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Habilitationsschrift

Die Dynamik und Statik des lumbo-sacralen Übergangs sowie Auswirkungen seiner anatomischen Variationen

zur Erlangung der Lehrbefähigung für das Fach
Experimentelle Orthopädie und Unfallchirurgie

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Abkürzungsverzeichnis

a.-p. = anterior-posterior

ALIF = anteriore lumbale intersomatische Fusion

CT = Computertomographie

IS = Iliumschraube

LL = Lumbale Lordose

LLIF = laterale lumbale intersomatische Fusion

LSTV = Lumbo-sacrale Übergangsstörung

M. = Musculus

MRT = Magnetresonanztomographie

OLIF = oblique lumbale intersomatische Fusion

PI = (eng.) Pelvic Incidence

PROMs = (eng.) Patient-reported outcome measures

PT = (eng.) Pelvic Tilt

S1PS = S1-Pedikel-Schraube

S2AIS = S2-Ala-Ilium-Schraube

S2AS = S2-Ala-Schraube

SS = (eng.) Sacral Slope

1. Einleitung

1.1 Aufrechter Gang: Evolution von Form und Funktion des Bewegungsapparates

Der Mensch wurde historisch betrachtet durch seinen prägenden Einfluss auf unsere Umwelt entsprechend der *Scala Naturae,* die das historische naturphilosophische Denken lange Zeit beeinflusste, in einer hierarchisch, nach vermeintlicher Komplexität und Vollkommenheit des Lebewesens organisierten Reihe, als das höchststehende Lebewesen definiert. Hierbei resultiert der Name der Ordnungsgruppe der Primaten, in die sich der rezente Homo sapiens sapiens in unserer heutig verwendeten Taxonomie eingliedert, vom lateinischen *primus* (der Erste) und bedient sich damit auch heute weiterhin einer Ordnungsbezeichnung auf Basis der *Scala Naturae*. Eine vergleichbare Auffassung der Rolle des Menschen spiegelt sich in der Schöpfungsgeschichte im Alten Testament im 1. Buch Mose (Genesis) – Kapitel 1 – Vers 28 wider: "[...] herrscht über die Fische im Meer und über die Vögel des Himmels und über alles Lebendige, das sich regt auf der Erde!". Diese lineare Ordnung wurde kontrastiert durch die Theorie der Veränderung von Arten durch die Vererbung erworbenen Verhaltens durch Lamarck zu Beginn des 19. Jahrhundert in seiner *Philosophie Zoologique* von 1809 [1], die im weiteren Verlauf durch die Evolutionstheorie auf Basis einer natürlichen Selektion von graduell zufällig veränderten Merkmalen in dem Werk *On the Origin of Species* von Charles Darwin von 1859 abgelöst wurde [2]. Mit der Entdeckung der Vererbung von Merkmalen über Gene, die Mutationen unterliegen, wurde die synthetische Evolutionstheorie als wissenschaftlich vorherrschende Meinung für das Entstehen von Arten