	36.7 (4.2)	**−53.2 (8.8)**	**−20.5 (5.8)**	43.6 (14.5)
medio(+)/lateral(−) COM to COP	8.0 (4.8)	**4.9 (1.1)**	3.4 (2.0)	0.6 (11.3)	**−0.9 (2.7)**	−1.4 (7.7)
whole leg length	**110.0 (1.5)**	93.1 (3.0)	110.1 (1.5)	**99.5 (4.3)**	93.0 (4.1)	111.1 (7.9)
lower leg length	**65.6 (2.5)**	49.6 (4.6)	65.4 (2.7)	**57.6 (3.1)**	52.2 (2.3)	67.8 (7.3)
COM velocity ($m\ s^{-1}$)						
anterior	**8.74 (0.59)**	8.05 (0.52)	8.13 (0.52)	**9.46 (0.32)**	8.52 (0.30)	8.32 (0.35)
medio(+)/lateral(−)	0.03 (0.13)	0.0 (0.11)	**−0.04 (0.13)**	−0.03 (0.11)	−0.21 (0.20)	**−0.38 (0.21)**
vertical	−0.51 (0.17)	1.68 (0.10)	2.86 (0.28)	−0.41 (0.11)	1.84 (0.44)	3.00 (0.28)

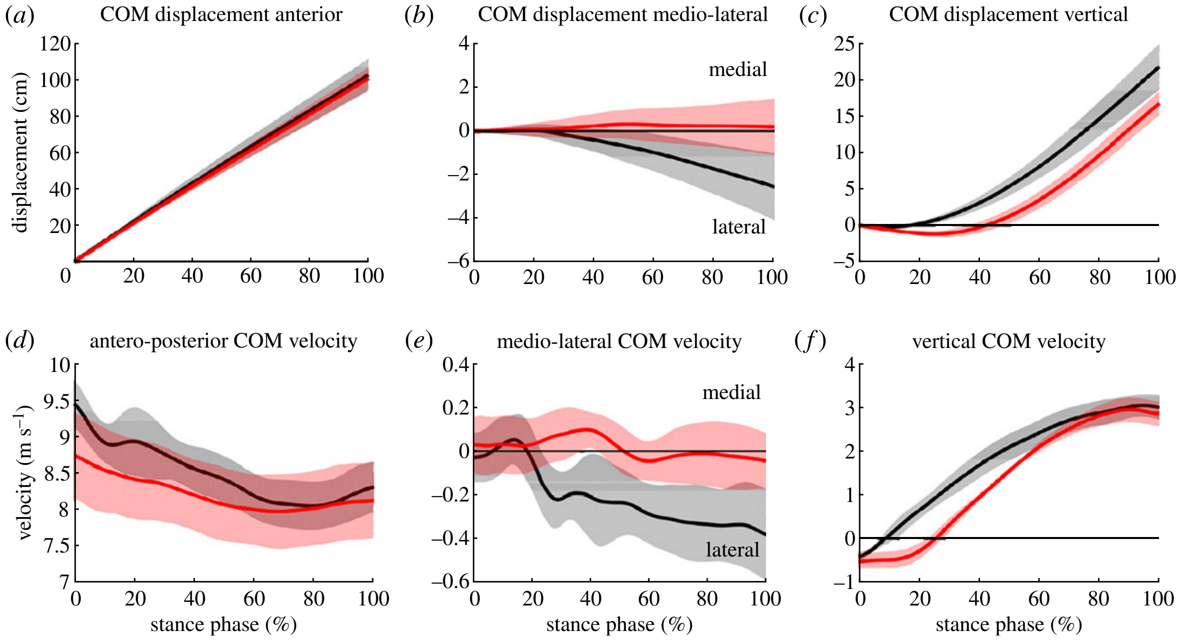

Figure 2. COM displacement (*a*–*c*) and velocity (*d*–*f*) during the take-off step stance phase for athletes with BKA ($n = 3$, red) and non-amputee athletes ($n = 7$, black) in the antero-posterior (*a*,*d*), medio-lateral (*b*,*e*) and vertical (*c*,*f*) directions.

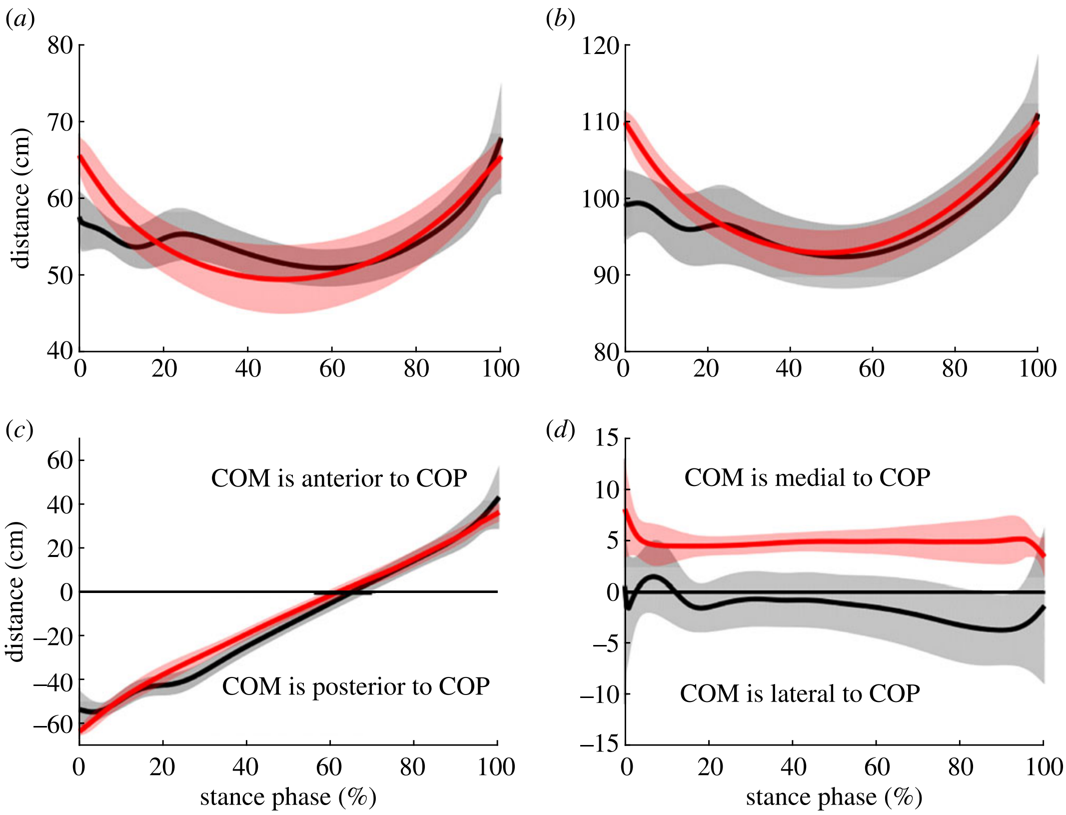

Figure 3. Lower leg length (*a*) and whole leg length (*b*) during the stance phase of the take-off step. Linear distance from the COM to the COP in the antero-posterior (*c*) and medio-lateral (*d*) directions during the stance phase of the take-off step. Athletes with BKA ($n = 3$) are indicated in red and non-amputee athletes ($n = 7$) are indicated in black.

extension angle at TO was 25.7 ± 3.4°. The sagittal plane hip angle of athletes with BKA displayed a near continuous extension and was not different at TD or TO compared to non-amputee athletes (both $p = 0.117$). However, at the instant of MKF, hip flexion was 72.6% lower in athletes with BKA compared to non-amputee athletes ($p = 0.017$) (table 3). In both groups, the hip joint angle switched from flexion to extension at about 70% of stance (BKA 68.2 ± 7.5%; non-AMP 70.4 ± 4.4%). The knee flexion angle was 38.7% lower at TD ($p = 0.033$) and 40.3% lower at MKF ($p = 0.017$) but not different at TO ($p = 0.517$) for athletes with BKA compared to non-amputee long jumpers.

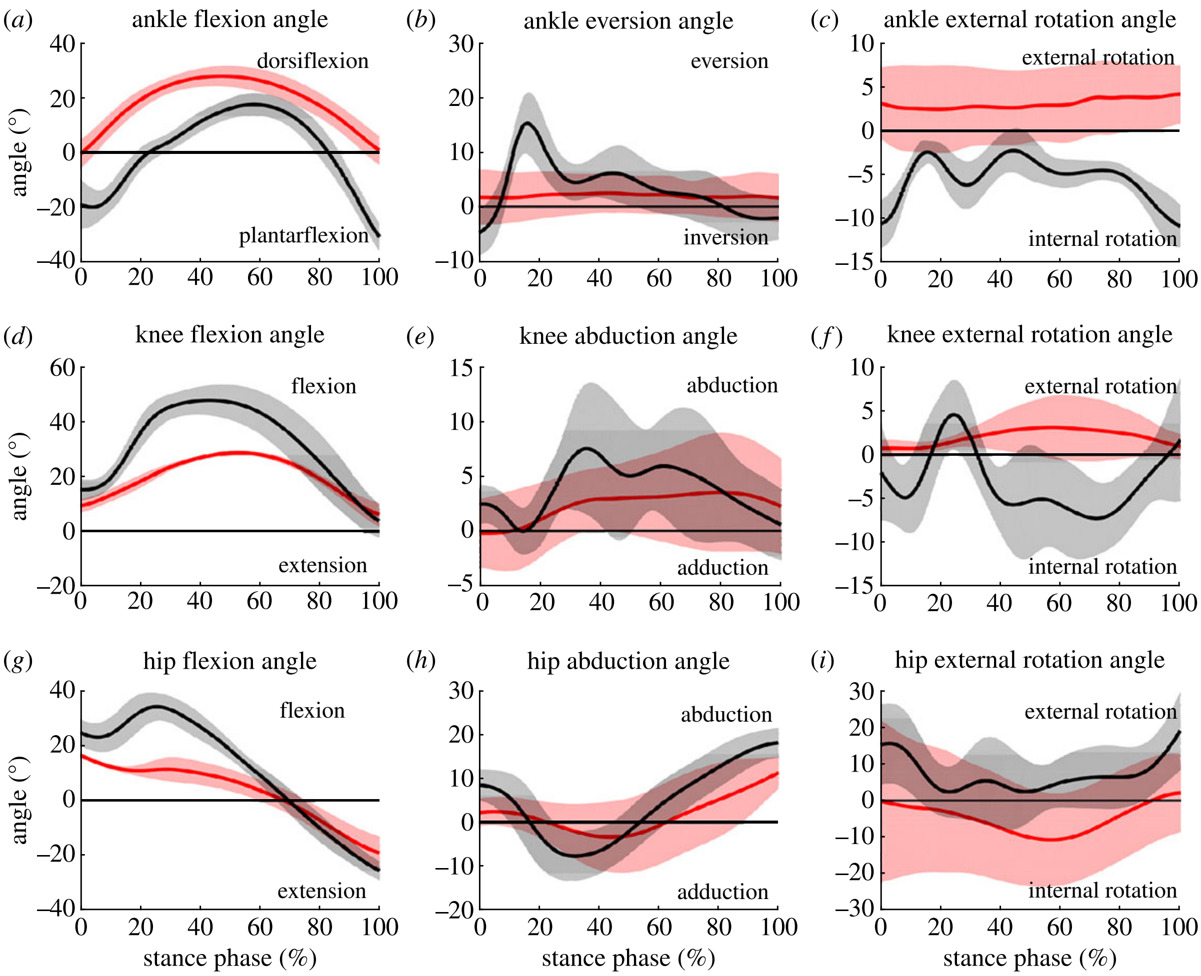

Figure 4. Joint angles during the stance phase of the take-off step for athletes with BKA ($n = 3$, red) and non-amputee athletes ($n = 7$, black) for the ankle (*a–c*), knee (*d–f*) and hip (*g–i*) in the sagittal (*a,d,g*), frontal (*b,e,h*) and transverse (*c,f,i*) planes.

Frontal and transverse plane prosthetic ankle angles of athletes with BKA were near constant throughout ground contact of the take-off step, whereas the ankle joint of non-amputee athletes displayed frontal and transverse plane ROMs of $20.6 \pm 6.9°$ and $10.6 \pm 3.7°$, respectively (figure 4; electronic supplementary material, table S1). At the instant of TD, frontal and transverse plane joint angles were not different between groups in the knee ($p = 0.183$, $p = 0.517$) and hip ($p = 0.117$, $p = 0.267$) (figure 4 and table 3). At MKF, the knee joint of the non-amputee athletes was internally rotated, whereas the knee joint of the athletes with BKA was externally rotated. At TO, athletes with BKA had 38.0% lower hip abduction and 89.1% lower hip external rotation compared to non-amputee athletes (both $p = 0.067$).

4. Discussion

The purpose of the current study was to quantify three-dimensional long jump take-off step COM and joint kinematics of athletes with BKA and compare those to non-amputee athletes. Long jumpers with BKA, who use their affected leg as their take-off leg, have different COM and joint kinematics throughout the stance phase of the take-off step compared to non-amputee athletes.

4.1. Sagittal plane COM kinematics

During the take-off step, non-amputee long jumpers use a mechanical mechanism called pivoting, where they rotate their COM about their foot to redirect a portion of the horizontal velocity into vertical velocity [15,27]. However, the pivot may be more effective if the athlete has greater eccentric strength providing a greater ability to resist knee flexion [14,15,27]. Resisting knee flexion would allow non-amputee athletes to keep their leg stiff, providing a stable lever. Athletes with BKA, even though they resist knee flexion more than non-amputees (figure 4 and table 3), had greater shortening of the whole leg and lower leg

Table 3. Joint angles. Joint angles as mean with standard deviations (s.d.), at the instances of TD, MKF and TO for the athletes with BKA ($n = 3$) and the non-amputee athletes (non-AMP, $n = 7$) during the take-off step of the long jump. (Dorsi)flexion, eversion/abduction and external rotation are indicated by positive values, whereas plantarflexion/extension, inversion/adduction and internal rotation are indicated by negative values. Bold values indicate significant differences between groups.

	athletes with BKA			non-amputee athletes		
joint angles (°)	TD	MKF	TO	TD	MKF	TO
ankle[a]						
dorsiflexion (+)	**−0.5 (5.1)**	**27.5 (4.2)**	**0.7 (5.1)**	**−18.8 (9.1)**	**13.2 (3.9)**	**−30.8 (5.2)**
eversion (+)	**1.7 (5.0)**	2.2 (3.4)	1.6 (4.3)	**−4.8 (4.2)**	5.7 (5.1)	−2.1 (4.0)
external rotation (+)	**3.2 (4.1)**	**3.0 (4.0)**	**3.3 (4.2)**	**−10.6 (2.7)**	**−2.9 (3.2)**	**−10.9 (2.4)**
knee						
flexion (+)	**9.4 (2.4)**	**28.7 (0.5)**	6.2 (4.3)	**15.3 (3.9)**	**48.2 (5.3)**	3.8 (5.9)
abduction (+)	−0.2 (3.2)	3.2 (3.4)	2.3 (4.4)	2.4 (1.8)	5.2 (6.3)	0.6 (3.3)
external rotation (+)	0.8 (1.0)	**3.2 (3.3)**	1.0 (1.4)	−2.0 (5.4)	**−4.1 (6.2)**	1.8 (7.1)
hip						
flexion (+)	16.6 (0.8)	**6.5 (2.9)**	−19.1 (5.9)	24.8 (4.8)	**23.6 (3.9)**	−25.7 (3.4)
abduction (+)	2.3 (3.1)	−2.5 (8.2)	**11.3 (3.7)**	8.4 (3.6)	−4.2 (4.9)	**18.1 (3.3)**
external rotation (+)	−0.2 (22.1)	−10.6 (12.9)	**2.1 (10.7)**	15.3 (11.1)	2.4 (11.3)	**19.2 (10.8)**

[a]Ankle in the BKA group refers to the point of the prosthesis' greatest curvature defined as the prosthetic ankle joint.

during the compression phase of the take-off step (figure 3 and table 2), indicating that their leg is not as rigid as it is for non-amputee athletes. Because leg stiffness is dictated by RSP stiffness during running [28], the use of a stiffer prosthesis by an athlete with BKA could increase leg stiffness during the long jump take-off step. However, a stiffer prosthesis might impair the elastic energy storage and return within the leg and result in higher impact forces leading to increased knee flexion. Therefore, prosthetic stiffness probably influences long jump performance and should be subject of future research.

As shown in our previous analysis of the same jumps, ground contact times of the take-off step were not different between non-amputee athletes (122 $\pm$ 9 ms) and athletes with BKA (124 $\pm$ 14 ms) who used their affected leg as their take-off leg [12]. For non-amputees, Lees *et al*. [15] define that the duration of the pivot equals the compression phase, from TD to MKF. During this phase, athletes generate 64–70% of the vertical take-off velocity [14,15,19]. Even though our results show different COM velocity profiles between athletes with BKA and non-amputee athletes from TD to TO of the take-off step (figure 2 and table 2), the generation of vertical velocity during the compression phase relative to the vertical velocity at TO was not different between groups (BKA: 59.3%, non-AMP: 60.5%), but slightly lower compared to previous research [14,15,19].

Good long jump performance of non-amputee athletes was related to their ability to tolerate high-impact forces [29] and to increase the height of the COM immediately after TD [30]. By contrast, other studies found that vertical velocity has a downward orientation at TD [13,15,19,20] that lasts for about 5% of the take-off step [19]. The vertical COM movement of the non-amputee athletes from the current study is in agreement with the results of Lees *et al*. [15], but vertical COM increase during the take-off step was about 7–8 cm lower than reported in other studies [19,20]. Based on the conflicting ideas mentioned above and a previous discussion by Hay *et al*. [13], an immediate upward movement of the COM at TD may not be a robust predictor of good long jump performance. Additionally, our results show that the vertical COM movement of athletes with BKA is different compared to non-amputee long jumpers presented here or previously [15,19]. Total vertical displacement of the COM was smaller in the athletes with BKA, but the vertical COM downward displacement lasted more than twice as long compared to non-amputee athletes. The latter, in combination with greater shortening of the lower leg during the compression phase and a 20.2% longer relative duration of the compression phase, emphasizes the inability of athletes with BKA to increase leg stiffness in their affected leg [23]. Thus, long jumpers with BKA must alter their movement strategy and predominately rely on energy storage and return in the RSP. By contrast, Luhtanen & Komi [29] argue that good non-amputee long jumpers are able to resist high-impact forces and subsequently ‘benefit more from the elastic behavior of the muscles’ [29, p. 273] during the take-off step. Therefore, it is important to differentiate between the required take-off strategies for the long jump elicited by non-amputee athletes and athletes with BKA who use their affected leg as their take-off leg. By using their RSP as a spring, the athletes with BKA had a vertical COM downward displacement during the first 42% of ground contact but still benefited from elastic energy storage and return, and thus elicited the same long jump performance. The movement patterns of athletes with BKA are likely to be dictated by the use of a prosthesis. Neither in the present nor in previous studies, have such patterns been reported for non-amputee long jumpers.

Based on COM kinematics during the take-off step, the determinants of long jump performance are different for non-amputees and athletes with BKA. Further research is needed to identify performance limiting factors for the long jump for athletes with BKA (e.g. duration and extent of the downward movement, as this is directly affected by the stiffness of the prosthesis). Knowledge about performance limiting factors may help coaches and biomechanical staff to adapt and enhance the performance analysis for long jumpers with BKA.

4.2. Non-sagittal plane COM kinematics

Medio-lateral COM position relative to the take-off foot was different throughout the stance phase between groups. The COM position was about 5 cm medial to the COP during most of the take-off step for athletes with BKA, whereas the non-amputee athletes had their COM 0.6 cm medial to the COP at TD and 1.4 cm lateral to the COP at TO. The results from non-amputees are in line with previous studies, which found that the COM was directly above the ankle at TD and then deviated laterally until TO [19,20]. Medial placement of the foot results in foot eversion during the early phase of ground contact (figure 4) to create a flat support area. Because an RSP is designed to primarily act in the sagittal plane, athletes with BKA cannot evert or invert their RSP, and a medial foot placement would result in a force applied to the lateral edge of the RSP, which would probably compromise dynamic stability and could result in a failed jump attempt or fall. The difference in prosthetic position of athletes with BKA compared to non-amputee athletes is probably constrained and induced by the RSP's design and rigidity in the frontal plane.

During ground contact of the take-off step, non-amputee athletes had increasing lateral velocity, which resulted in a distinct 2.6 cm lateral COM displacement at TO (table 2). This lateral COM displacement probably results from placing the take-off foot beneath the COM and the resulting lateral ground reaction force (GRF) peak during the early phase of ground contact [12]. Athletes with BKA did not have a lateral GRF peak [12] and, therefore, did not have a lateral COM displacement.

The effect of a lateral take-off velocity on absolute horizontal jump distance can be calculated by using the aerial time calculated in our previous analysis for the same jumps [7]. An aerial time of 0.882 s [7] and a take-off velocity of 0.38 m s^{-1} in the lateral direction, shown by the non-amputee athletes (table 2), would result in a sidewise COM displacement of 0.34 m during the flight phase—neglecting air resistance. Using trigonometry and a theoretical jump distance of 7.26 m, a lateral displacement of 0.34 m would result in a 0.8 cm increase in the absolute linear horizontal jump distance. Therefore, a lateral take-off velocity has a minimal effect on non-amputee athletes' long jump performance.

4.3. Sagittal plane joint angles

Hip flexion angles of non-amputee athletes at TD were about 6–9° lower in this study compared to data from previous studies of non-amputee long jumpers, who reached effective distances of 7.45 ± 0.18 m [19], 7.96 ± 0.15 m [20] and 7.79 ± 0.24 m [15], respectively. Furthermore, non-amputee athletes from the present study did not reach peak hip flexion prior to 25 ± 1.7% of the stance phase, and then reached maximum extension of the hip at TO with values similar to those in [19,20] but about 12° greater compared to those in [15]. This discontinuous sagittal plane hip motion contrasts with previous studies that reported continuous hip extension throughout ground contact [19,20]. These differences between studies, especially during the early stance phase of the take-off step, might be due to a shorter average jump distance in our study or due to lower sampling rates (100 or 125 Hz) [15,19,20] and lower cut-off frequencies (8 or 8.3 Hz) [15,19] used in previous studies. When analysing the ground contact phase of the long jump take-off step, which lasts about 0.12 s, low sampling rates and cut-off frequencies underestimate peak values by smoothing the data. This could lead to the neglect of values potentially important for identifying movement strategies. Our study (together with [7] and [12]) is the first to use an optoelectronic, marker-based system for data collection as well as sampling frequencies [25,31] and filtering regimes [24,25] similar to those recently used for sprint running analyses. Compared to non-amputee long jumpers, athletes with BKA have lower peak ground reaction forces in the vertical and posterior directions during the take-off step [7,12], which result in lower sagittal plane peak hip and knee joint moments [12]. Therefore, athletes with BKA had less knee flexion and had continuous hip joint extension compared to non-amputee athletes.

The knee flexion angle of the non-amputee athletes was similar at TD, about 7–13° higher at MKF and about 2–7° lower at TO compared to previous studies of non-amputee long jumpers [15,19,20]. As discussed previously, these differences could be due to different jump distances or different sampling rates and filtering procedures. Hip and knee joint sagittal ROM were lower (both $p = 0.017$) in athletes with BKA (35.6°, 22.5°) compared to non-amputee athletes (60.1°, 44.4°) (figure 4). Apparently, athletes with BKA seek to keep their leg straight during the take-off step of the long jump, most likely to optimize the energy exchange with the prosthesis. A similar strategy of stiffening the affected leg was observed when comparing the take-off step characteristics of athletes with BKA using their unaffected leg versus athletes with BKA using their affected leg for the take-off step [11]. The effectiveness of this prosthetic 'springboard' [11, p. 304] motion probably depends on the prosthetic configuration (e.g. stiffness, height) and its alignment. However, the choice of prosthetic configuration is subjective and not based on systematic research. Future research should determine the effects of different prosthetic configurations on long jump performance in athletes with BKA and further research is needed that addresses the influence of socket fit (interface between the RSP and residual limb) on performance.

4.4. Non-sagittal plane joint angles

Frontal plane hip angles for non-amputee athletes are in accordance with values reported in previous studies [19,20]; the hip is abducted at TD and TO. During the first half of the stance phase, non-amputee athletes were not able to resist hip adduction, which is shown by a slight frontal plane bend of the thigh relative to the pelvis (figure 4). Athletes with BKA, in general, had a similar, but less pronounced pattern for frontal plane hip and knee motion compared to non-amputee athletes. Frontal plane joint motion confirms the importance of muscles relevant for frontal plane stabilization and body weight support [32] in both groups of athletes.

To our knowledge, this is the first study to report transverse plane joint angles during the long jump take-off step. Transverse plane hip and knee angles of non-amputee long jumpers are similar to those reported for sprinting [25]. One study found that the ankle was predominantly externally rotated during ground contact for non-amputee sprinters [25], whereas the ankle joint was internally rotated during the take-off step of non-amputee long jumpers in the present study. The internally rotated ankle may result from the non-amputee long jumpers' ambition to position their foot beneath the COM (figure 3). However, during the compression phase of the take-off step, the ankle of the non-amputees rotated externally from 10.6° internal rotation at TD to 2.9° internal rotation at MKF (table 3 and figure 4). An external rotation of the foot relative to the shank segment implies an internal rotation of the tibia relative to the foot. Together with the frontal plane foot eversion (figure 4), the non-amputee long jumpers in the present study elicited motions that resemble the tibiocalcaneal coupling previously reported for the stance phases of sprinting [25] and running [33].

4.5. Limitations

A limited number of long jumpers with BKA participated in this study; however, these include three out of the four best long jumpers who participated in the 2016 Paralympic Games. Due to the high inter-athlete performance differences in Paralympic long jump, a greater sample size might increase variability and the risk of overlooking movement patterns unique for long jumpers with BKA competing at the highest performance level. Although there are advantages of optoelectrical systems (e.g. high accuracy, no manual digitizing), marker movement on the skin in high-impact movements might influence joint angle calculations. The individual alignment and type of prosthesis used by athletes with BKA probably affect take-off step kinematics. However, all of the RSP models currently used by elite athletes provide the same spring-like function; thus, there are not likely differences in movement strategies between athletes due to different RSP models. In the present analysis, all athletes with BKA used the same type of RSP (Cheetah Xtreme; Össur, Reykjavik, Iceland) with their individual alignment. Future research should investigate the effects of different RSP configurations that optimize fit and performance.

5. Conclusion

Long jumpers with BKA positioned their prosthesis more laterally compared to the foot placement beneath the COM used by non-amputee athletes. This strategy may avoid GRF placement on the edge of the prosthesis and, furthermore, may explain the absence of any relevant medio-lateral GRF application [12] and medio-lateral COM movement. Compared to non-amputee athletes, long jumpers with BKA had less sagittal plane ROM in the hip and knee joints during stance but greater shortening of the whole leg and lower leg during the compression phase, which is due to the compression of the prosthesis compared to the biological leg. In general, long jumpers with BKA had a longer compression phase and a prominent downward movement of the COM, indicating a less rigid lever compared to the biological leg of non-amputees. Thus, the redirection of horizontal velocity to vertical velocity in athletes with BKA is different compared to non-amputee athletes. The motion of athletes with BKA does not reflect the strategy of pivoting shown by non-amputee athletes, but resembles the use of a 'springboard' [11, p. 304]. However, these different take-off step techniques lead to the same long jump performance.

In our previous paper [7], we pointed out how non-amputee long jumpers cannot adopt the technique elicited by athletes with BKA, even if they would intend to, due to their limited capacity for storing and returning energy in their biological structures. On the other hand, in the present study, we show that, due to the mechanical constraints of the prosthesis, long jumpers with BKA are unable to actively regulate their lower leg stiffness and have to regulate the stiffness of the whole leg by reducing knee ROM during the take-off step.

In sum, long jumpers with BKA who use their affected leg as their take-off leg cannot adopt the take-off technique elicited by non-amputee long jumpers and vice versa. Thus, our results can be used to enhance athletic performance of long jumpers with BKA and the design of future prostheses. Additionally, they may inform decision makers during the revision of Olympic and Paralympic regulations.

Ethics. All athletes gave voluntary informed consent to participate in the study. The study design was in line with the declaration of Helsinki and was approved by the ethical committee board of the German Sport University Cologne (approval number: 040/2016).

Data accessibility. Data available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.t7d934c [34].

Authors' contributions. W.P., H.H., A.M.G., S.W., J.F. and R.M. designed and managed the study. Data capturing was executed by J.F., S.W., R.M., H.H., A.M.G. and W.P. Model and parameter calculations were performed by K.H., J.F. and S.W. All authors interpreted the data. J.F. drafted and wrote the manuscript with contribution from A.M.G., S.W., H.H., W.P., R.M. and K.H. All authors gave final approval for publication.

Competing interests. None of the authors has any conflict of interest associated with the study.

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Tabelle 4. **Zentrale Erkenntnisse Studien 1 - 3**

Leistungs- und Belastungscharakteristika im leichtathletischen Weitsprung mit Unterschenkelprothese			
Studie 1 *Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes* *Willwacher et al., 2017, Sci. Rep.*	Studie 2 *Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation* *Funken et al., 2019, Med. Sci. Sports Exercise*	Studie 3 *Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics* *Funken et al., 2019, R. Soc. Open Sci.*	Studie 4 *Leg stiffness during the long jump take-off step of athletes with and without a transtibial amputation* *Funken et al., nicht* publiziert
Athleten mit BKA*, die ihre Prothese für den Absprung nutzen**, haben im Vergleich zu nicht amputierten Athleten einen Vorteil im Absprung. Athleten mit BKA laufen im Vergleich zu nicht amputierten Athleten langsamer an, was zu einem Nachteil führt. Der Absprung im Weitsprung unterscheidet sich grundlegend zwischen Athleten mit und ohne BKA hinsichtlich der, bezogen auf den Körperschwerpunkt, gespeicherten und zurückgegebenen Energie. Die Prothese der Athleten mit BKA verfügt über größere Energiespeicherkapazität als der Muskel-Sehnen-Band-Apparat der unteren Extremität bei nicht amputierten Athleten.	Die Hebelarme zwischen dem Vektor der Bodenreaktionskraft und dem Knie- bzw. Hüftgelenk sind bei Athleten mit BKA während des Absprungs kürzer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung am Knie und an der Hüfte während des Absprungs ist bei Athleten mit BKA geringer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung während des Absprungs von Athleten mit BKA konzentriert sich, speziell an der Hüfte, nahezu ausschließlich auf die Sagittal-ebene, während bei nicht amputierten Athleten die Strukturen in der Frontalebene in erheblicher Weise mitbelastet werden.	Athleten mit BKA sinken während des Absprungs deutlich in ihre Prothese ein und haben ein, im Vergleich zu nicht amputierten Athleten, reduziertes Bewegungsausmaß im Kniegelenk Bzgl. der medio-lateralen Ausrichtung positionieren Athleten mit BKA ihre Prothese während des Absprungs weiter entfernt in Relation zum Körperschwerpunkt als nicht amputierte Athleten ihren Fuß. Athleten mit BKA können während des Absprungs nicht den Hebelmechanismus von nicht amputierten Athleten adaptieren und gleichzeitig die Energiespeicherkapazität ihrer Prothese ausnutzen.	

* BKA: Unterschenkelamputation (abgeleitet aus dem Englischen: Below the Knee Amputation
** Es wird im Folgenden vorausgesetzt, dass Athleten mit BKA ihre Unterschenkelprothese für den Absprungschritt nutzen

Appendix Studie 3

Supplementary Table 1 3D Peak joint angles

Der Verlauf des *Review*-Verfahrens kann online eingesehen werden.

Funken et al., 2019 Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics (Supplemental material: Review History). *R. Soc. Open Sci*. 6(4):190107.

https://royalsocietypublishing.org/action/downloadSupplement?doi=10.1098%2Frsos.190107&file=rsos190107_review_history.pdf

Supplementary Table 1, for Funken et al. (2019) Royal Society Open Science, 6:190107.

Supplementary Table 1. Peak joint angles.

	Athletes with BKA			Non-amputee athletes			Difference BKA to nonAMP	
Peak joint angles [°]	Mean (SD)	Min	Max	Mean (SD)	Min	Max	[%]	p
Ankle[a]								
Dorsiflexion (+)	27.9 (3.7)	24.4	31.8	17.6 (4.1)	13.4	23.6	58.8	**.017**
Plantarflexion (-)	-1.1 (5.2)	4.7	-5.6	-31.5 (5.5)	-21.0	-38.1	-96.5	**.017**
Eversion (+)	2.8 (3.9)	-1.22	6.6	15.8 (5.4)	6.3	22.4	-82.6	**.033**
Inversion (-)	0.9 (4.1)	4.7	-3.5	-4.8 (4.2)	1.54	-9.9	-118.7	.117
External rotation (+)	5.2 (2.8)	3.1	8.4	-1.2 (2.2)	-3.8	2.4	-529.0	**.017**
Internal rotation (-)	1.2 (4.9)	6.6	-3.0	-11.8 (1.8)	-8.7	-14.5	-110.7	**.017**
Knee								
Flexion (+)	28.7 (0.5)	28.3	29.3	48.2 (5.3)	41.0	55.0	-40.3	**.017**
Extension (-)	6.2 (4.3)	10.9	2.6	-3.8 (6.0)	11.5	-4.1	64.8	.517
Abduction (+)	4.9 (3.9)	2.2	9.3	9.4 (4.5)	3.3	16.2	-48.3	.117
Adduction (-)	-1.1 (3.4)	2.4	-4.2	-1.8 (3.1)	2.2	-5.9	-37.0	.833
External rotation (+)	3.8 (2.7)	0.8	6.2	6.8 (2.9)	2.0	10.3	-44.2	.183
Internal rotation (-)	0.2 (1.4)	1.6	-1.2	-10.8 (3.1)	-6.4	-14.3	-101.5	**.017**
Hip								
Flexion (+)	16.6 (0.8)	15.9	17.4	34.4 (5.1)	27.2	42.2	-51.8	**.017**
Extension (-)	-19.1 (5.9)	-13.8	-25.4	-25.7 (3.4)	-19.9	-31.3	-25.7	.117
Abduction (+)	11.3 (3.7)	8.8	15.6	18.2 (3.3)	15.2	24.6	-37.8	**.033**
Adduction (-)	-3.7 (7.7)	5.1	-9.2	-8.2 (5.8)	-2.2	-15.7	-55.0	.667
External rotation (+)	5.5 (16.5)	-6.8	24.3	24.0 (8.3)	11.5	37.2	-77.0	.183
Internal rotation (-)	-11.0 (13.0)	3.2	-22.3	-1.3 (8.3)	8.0	-12.9	748.8	.183

Peak joint angles as mean with standard deviations (SD), within-group minimum and maximum values for athletes with a below the knee amputation (BKA) and non-amputee athletes (nonAMP) during the take-off step of the long jump. The differences between mean values from non-amputee athletes and athletes with BKA are presented as percentages. Bold p-values indicate significant differences.

[a] Ankle in the BKA group refers to the point of the prosthesis' greatest curvature defined as the prosthetic ankle joint

VIERTE STUDIE

Manuskript in Vorbereitung

Leg stiffness during the long jump take-off step of athletes with and without a below the knee prosthesis

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Nicht publiziert

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Abstract

Leg stiffness (k_{leg}) and vertical stiffness (k_{vert}) are frequently used parameters for describing leg function and gait characteristics in different locomotive tasks. However, information on k_{leg} and k_{vert} during the long jump take-off step are scarce for non-amputee athletes and are missing for athletes with below the knee amputation (BKA), who use their affected leg as their take-off leg. This is an issue due to the importance of k_{leg} and k_{vert} for understanding general locomotion characteristics of the long jump with and without BKA. We used three-dimensional motion analysis and force plate data for comparing k_{leg} and k_{vert} of three elite long jumpers with BKA during the take-off step to a group of non-amputee athletes. Using a 3D calculation approach based on kinematically measured leg length change and assuming a single linear leg-spring, we found that k_{vert} but not k_{leg} was significantly different during the take-off step between the groups. Our results underline the spring-like leg function during the take-off step in long jumpers with BKA, who use their affected leg for the take-off step, whereas the leg-spring characteristics of the non-amputee athletes were highly individual and k_{leg} might not be describable by the same linear spring-mass model for both groups.

[F] Zum Zeitpunkt der Einreichung der Dissertation hat den aufgelisteten Co-Autor*innen das vorliegende Manuskript der vierten Studie noch nicht vorgelegen.

INTRODUCTION

Leg stiffness (k_{leg}) is a frequently used parameter for biomechanical analyses of different forms of bi- and multipedal terrestrial locomotion in animals - including humans [1–3]. In this context the human body is often considered as a spring-mass system represented by the centre of mass (COM) and a single linear spring representing the leg [2,4] and k_{leg} is generally described as the ratio of the force compressing the spring and the maximal shortening of the leg [2,5,6]. However, definitions and calculation methods of k_{leg}, or more specifically, of the force and the leg shortening, vary depending on the form of locomotion and measuring equipment available [3,5,7,8].

In athletes with an amputation at the lower extremities who use running-specific prostheses (RSPs), a part of the biological leg-spring is replaced by a mechanical spring, attached to the residual leg. Numerous studies have analysed the spring-like movement behaviour in terms of k_{leg} during hopping [9], running [10–14] and sprinting [14,15] of athletes with an amputation at the lower extremities who use running-specific prostheses (RSPs). For the long jump take-off step, information on k_{leg} is missing for athletes with a below the knee amputation (BKA) and only one study [8] calculated k_{leg} for non-amputee athletes (sport students, average distance jumped: 5.49 m).

Based on a competition analysis executed during the 2004 Paralympic Games, Nolan and colleagues [16] found that athletes with BKA who used their affected leg for the long jump take-off step (n=5, average distance jumped: 6.04 m) resembled the use of a ‘springboard’, whereas athletes with BKA who used their unaffected limb for the take-off step (n=5, average distance jumped: 5.22 m) had higher range of motion in the hip (compared to athletes who used their affected leg for the take-off) and relied on knee and hip extension [17]. Today, almost all elite long jumpers with unilateral BKA use their affected leg for the take-off step. A recent comparison between non-amputee long jumpers (n=7, average distance jumped: 7.27 m) and long jumpers with a BKA (n=3, average distance jumped: 7.26 m) who used their affected leg for the take-off step [18] confirmed previous findings from Nolan and colleagues [16]. The authors show that long jumpers with BKA, unlike non-amputees, are not able to actively control the lower leg stiffness of their affected leg during the take-off step but regulate the stiffness of the whole leg by reducing the range of motion in the knee joint. They also found a greater vertical COM downward displacement in athletes with BKA compared to non-amputee athletes during the take-off step, which potentially results from a lower vertical stiffness (k_{vert}) in athletes with BKA compared to non-amputee athletes during the take-off step. However, besides of COM and joint kinematics, their [18] argumentation was mainly based on whole leg and lower leg deformation during stance - k_{leg} or k_{vert} were not calculated. Information on k_{leg} and/or k_{vert}, however, is important for understanding general movement characteristics and would be valuable information for athletes and coaches to adapt training protocols and enhance long jump performance.

Therefore, this study aimed to calculate k_{leg} and k_{vert} for athletes with BKA during the long jump take-off step and compare the results to a group of non-amputee athletes. Based on previous research we hypothesis that k_{leg} and k_{vert} will be lower for athletes with BKA compared to non-amputee athletes during the long jump take-off step.

METHODS

Participants and study design:

Data collection for this cross-sectional study was conducted at the German Sport University Cologne (GSU) and the Japan Institute of Sport Sciences (JISS). The study design was approved by the GSU ethical committee (approval number: 040/2016) and was in line with the declaration of Helsinki. Ten male athletes gave informed consent and participated voluntarily - three athletes with a BKA at their right leg (personal record at time of study [PR]: 7.43 ± 0.99 m, age: 26.0 ± 1.7 yr, body height: 1.83 ± 0.04 m, mass [including prosthesis and socket]: 78.7 ± 9.8 kg) and seven non-amputee athletes (PR: 7.65 ± 0.65 m, age: 24.6 ± 2.5 yr, body height: 1.82 ± 0.07 m, mass: 80.1 ± 6.2 kg). After an individual competition specific warm-up, all athletes were asked to perform full effort long jumps. All three athletes with BKA performed the take-off step using their affected leg.

Data collection, data processing and modelling procedures:

Three-dimensional (3D) marker trajectories (250Hz [GSU], 500 Hz [JISS], Vicon, Oxford, UK) and 3D ground reaction force (GRF) data (1000 Hz, Kistler, Winterthur, Switzerland) along with athlete specific anthropometrics served as input parameters for a modified mathematical rigid body model (Dynamicus, Alaska, The Institute of Mechatronics, Chemnitz, Germany). For the athletes with BKA, the model was adapted by replacing the lower part of the shank and the foot by a prosthesis. For the detection of ground contact we used a vertical GRF threshold of 10 Newton and touch down (TD) was defined as the first frame above the threshold and toe-off (TO) as the last frame above the threshold. Further details on data collection, data processing and modelling procedures are in our previous studies [18–20].

Parameter calculation:

To avoid influences of landing technique on long jump distance, we used the theoretical jump distance previously calculated [19] for the same jumps. The longest jump of each athlete was used for further calculations. The position of the centre of pressure (COP), as well as the magnitude and orientation of the GRF vector during the stance phase of the long jump take-off step, were obtained from the force plate data. The COM position was obtained from the model calculations.

k_{leg} was calculated as:

$$k_{leg} = \frac{F_{\parallel\, max_S}}{\Delta L_{max_S}} \qquad (1)$$

with L being the leg length, defined as the linear distance between the COM and the COP [3], and ΔL_{max_S} describing the maximum shortening of the leg length. Three non-amputee athletes showed heel strike patterns, therefore L increased during plantar flexion in the initial phase of ground contact and the subsequent anterior movement of the COP (see Figure 2 and Supplementary Figure 1). To avoid overestimation of k_{leg}, ΔL_{max_S} was calculated as the absolute difference between the greatest leg length in the first 50% of stance (L_0) and the minimum leg length (L_{min}).

To account for previously reported GRF orientation [20], which does not necessarily match with the orientation of the leg spring, we merely used the portion of the GRF which was parallel with the leg spring ($F_{\|}$) [7] for further calculations. $F_{\| \, max_S}$ in this context describes the value of $F_{\|}$ at the instant of maximum shortening of the leg length. $F_{\|}$ was calculated as the resultant GRF (GRF_{res}) projected into the axis of the spring mass model [7].

$$F_{\|} = GRF_{res} \cdot \cos(\alpha) \quad (2)$$

with

$$GRF_{res} = \overline{|GRF|} \quad (3)$$

and α being the angle between the vector of the GRF and the vector pointing from the COP to the COM ($\overline{com}$).

$$\alpha = arccos\left(\frac{\overline{GRF} \cdot \overline{com}}{|\overline{GRF}| \cdot |\overline{com}|}\right) \quad (4)$$

k_{vert} was calculated as:

$$k_{vert} = \frac{F_{\uparrow COM_{min}}}{\Delta y_{COM_{min}}} \quad (5)$$

with $F_{\uparrow}$ being the vertical GRF and Δy being the change in the vertical COM position. COM_{min} defines the instant of the lowest vertical COM position during the stance phase. Therefore, $\Delta y_{COM_{min}}$defines the maximal vertical downward displacement and $F_{\uparrow \, COM_{min}}$

defines the vertical GRF at the instant of maximal vertical downward displacement. All GRF values were normalized to the athletes' body weight (BW).

Statistics:

Due to the limited number of athletes, we used Wilcoxon's non-parametric rank sum test for tests between groups and set the level of significance to p=0.10 [18,19]. Additionally, we present percentage differences between the athletes with BKA in relation to the non-amputee athletes.

RESULTS

Theoretical jump distances were not different between groups (BKA: 7.26 ± 0.77 m, nonAMP: 7.27 ± 0.45 m, p = 1.000). k_{leg} was 33.4% lower in athletes with BKA compared to the non-amputee athletes, however level of significance was missed due to a relatively high inter-individual difference in the group of non-amputee athletes (p=0.383, Figure 1). k_{vert} was 85.2% lower in athletes with BKA compared to the non-amputee athletes (p=0.017, Figure 1). See Supplementary Table 1 for additional discrete values.

Plotting $F_{\|}$ over leg length change (ΔL) (Figure 2, Supplementary Figure 1) revealed that the corresponding force-leg-shortening curves of the non-amputee athletes, had a very individual development for each athlete but also showed some general patterns. The force-leg-shortening curves of the athletes with BKA were more uniform compared to the non-amputee athletes.

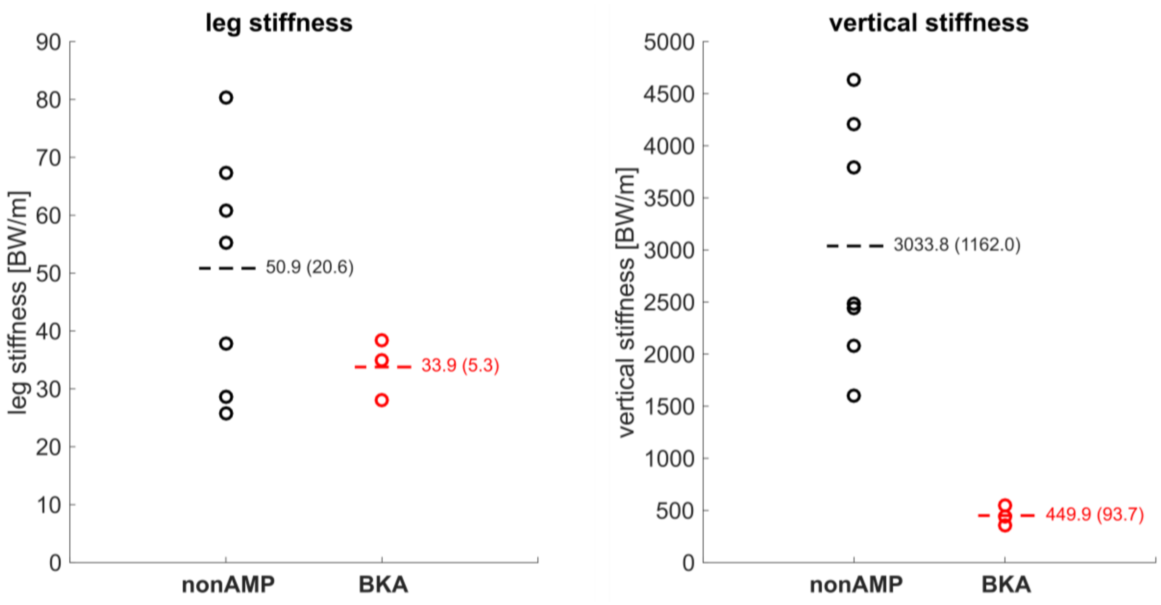

Figure 1: Leg stiffness (k_{leg}, left) and vertical stiffness (k_{vert}, right) for non-amputee athletes (nonAMP, black) and athletes with below the knee amputation (BKA, red). Stiffness values were normalised to body weight (BW). The dashed line indicates the mean with standard deviation (SD).

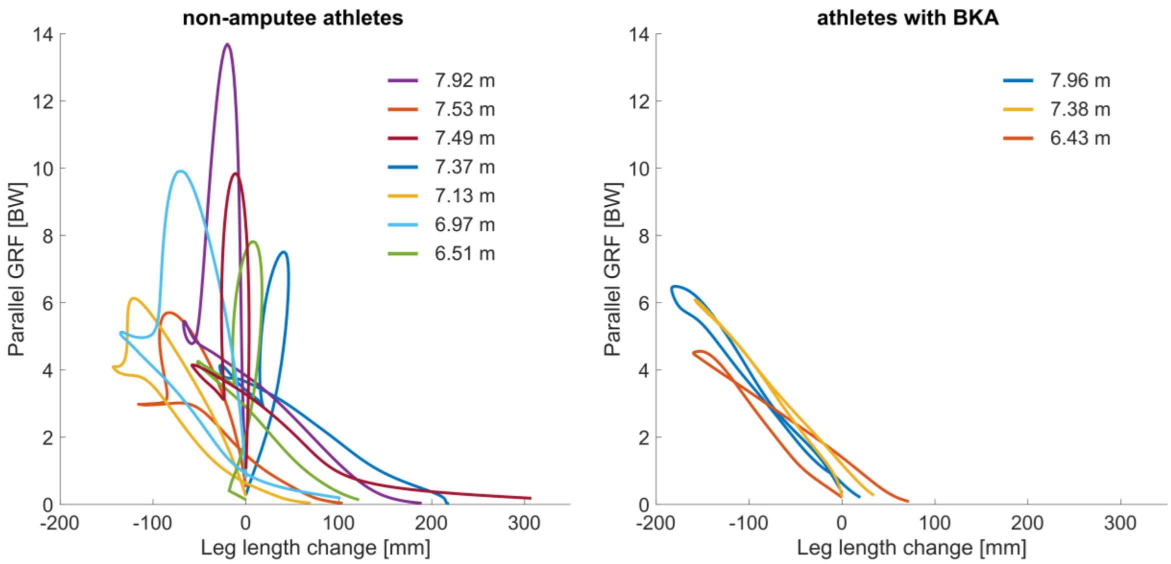

Figure 2: Parallel ground reaction force ($F_{\parallel}$) versus leg length change (ΔL) for non-amputee athletes (left) and athletes with below the knee amputation (BKA, right). $F_{\parallel}$ values were normalised to body weight (BW).

The instants of peak $F_{\parallel}$ and L_{min} (BKA: $F_{\parallel}$ at 37.8 ± 8.8% and L_{min} at 43.0 ± 2.6% of stance; nonAMP: $F_{\parallel}$ at 11.1 ± 2.1% and L_{min} at 42.7 ± 4.5% of stance) occurred within a shorter relative time period during the take-off step for the athletes with BKA compared to the non-amputee athletes (BKA: within 6.2 ± 4.8% of stance, nonAMP: within 31.6 ± 5.0% of stance, p=0.017) Except for one athlete with BKA, in all athletes $F_{\parallel}$ occurred prior to the instant of L_{min} (Figure 2). In contrast, the instants of peak $F_{\uparrow}$ and $\Delta y_{COM_{min}}$ (BKA: $F_{\uparrow}$ at 40.0 ± 8.5% and $\Delta y_{COM_{min}}$ at 25.2 ± 2.6%; nonAMP: $F_{\uparrow}$ at 11.0 ± 2.2% and $\Delta y_{COM_{min}}$ at 9.4 ± 2.6%) occurred within a longer relative time period during the take-off step for athletes with BKA compared to the non-amputee athletes (BKA: within 14.8 ± 7.9% of stance, nonAMP: within 1.7 ± 1.0% of stance, p=0.017). Except for one non-amputee athlete, in all athletes $\Delta y_{COM_{min}}$ occurred prior to peak $F_{\uparrow}$ (Figure 3). See Supplementary Table 1 for additional discrete values.

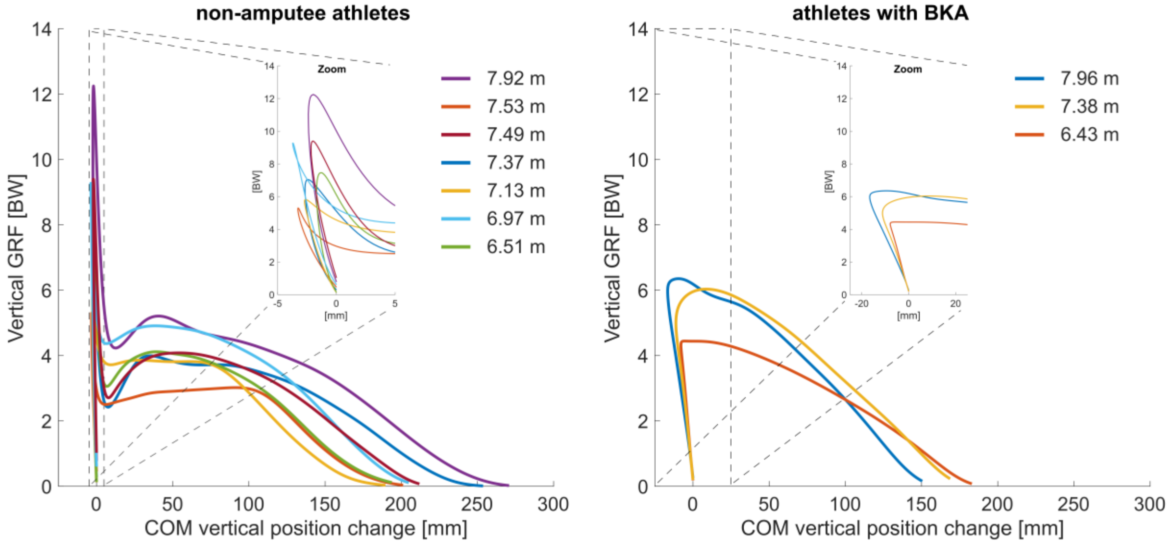

Figure 3: Vertical ground reaction force ($F_{\uparrow}$) versus vertical centre of mass (COM) position change (Δy) for non-amputee athletes (left) and athletes with below the knee amputation (BKA, right). $F_{\uparrow}$ values were normalised to body weight (BW).

DISCUSSION

The purpose of the current study was to calculate k_{leg} and k_{vert} for athletes with BKA during the long jump take-off step and compare the results to a group of non-amputee athletes.

Leg stiffness and vertical stiffness:

Arampatzis and colleagues [3] calculated k_{leg} for a range of different running velocities (2.5 – 6.5 m/s) with two different approaches. k_{leg} was either calculated using (1) the theoretically calculated leg length change based on McMahon and colleagues [4] or (2) based on the kinematically measured leg length change. They found, that, especially for higher running velocities, the first approach resulted in significantly greater shortening of the leg and thus lower k_{leg} compared to the second approach in non-amputee athletes [3].

k_{leg} of the non-amputee athletes during the take-off step in the current study was about 15% higher compared to k_{leg} values presented previously [3] for running at 6.6 m/s and kinematically measured leg length change, but was about 2-fold higher compared to k_{leg} calculated based on the theoretically calculated leg length change for running at 6.6 m/s [3] or 9m/s [14], respectively. k_{leg} of the non-amputee athletes in the current study for the take-off step was about 2.3-fold higher compared to values previously calculated by Seyfarth and colleagues [8] during the take-off step of 30 long jumps (sport students, average distance jumped: 5.49 ± 0.86 m). Higher values for k_{leg} compared to those in [8] are likely due to different calculation approaches used but also due to different skill level, both potential reasons for the greater maximum leg length shortening in [8] compared to our results. Even though all values in the current analysis on the take-off step were calculated in 3D, the approach for calculating k_{leg} is similar to the approach of using the kinematically measured leg length change as per Arampatzis and colleagues [3]. Therefore, it is coherent that the values of k_{leg} calculated for the take-off step in the current study for non-amputee athletes are close to those calculated by Arampatzis and colleagues [3] but are higher compared to those reported elsewhere for running at high velocities [14] or the long jump take-off step [8].

k_{vert} during the take-off step of the non-amputee athletes in the current study was about 17-fold higher compared to running at 9m/s [14]. Besides using different calculation approaches, the great difference in k_{vert} when comparing running at 9 m/s [14] with the take-off step of non-amputee athletes likely results from the differences in execution of the movement. Non-amputee long jumpers lower their COM during the last steps before take-off [21,22] and from there the direction of the movement is mainly upwards oriented with only a minimal COM downward displacement [18,23], but with about 2-fold higher peak vertical GRF application compared to fast running and sprinting [14,20,24].

Recent studies on running [10–13] and sprinting [15] of athletes with an amputation at the lower extremities who use running-specific prostheses (RSPs) mostly calculated k_{leg} utilising the model proposed by McMahon and colleagues [4]. However, it is unknown how the model corresponds to higher running/movement velocities in athletes using RSPs compared to an approach using kinematically measured leg length change.

k_{leg} during the take-off step of athletes with BKA in the current study was higher (between approximately 1.7 – 2-fold) compared to values published for the prosthetic limb of persons with a unilateral amputation running at different velocities (3.5 m/s [10], 7m/s [12], 9m/s [14]). k_{vert} during the take-off step of athletes with BKA in the current study was about 9-fold or 3-fold higher compared to values published for the prosthetic limb of persons with a unilateral amputation running at 3.5 m/s [10] or 9m/s [14], respectively. Higher values of k_{leg} in the long jump take-off step of athletes with BKA compared to running with a BKA [12,14] might result from different calculation approaches but also from stiffer prosthesis chosen by athletes for the long jump compared to running/sprinting.

Maximal shortening of the leg in the current study (0.17 m) was greater but vertical COM downward displacement (0.01 m) was lower during the take-off step of athletes with BKA compared to values reported for the prosthetic leg during running (3,5 m/s) of persons with a unilateral BKA (0.12 m and 0.04 m, respectively) [10]. Maximal shortening of the prosthetic leg in athletes with BKA while running at 7/ms (~0.16 m) [12] was similar to those calculated in the current study for the take-off step, whereas the values reported for running at 9 m/s (~0.25 m) [14] were somewhat higher compared to the current results for the long jump take-off step.

Higher values of k_{vert} in non-amputee athletes compared to athletes with BKA during the take-off step are in line with the findings of our previous study [18], where athetes with BKA had a pronounced vertical downward displacement of the COM during the first 42% of the stance phase. The downward displacement of the non-amputee athletes was less pronounced and lasted for a shorter duration.

Force-leg-length-change / force-displacement profiles:

In general, the $F_{\parallel}$-ΔL profiles (Figure 2, Supplementary Figures 1 and 2) of the non-amputee athletes during the take-off step in the current study showed similar patterns compared to those reported by Seyfarth and colleagues [8]. As shown in the figures (Figure 2, Supplementary Figures 1 and 2), the occurrence of peak $F_{\parallel}$ timely corresponds to the occurrence of L_{min} reasonably well in athletes with BKA but not in athletes with non-amputee athletes.

The $F_{\parallel}$-ΔL profiles of the non-amputee athletes were highly individual (Figure 2, Supplementary Figure 1). This might in some way influence the COM energy change during the take-off step. However, based on qualitative inspection, there was no obvious relationship between the individual COM energy absorption and generation during the take-off step as presented in our previous study [19, Fig. 5a/b] and the individual $F_{\parallel}$-ΔL profiles (Figure 2, Supplementary Figure 1) presented in the current analysis for the same jumps.

When approximating the line from the orgin of the $F_{\parallel}$-ΔL plot to peak $\mathrm{F}_{\parallel}$ and to L_{min}, respectively, for each athlete individually (Supplementary Figure 1), qualitative visual inspection of the angular intersection of both lines revealed that a linear force-leg-shortening relationship is virtually non-existent for the non-amputee athletes but might be assumed in all conscience for the athletes with BKA. It is, therefore, questionable whether or not it is reasonable to assume that the leg of non-amputee athletes, with their non-sinodial vertical GRF application characteristics [19,20], can be reduced to a linear spring and k_{leg} being represented by a single number based on classic stiffness calculation methods. This argumentation is in line with Seyfarth and colleagues [8], who successfully modelled the take-off step force-leg-length-change profiles for non-amputee athletes using a two-mass model with adjusted displacement and also calculated a dynamic leg stiffness.

In sum: We only partly accept our hypothesis that k_{leg} and k_{vert} are lower for athletes with BKA compared to non-amputee athletes during the long jump take-off step. k_{vert} was 8-fold lower for athletes with BKA compared to non-amputee athletes with similar mean jump distances. k_{leg} of the athletes with BKA was 33.4% lower compared to non-amputee athletes but level of significance was missed when using a 3D calculation model based on a single leg spring and kinematically measured leg length change. However, during the take-off step of the long jump the take-off leg appears to work like a linear spring until maximum leg compression in athletes with BKA, who use their affected leg as their take-off leg, but not in non-amputee athletes. Together with the limited number of athletes analysed, the latter might serve as a possible reason why k_{leg} was not significantly different between the groups, when applying the same leg-spring model for both groups. Nonetheless, and as discussed in our previous publications [18,19] it becomes obvious from differences in k_{vert} between the two groups in the current study, that the take-off leg function is different between long jumpers with and without BKA.

Limitations:

A limited number of athletes with BKA participated in the study. However, the group of athletes with BKA comprised three out of the four best athletes with BKA who competed in the long jump during the 2016 Paralympic Games. This provided us with the chance to identify movement chracteristics potentially unique to an elite sub-group of long jumpers with BKA. Calculation of leg stiffness based on COM position obtained from kinematic measures and model calculation on the one hand and COP calculation from force plate data one the other hand made it necessary to compensate for an initial leg lengthening in some athletes with a heel strike pattern. Even though it is not a direct limitation, it might affect the comparability to previous studies. k_{leg} of athletes with BKA is affected by prosthetic stiffness during running [11]. Therefore, it is reasonable to assume, that k_{leg} in long jumpers with BKA during the take-off step also depends on the prosthesis' stiffness chosen by the athletes and might to some extend affect the stiffness values present in the current analysis.

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Conflict of interest

None of the authors has any conflict of interest associated with the study.

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Authors contributions (preliminary):

WP, HH, AMG, SW, JF and RM designed and managed the study. Data capturing was executed by JF, SW, RM, HH, AMG and WP. Model and parameter calculations were performed by KH, JF and SW. JF and WP discussed and interpreted the results. JF wrote the manuscript. (Further contributions will be added after co-authors' revision).

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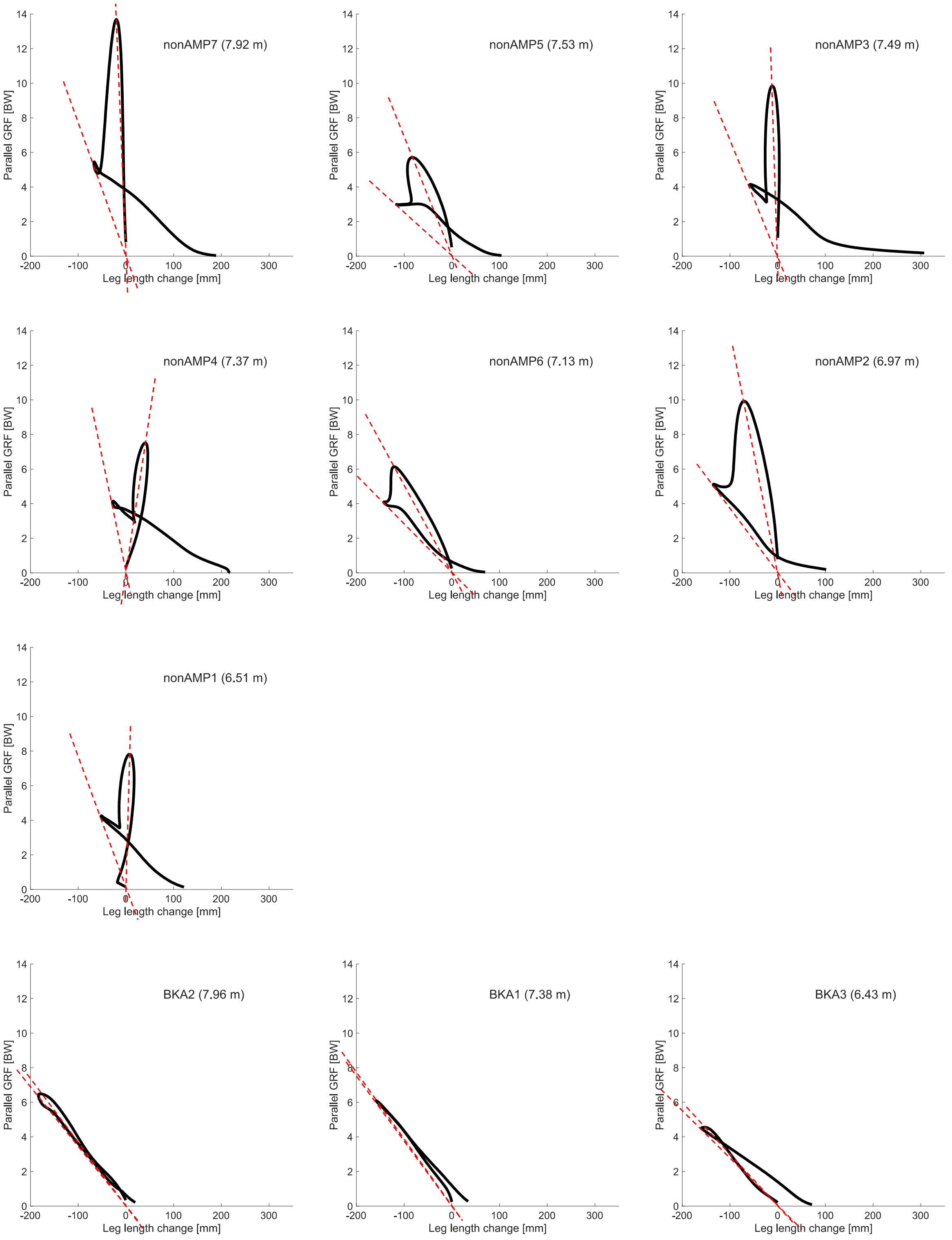
Tabelle 5. **Zentrale Erkenntnisse Studien 1 -4**

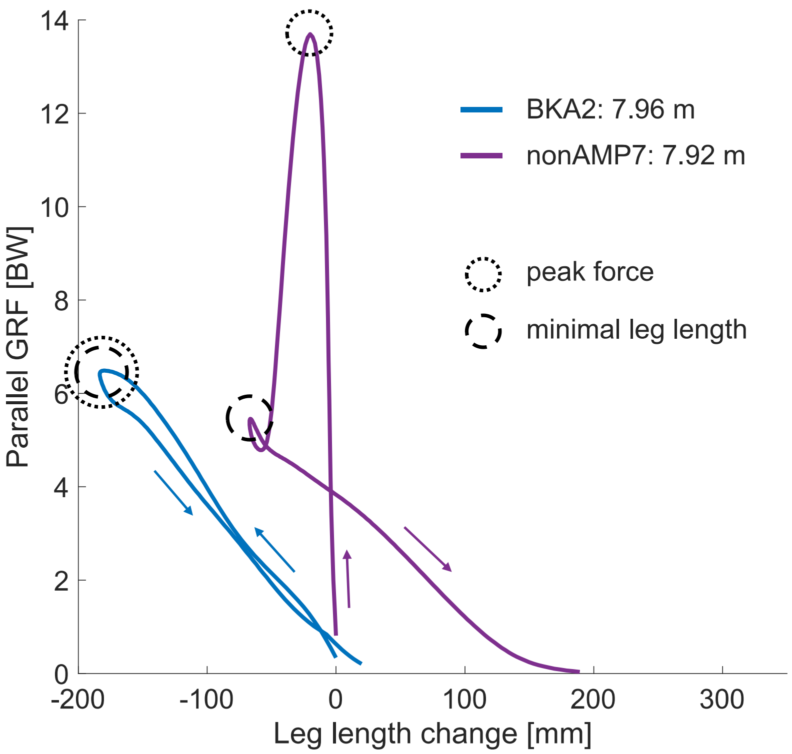
Leistungs- und Belastungscharakteristika im leichtathletischen Weitsprung mit Unterschenkelprothese			
Studie 1 *Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes* *Willwacher et al., 2017, Sci. Rep.*	Studie 2 *Three-Dimensional Takeoff Step Kinetics of Long Jumpers with and without a Transtibial Amputation* *Funken et al., 2019, Med. Sci. Sports Exercise*	Studie 3 *Long jumpers with and without a transtibial amputation have different three-dimensional centre of mass and joint take-off step kinematics* *Funken et al., 2019, R. Soc. Open Sci.*	Studie 4 *Leg stiffness during the long jump take-off step of athletes with and without a transtibial amputation* *Funken et al., nicht publiziert*
Athleten mit BKA*, die ihre Prothese für den Absprung nutzen**, haben im Vergleich zu nicht amputierten Athleten einen Vorteil im Absprung. Athleten mit BKA laufen im Vergleich zu nicht amputierten Athleten langsamer an, was zu einem Nachteil führt. Der Absprung im Weitsprung unterscheidet sich grundlegend zwischen Athleten mit und ohne BKA hinsichtlich der, bezogen auf den Körperschwerpunkt, gespeicherten und zurückgegebenen Energie. Die Prothese der Athleten mit BKA verfügt über größere Energiespeicherkapazität als der Muskel-Sehnen-Band-Apparat der unteren Extremität bei nicht amputierten Athleten.	Die Hebelarme zwischen dem Vektor der Bodenreaktionskraft und dem Knie- bzw. Hüftgelenk sind bei Athleten mit BKA während des Absprungs kürzer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung am Knie und an der Hüfte während des Absprungs ist bei Athleten mit BKA geringer als bei nicht amputierten Athleten. Die muskulo-skelettale Belastung während des Absprungs von Athleten mit BKA konzentriert sich, speziell an der Hüfte, nahezu ausschließlich auf die Sagittalebene, während bei nicht amputierten Athleten die Strukturen in der Frontalebene in erheblicher Weise mitbelastet werden.	Athleten mit BKA sinken während des Absprungs deutlich in ihre Prothese ein und haben ein, im Vergleich zu nicht amputierten Athleten, reduziertes Bewegungsausmaß im Kniegelenk Bzgl. der medio-lateralen Ausrichtung positionieren Athleten mit BKA ihre Prothese während des Absprungs weiter entfernt in Relation zum Körperschwerpunkt als nicht amputierte Athleten ihren Fuß. Athleten mit BKA können während des Absprungs nicht den Hebelmechanismus von nicht amputierten Athleten adaptieren und gleichzeitig die Energiespeicherkapazität ihrer Prothese ausnutzen.	Wird die Beinsteifigkeit auf einen einzelnen Wert reduziert, zeigt sich kein Unterschied zwischen Athleten mit und ohne BKA. Die vertikale Steifigkeit während des Absprungs ist bei nicht amputierten Athleten deutlich größer als bei Athleten mit BKA. Anders als bei nicht amputierten Athleten, verhält sich das Bein mit Unterschenkelprothese bei Athleten mit BKA während des Absprung bis zum Zeitpunkt der maximalen Beinverkürzung nahezu wie eine lineare Feder.

* BKA: Unterschenkelamputation (abgeleitet aus dem Englischen: Below the Knee Amputation
** Es wird im Folgenden vorausgesetzt, dass Athleten mit BKA ihre Unterschenkelprothese für den Absprungschritt nutzen

Appendix Studie 4



Supplementary Figure 1: Individual plots of parallel ground reaction force ($F_{\parallel}$) versus leg length change (ΔL) for non-amputee athletes (nonAMP, first three rows) and athletes with below the knee amputation (BKA, bottom row). $F_{\parallel}$ values were normalised to body weight (BW). Red dashed lines schematically approximate the line from the orgin of the plot to peak $F_{\parallel}$ and to minimum leg length (L_{min}), respectively.



Supplementary Figure 2: Parallel ground reaction force ($F_{\parallel}$) versus leg length change (ΔL) of one non-amputee athlete (nonAMP7, 7.92 m, purple) and one athlete with below the knee amputation (BKA2, 7.96 m, blue). $F_{\parallel}$ values were normalised to body weight (BW). Instants of peak $F_{\parallel}$ and minimum leg length (L_{min}) were visually approximated and are indicated schematically.

***Supplementary Table 1, Funken et al. (in preparation),* Leg stiffness during the long jump take-off step of athletes with and without a below the knee prosthesis**

Supplementary Table 1. Individual values of measures relevant for stiffness calculations

Measure	Leg stiffness (BW/m)	Vertical stiffness (BW/m)	Maximum leg shortening (mm)	Maximum vertical downward displacement (mm)*	Peak $F_{\parallel}$ (BW)	Peak $F_{\uparrow}$ (BW)*	Theoretical Jump Distance (m)*
Non-amputee athletes							
nonAMP7	80.3	4629.2	67.2	2.4	13.7	12.2	7.92
nonAMP5	25.8	1601.8	115.8	3.3	5.7	5.3	7.53
nonAMP3	67,4	4206.5	61.5	2.2	9.8	9.4	7.49
nonAMP4	55.3	2438.9	74.0	2.7	7.5	7.0	7.37
nonAMP6	28.7	2084.0	142.8	2.7	6.1	5.8	7.13
nonAMP2	37.7	2485.0	135.1	3.7	9.9	9.3	6.97
nonAMP1	60.9	3791.1	69.3	1.7	7.8	7.5	6.51
Mean (SD)	**50.9 (20.6)**	**3033.8 (1162.0)**	**95.1 (34.9)**	**2.7 (0.7)**	**8.7 (2.8)**	**8.1 (2.4)**	**7.27 (0.45)**
Athletes with BKA							
BKA2	35.0	358.9	183.4	16.6	6.5	6.4	7.96
BKA1	38.5	444.9	158.2	11.2	6.1	6.0	7.38
BKA3	28.1	546.0	160.0	7.9	4.6	4.4	6.43
Mean (SD)	**33.9 (5.3)**	**449.9 (93.7)**	**167.2 (14.1)**	**11.9 (4.4)**	**5.7 (1.0)**	**5.6 (1.0)**	**7.26 (0.77)**
p-value	0.383	0.017	0.017	0.017	0.117	0.183	1.000
BKA vs nonAMP (%)	-33.4	-85.2	+75.8	+346.9	-34.0	-30.5	-0.2

Individual values and mean values with standard deviation (SD) of leg stiffness, vertical stiffness, maximum leg shortening, maximum downward displacement, peak parallel ground reaction force (peak $F_{\parallel}$), peak vertical ground reaction force (peak $F_{\uparrow}$) and theoretical jump distance for non-amputee athletes (nonAMP) and athletes with below the knee amputation (BKA).

* *Some values of the indicated parameters were presented before in our previous papers [18,19,20] but are presented again here due to the different scope of this study.*

DISKUSSION

In diesem Kapitel werden die drei Leitfragen dieser Dissertation auf Basis der vier vorgestellten Studien diskutiert und daraus abgeleitete Schlussfolgerungen in einen übergeordneten Kontext eingebunden. Abschließend werden Perspektiven für zukünftige Forschungsansätze aufgezeigt.

Leitfragen

Im Verlaufe des Forschungsprojektes hat sich ergeben, dass für eine umfassende Diskussion der erste Leitfrage zunächst die Beantwortung der zweiten Leitfrage erforderlich ist. Aus diesem Grund wird die Diskussion der zweiten Leitfrage vorgezogen.

An diesem Punkt sei darauf hingewiesen, dass die im Manteltext dieser Dissertation erläuterten Gedanken nicht notwendigerweise auch den Meinungen oder Ansichten aller an den Studien beteiligten Co-Autor*innen entsprechen.

Basiert der Absprung im leichtathletischen Weitsprung von Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung nutzen, und nicht amputierten Athleten auf den gleichen physikalisch-biomechanischen Mechanismen?

Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung nutzen, wiesen im Verlauf des Absprungs einen, im Vergleich zu nicht amputierten Athleten, unterschiedlichen Energieaustausch bezogen auf den Körperschwerpunkt auf (Studie 1). Während nicht amputierte Athleten eine negative Energiebilanz aufwiesen, konnten Athleten mit Unterschenkelprothese die Körperschwerpunktenergie während des Absprungs noch steigern. Dies wurde zum einen durch die Effizienz der Feder begünstigt und zum anderen durch das Hinzufügen von positiver Arbeit über das Hüftgelenk erreicht (Studie 1 und 2).

Athleten ohne Amputation nutzten während des Absprungs den in der Literatur beschriebenen Hebelmechanismus [16,23] (Studie 3) und erreichten dabei eine große vertikale Steifigkeit (Studie 4). Die Athleten mit Unterschenkelprothese hingegen sanken deutlich in ihre Prothese ein (Studie 3) und wiesen eine, im Vergleich zu nicht amputierten Athleten, geringere vertikale Steifigkeit auf (Studie 4).

In der zweiten Studie konnte weiterhin gezeigt werden, dass Athleten mit Sportprothese die Hebelarme zwischen Bodenreaktionskraftvektor und Knie- bzw. Hüftgelenkszentrum im Vergleich zu nicht amputierten Athleten gering halten. Dies führt laut Biewener [39] zu einer Vergrößerung des effektiven mechanischen Vorteils des Muskels am Gelenk. Im Vergleich zu den nicht amputierten Athleten scheinen die Athleten mit Unterschenkelamputation während des Absprungs gezielt ihre Prothese zu belasten, Energie in ihr zu speichern und die Strukturen an Knie und Hüfte zu entlasten. Hierdurch wird die Fähigkeit der Prothesenfeder, Energie zu speichern ausgenutzt und ein potentieller Energieverlust an anderen Gelenken reduziert. Diese Beobachtung steht im Einklang, mit dem ebenfalls reduzierten Bewegungsausmaß am Kniegelenk (Studie 3).

Die Verläufe der horizontalen und vertikalen Bodenreaktionskräfte von Weitspringern mit Unterschenkelprothese während des Absprungs (Studie 1 und 2) zeigen Ähnlichkeiten zu den für Wallabys ,während dem Hüpfen mit konstanter Geschwindigkeit (4,2 m/s) [40], dokumentierten Bodenreaktionskraftverläufe. Dies ist unter der Prämisse bemerkenswert, dass die hüpfende Fortbewegung von Wallabys mit konstanter Geschwindigkeit zu einem großen Teil auf der Speicherung und Rückgabe von Energie in elastischen Strukturen beruht [41]. An dieser Stelle sei angemerkt, dass diese Beobachtung nicht zum Ausdruck bringen soll, dass Athleten mit Unterschenkelprothese hüpfen/springen wie Wallabys, sondern lediglich als weiterer Anhaltspunkt für die Federartigkeit (Speicherung und

Rückgabe von Energie) des im Absprung genutzten Lokomotionsmechanismus von Weitspringern mit Unterschenkelprothese dienen soll.

Bezogen auf die zu beantwortenden Leitfrage und basierend auf den dargestellten Untersuchungen, lässt sich somit feststellen, dass der Absprung von nicht amputierten Athleten und Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung verwenden, auf fundamental unterschiedlichen physikalisch-biomechanischen Mechanismen beruht. Die Absprungtechnik von Weitspringern mit Unterschenkelprothese auf dem aktuellen Leistungsniveau erinnerte an die, bereits von Nolan und Kollegen [31] beschriebene, Nutzung eines ‚Sprungbrettes'. Nicht amputierte Athleten hingegen nutzen den aus der Literatur bekannten *„Pivot"*-Mechanismus [16,23]. Hierbei ist weiterhin wichtig zu beachten, dass, bedingt durch die fehlenden Energiespeicherkapazitäten auf der einen Seite und mechanische Limitationen auf der anderen Seite, beide Athletengruppen nicht die Bewegungsstrategie bzw. den Bewegungsmechanismus der jeweils anderen Gruppe adaptieren können.

Das hier dargestellte Wissen kann dazu dienen, die Leistungsdiagnostik auf die Bedürfnisse von Athleten mit Unterschenkelamputation anzupassen und weiterhin ist es von erheblicher Relevanz für das Verständnis, die Vermittlung und die Optimierung von Bewegungsabläufen.

Führt die Nutzung einer Sportprothese, durch einen Athleten mit Unterschenkelamputation, im leichtathletischen Weitsprung möglicherweise zu einem Vorteil oder Nachteil hinsichtlich der Wettkampfleistung im Vergleich zu nicht amputierten Athleten?

Basierend auf den Ergebnissen aus der ersten Studie konnte mittels einer konservativen Abschätzung ein Vorteil von 13 cm von Athleten mit Unterschenkelprothese gegenüber nicht amputierten Athleten während des Absprungs quantifiziert werden. Für den Anlauf manifestiert sich hingegen ein Nachteil von Athleten mit Unterschenkelprothese gegenüber nicht amputierten Athleten in Form einer geringeren Anlaufgeschwindigkeit. Die

Quantifizierung dieses Nachteils im Hinblick auf die Weitsprungleistung fällt jedoch schwer. Bei der Betrachtung des Weitsprungs als Gesamtbewegung, bestehend aus Anlauf und Absprung, ist eine Gewichtung bzw. Abwägung von Vor- und Nachteil auf Basis der aktuellen Analysen demnach nicht abschließend möglich bzw. nicht quantitativ darzustellen.

Der offensichtliche Hintergrund der Vorteils-Nachteils-Frage ist dabei, ob sich Athleten mit Unterschenkelamputation und nicht amputierte Athleten im sportlichen Wettkampf, innerhalb derselben Wertungskategorie miteinander messen sollten. Nähert man sich dieser Frage in dem man die Vorteils-Nachteils-Frage stellt, wird man, wie oben dargelegt, zu keiner eindeutigen Beantwortung kommen können. Abhilfe kann hier ein Perspektivwechsel und Gedankengang schaffen, welcher im Folgenden in einer kurzen Ausführung erläutert werden soll.

Hierzu zunächst ein Beispiel aus dem leichtathletischen Hochsprung: Hier ist es den Athlet*innen freigestellt, welche Technik (z.B. Flop, Schersprung, Wälzsprung) sie zur Überquerung der Latte nutzen, so lange der Absprung von nur einem Bein erfolgt [42]. Jede*r Athlet*in kann also selber wählen bzw. frei entscheiden, welche Technik er/sie für die Lattenüberquerung nutzt.

Im Rahmen der vorliegenden Arbeit zum Weitsprung wurde gezeigt, dass sich die verwendeten Bewegungscharakteristika im Absprung deutlich zwischen Athleten mit und ohne Unterschenkelprothese unterscheiden. Basierend auf den Ergebnissen der ersten und dritten Studie im Speziellen konnte weiterhin gezeigt werden, dass Athleten mit Amputation, die eine Unterschenkelprothese für den Absprungschritt nutzen nicht die Technik übernehmen können, die nicht amputierte Athleten verwenden. Selbiges gilt für den umgekehrten Vergleich. Mit anderen Worten: Die verwendete Bewegungstechnik ist nicht frei wählbar, sondern wird durch die Nutzung/Nicht-Nutzung einer Prothese für den Absprungschritt in wesentlichen Teilen vorgegeben.

Um mögliche Konsequenzen für Wettkampfregularien herauszustellen, welche sich aus der vorrangegangenen Überlegung zur Determinierung der Bewegungscharakteristika durch die Nutzung/Nicht-Nutzung einer Unterschenkelprothese ergeben, werden im Folgenden zunächst die Begriffe "Sportart" und "Disziplin" erarbeitet.

Eine Sportart beschreibt eine "historisch entstandene Vollzugsform des Sporttreibens" [43, S. 766], welche sich dadurch auszeichnet, dass sie durch einen Verband organisiert wird und einem festen Regelwerk folgt [43,44]. Eine Sportart kann in verschiedene Disziplinen untergliedert werden [43,44], welche "hinsichtlich der spezifischen Ausführung der Körperübungen, der Charakteristik des Wettkampfes sowie der Wettkampfbestimmungen und -regeln eine bestimmte - jedoch unterschiedlich ausgeprägte - Eigenständigkeit" [43, S. 216] aufweisen.

Übrig bleibt die Frage: Was macht die o.g. Eigenständigkeit hinsichtlich der "spezifischen Ausführung der Körperübungen"[43, S. 216] aus, die Nötig ist, um die eine Disziplin von der Anderen abzugrenzen? Die Grenzen scheinen hier nicht eindeutig definiert zu sein und vielmehr dem generischen Wissen (nach [45], Kap. 2.1), also dem "Normalfallwissen" (nach Stekeler-Weithofer [46, S. 419] zitiert in [45]) zu entspringen. Laut Schürmann (2018) [45, Kap. 2.1] ist es zulässig, Begrifflichkeiten in einem bestimmten Kontext zu definieren und sie dabei, notwendigerweise, mit einem eigenen Vorverständnis zu hinterlegen. Daher sollte es ebenfalls zulässig sein, im vorliegenden Fall die Abgrenzung zwischen zwei Disziplinen auf Grundlage eines eigenen Vorverständnisses zu definieren.

Eine Form der Abgrenzung, könnte nun die Unterscheidung zu Grunde legen, ob die verwendeten Techniken/Bewegungsausführungen von allen Athlet*innen in gleichem Maße ausgeführt werden können. Ist dies nicht der Fall, weil z.B. für die eine Technik eine mechanische Komponente (Prothese) nötig ist und für die andere Technik eben diese Komponente limitierend wirkt, könnte hier eine Unterteilung in zwei Disziplinen stattfinden. Beide Disziplinen wären hinsichtlich der "spezifischen Ausführung der Körperübungen" [43, S. 216] eigenständig. In dem vorliegenden Fall würde die Unterscheidung zwischen zwei

Disziplinen demnach durch die Unterschiede in den zugrundeliegenden physikalisch-biomechanischen Mechanismen begründet; in relevanter Weise erweitert durch zwei Feststellungen:

1. Die beiden hier untersuchten Athletengruppen können, unter den in dieser Arbeit dargestellten Bedingungen, nämlich, dass die Athleten mit Unterschenkelamputation von ihrer Prothese abspringen, nicht den Bewegungsmechanismus der jeweils anderen Gruppe adaptieren.
2. Für nicht amputierte Athlet*innen besteht realistischerweise gar nicht die Option den Unterschenkel durch eine Sportprothese zu ersetzten, während Athlet*innen mit einseitiger Unterschenkelamputation von ihrem biologischen Bein abspringen könnten.

Vernachlässigt man nun die organisatorische Tatsache, dass die paralympische und olympische Leichtathletik durch unterschiedliche Dachverbände vertreten werden, würde es sich beim Weitsprung von Athleten mit Unterschenkelprothese und nicht amputierten Athleten, basierend auf der hier ausgearbeiteten Begriffsinterpretation, um dieselbe Sportart handeln - beides wäre der Leichtathletik zuzuordnen. Je nach Differenzierungslevel würde man für beides auch den Übergriff Sprungdisziplin nutzen. Ab hier würde man jedoch, dem oben erarbeiteten Gedankengang folgend, die beiden Einzeldisziplinen *Weitsprung mit Unterschenkelprothese* und *Weitsprung nicht amputierter Athleten* unterscheiden.

Das im Rahmen dieses Promotionsprojektes erarbeitete Wissen und Gedankengut kann für Entscheidungsträger*innen in Gremien von Dachverbänden oder Sportorganisationen bei der Ausarbeitung und Anpassung von allgemeinen Regularien und Regelwerken von Nutzen sein.

Im Hinblick auf die Gestaltung zukünftiger Wettkämpfe ist der unten stehende Auszug interessant, der aus einem Interview von Markus Rehm mit Maximilian Längen (ML) stammt, welches bei „Süddeutsche Zeitung" (SZ.de, 23.09.2017 [47]) in Gänze nachgelesen werden kann.

ML: *„[...] Was kann in der Forschung noch getan werden, um zu einem definitiven Ergebnis zu kommen?"*

Rehm: *„Für mich ist das ein Endresultat, damit müssen wir arbeiten. Wir können Absprung und Anlauf nicht aufwiegen. Auf der Basis, die wir jetzt haben, müssen wir Entscheidungen treffen. Gemeinsame Wettkämpfe ja. Aber getrennte Wertungen müssen das Fairplay erhalten.“*

Welchen Belastungen wird das muskulo-skelettale System von Athleten mit und ohne Sportprothese während des Absprungs im leichtathletischen Weitsprung ausgesetzt?

In der zweiten Studie konnte gezeigt werden, dass nicht amputierte Athleten während des Absprungschritts Belastungen (Bodenreaktionskräfte) ausgesetzt sind, die in Studien am Präparat bereits mit dem Versagen von Strukturen am Sprunggelenk in Zusammenhang gebracht wurden [48,49]. Aus den kalkulierten Gelenkmomenten in der Sagittalebene, die im Einklang stehen mit vorherigen Untersuchungen [18], konnte abgeleitet werden, dass die für die Knie- und Hüftextension zuständige Muskulatur von nicht amputierten Athleten während des Absprungs Belastungen ausgesetzt wird, die größer sind als die aus der Literatur bekannten Belastungen für das Sprinten [50,51]. Weiterhin konnte erarbeitet werden, dass der Absprungschritt von nicht amputierten Athleten, ebenfalls die Teile der Muskulatur, welche für die Stabilisierung des Beins in der Frontalebene verantwortlich sind, zu einem nicht unerheblichen Teil beansprucht. Ein Grund hierfür könnte das Auftreten einer Bodenreaktionskraftspitze in, bezogen auf den Fuß, laterale Richtung sein (Studie 2). Diese, während der ersten ca. 20% der Stützphase des Absprungs auftretende, Kraftspitze resultiert vermutlich daher, dass nicht amputierte Athleten ihren Fuß, bezogen auf die medio-lateral Ausrichtung, relativ dicht unter dem Körperschwerpunkt positionieren

(Studie 3). Athleten mit Unterschenkelprothese positionieren diese hingegen weiter lateral (Studie 3) und weisen während des Absprungs keine relevante medio-laterale Bodenreaktionskraft auf. Im Allgemeinen sind die muskulo-skelettalen Belastungen an Knie und Hüfte geringer bei Athleten mit Unterschenkelamputation, die ihre Prothese für den Absprung verwenden, im Vergleich zu nicht amputierten Athleten (Studie 2).

Bezogen auf die Drehmomente am Knie in der Frontalebene (Studie 2) ist weiterhin aufgefallen, dass die Knieadduktionsmomente bei nicht amputierten Athleten die aus der Literatur [50] bekannten Momente für das Sprinten deutlich übersteigen. Für die Athleten mit Unterschenkelamputation fiel hingegen auf, dass auf das Knie während des Absprungs vornehmlich ein externes Abduktionsmoment wirkte, während in Alltagssituationen eher ein Adduktionsmoment erwartet wird [52]. Beim Absprung kommt es demnach zu einer Belastung von Strukturen (z.B. lateraler Gelenkknorpel), die potentiell weniger durch einen alltäglichen Stimulus angepasst wurden.

Insgesamt konzentriert sich die muskulo-skelettale Belastung beim Absprungschritt von Athleten mit Unterschenkelprothese, speziell an der Hüfte, hauptsächlich auf die Sagittalebene während bei nicht amputierten Athleten die Strukturen der Frontalebene in relevanter Weise mit beansprucht werden. Aus diesem Grund, und weil die muskulo-skelettale Belastung in der Frontaleben während des Absprungs die des Sprints deutlich übersteigt, wurde in der zweiten Studie darauf hingewiesen, dass nicht amputierte Athleten die Muskulatur, welche für die Hüftstabilität verantwortlich ist, gezielt aufarbeiten sollten bevor sie Weitsprünge aus einem vollen Anlauf trainieren.

Das im Rahmen der vorliegenden Dissertation erarbeitet Wissen zur muskulo-skelettalen Belastung beim Weitsprung von Athleten mit und ohne Unterschenkelamputation ist wichtig für die Diagnostik sowie die Prävention von Verletzungen, die durch akute oder chronische strukturelle Überbeanspruchungen induziert werden können. Trainer und medizinisches Personal können die vorliegenden Informationen nutzen, um Trainings- sowie Rehabilitationsprozesse gezielt auf das Belastungsprofil der Athleten anzupassen.

Weiterhin können die gewonnenen Informationen für die gezielte Weiterentwicklung von Sportprothesen genutzt werden.

Forschungsperspektiven

Zukünftige Analysen zum Weitsprung mit und ohne Sportprothese könnten durch die Anwendung von Muskelmodellen erweitert werden. Allgemeine Muskelmodelle, wie sie beispielsweise in manchen kommerziellen oder freizugänglichen Softwarepaketen zur biomechanischen Mehrkörpermodellierung implementiert sind, können wichtige zusätzliche Informationen über muskulo-skelettale Belastungen generieren und lassen Ableitungen zur Beanspruchung einzelner Strukturen zu [53]. In einem nächsten Schritt wäre es nun denkbar, Daten von Magnetresonanztomographien dazu zu nutzen, individualisierte Muskelmodelle zu erstellen, um speziell die muskulären Charakteristika von Eliteathleten mit und ohne Amputation abzubilden. Die muskuläre Abbildung, des Beinstumpfes, inklusive Muskelansätzen, bei Athleten mit einer Amputation stellt hier eine besondere Herausforderung dar, könnte aber auch wesentliche Informationen für den Trainingsprozess oder das Design zukünftiger Prothesengenerationen liefern.

In weiteren Analysen sollte zudem ein besonderes Augenmerk auf die muskulo-skelettale Belastung im Weitsprunganlauf gelegt werden. Durch die einseitige Nutzung einer Prothese beim Sprint kommt es zu einer asymmetrischen Bewegung, welche sich auch durch Unterschiede bezüglich der, auf die Strukturen des biologischen bzw. des prothetischen Beins wirkenden ‚Bodenreaktionskraft manifestiert [54,55, Studie 1]. Eine Analyse der Drehmomente bei einseitig transtibial amputierten Athleten im Sprint fehlt bislang. Durch die asymmetrische Belastung ist es denkbar, dass das biologische Bein einseitig amputierter Athleten einer anderen und unter Umständen sogar höheren muskulo-skelettalen Belastung ausgesetzt wird als bei nicht amputierten Athleten. Es kann also auch zu Überlastungen in den vermeintlich nicht beeinträchtigten Strukturen des biologischen Beines kommen.

Die in dieser Arbeit gewonnenen Erkenntnisse können genutzt werden, um die Leistungsdiagnostik von Weitspringern mit Unterschenkelprothese auf die spezifischen Bewegungsmechanismen anzupassen. Weiterhin wäre eine enge Zusammenarbeit mit Prothesenherstellern wünschenswert, um einerseits die Passform der Prothese, inklusive Schaft, zu optimieren und andererseits die Form der Prothesenfeder an die sportartspezifischen, physikalisch-biomechanischen Begebenheiten sowie Bedürfnisse der Athleten anzupassen. Denkbar wäre es in diesem Zusammenhang auch, Fenite-Element-Methoden einzusetzen, um auf Grundlage der bereitgestellten Bodenreaktionskräfte und Drehmomente Kalkulationen bzgl. der Stabilität der Prothesen-Knochen-Schnittstelle bei osseointegrierten Prothesen durchzuführen, deren Nutzung laut aktuellem IPC Regelwerk im Wettkampf nicht zugelassen ist [56].

In den Studien, die dieser Dissertation zu Grunde liegen, wurden ausschließlich männliche Athleten und keine Athletinnen untersucht. Aus diesem Grund wurden generalisierte, beide Geschlechter umfassende, Aussagen vermieden. Frühere Studien haben jedoch gezeigt, dass die von nicht amputierten Weitspringerinnen während des Absprungs verwendete Technik ebenfalls einem Umlenkmechanismus um einen rigiden Hebel entspricht, der durch eine gute Kraftfähigkeit in der beteiligten Muskulatur begünstigt wird [24]. Eine frühere Untersuchung zu transtibial amputierten Weitspringerinnen, hat nicht zwischen dem Absprung von der Prothese bzw. dem biologischen Bein unterschieden [30], so dass zum Absprung von der Prothese bei Athletinnen mit Unterschenkelprothese keine differenzierten Ergebnisse vorliegen. In der vorliegenden Arbeit wurde jedoch gezeigt, dass die von Weitspringern mit Unterschenkelamputation gezeigten Bewegungscharakteristika während des Absprungs maßgeblich auf die Nutzung einer Unterschenkelprothese zurückzuführen sind. Eine, durch zukünftige Forschungsarbeiten zu bestätigende, Hypothese wäre demnach: Weitspringerinnen mit Unterschenkelamputation, die ihre Prothese für den Absprung verwenden, weisen während des Absprungs Bewegungscharakteristika aufweisen, die in ähnlicher Weise von den Bewegungscharakteristika nicht amputierter Athletinnen abweichen, wie dies für Weitspringer mit Unterschenkelprothese im Vergleich zu nicht amputierten Athleten zu beobachten ist.

ZUSAMMENFASSUNG

Weitspringer mit Unterschenkelamputation, die ihre Prothese für den Absprungschritt nutzen, sind in der Lage außerordentliche Weiten zu erzielen. Die zu Grunde liegende Biomechanik ist allerdings nicht umfassend bekannt. Wissen hierüber ist jedoch wichtig, um Trainingsprotokolle anzupassen, Verletzungsmechanismen zu erkennen und Sportprothesen weiterzuentwickeln. Weiterhin können die gewonnenen Erkenntnisse als wichtige Informationsquelle für zukünftige Anpassungen in olympischen und paralympischen Regularien genutzt werden.

Im Rahmen eines multinationalen Forschungsprojektes, aus dem die vorliegende Dissertation hervorgeht, wurden drei Weitspringer mit Unterschenkelamputation und sieben nicht amputierte Athleten unter Laborbedingungen bewegungsanalytisch untersucht. Während des Absprungs beim Weitsprung und während des maximalen Sprints wurde die Kinematik und Kinetik der Athleten erfasst und zusammen mit der probanden-spezifischen Anthropometrie als Eingangsdaten für ein invers dynamisches Mehrkörpermodel zur detaillierten dreidimensionalen Analyse genutzt.

Athleten mit Unterschenkelprothese zeigten andere Merkmale bzgl. Körperschwerpunkt- und Gelenkmechanik während des Sprints und dem Absprung als nicht amputierte Athleten. Athleten mit Unterschenkelprothese liefen langsamer an, aber sprangen effizienter ab als nicht amputierte Athleten. Während des Absprungschrittes platzieren die amputierten Athleten ihre Prothese anders in Relation zum Körperschwerpunkt als nicht amputierte Athleten ihren Fuß und die Bewegungscharakteristik des Körperschwerpunks wies deutliche Unterschiede zwischen den beiden Gruppen auf. Im Allgemeinen war die muskulo-skelettale Belastung an der Hüfte und am Knie geringer während des Absprungs bei Athleten mit Unterschenkelprothese als bei nicht amputierten Athleten. Dies resultierte vornehmlich aus geringeren Abständen zwischen den Gelenkszentren und dem Vektor der Bodenreaktionskraft bei Athleten mit Unterschenkelprothese im Vergleich zu nicht

amputierten Athleten. Das Absprungverhalten von Athleten mit Unterschenkelprothese glich dem Sprung von einem Sprungbrett, während die nicht amputierten Athleten den bekannten Hebelmechanismus (Pivot) nutzten, um vertikale Abfluggeschwindigkeit zu generieren.

Resultierend aus begrenzten muskulo-skelettalen Kapazitäten oder mechanischen Beschränkungen weisen Weitspringer mit bzw. ohne Unterschenkelprothese, speziell im Absprungschritt, Bewegungscharakteristika auf, die einerseits auf unterschiedlichen Lokomotionsmechanismen basieren und andererseits von der jeweils anderen Gruppe nicht adaptiert werden können.

SUMMARY

Long jumpers with a below the knee amputation (BKA) who use their prosthesis for the take-off step are able to achieve remarkable performances. Yet, the underlying biomechanics are not comprehensively understood. However, knowledge of this is important for adapting training protocols, for distinguishing injury mechanisms, and for informing the devolvement of prosthetic design. Furthermore, the findings of this project might be a relevant source of information for future adaptation of olympic and paralympic regulations.

Within the framework of a multinational research project, from which the present dissertation results, motion analyses were conducted on three long jumpers with BKA and seven non-amputee athletes. Kinematics and kinetics during sprinting and the long jump take-off step together with athlete-specific anthropometrics served as input data for an inverse dynamic multi-segment model used for detailed three-dimensional analyses.

Athletes with BKA demonstrated different characteristics in terms of centre of mass (COM) and joint mechanics during sprinting and the long jump take-off compared to non-amputee athletes. Athletes with BKA had a slower run-up velocity but had a more efficient take-off step. During the take-off step, athletes with BKA positioned their prosthesis differently in relation to their COM compared to the foot positioning of the non-amputee athletes, and the COM motion characteristics were different between the two groups. In general, athletes with BKA had lower muscular-skeletal loading at the hip and knee joints during the take-off step, which results from shorter lever arms between the ground reaction force vector and the joint centres in athletes with BKA compared to the non-amputee athletes. The take-off characteristics of athletes with BKA were similar to the jump off a springboard, whereas the take-off step characteristics of non-amputee athletes resembled the known mechanism of "pivoting" to generate vertical take-off velocity.

As a result of mechanical constraints or limited muscular-skeletal capacities, long jumpers with or without BKA, respectively, illustrate motion characteristics, particularly during the

take-off step of the long jump, which on the one hand are based on different locomotion mechanisms and on the other hand cannot be adopted by the other group.

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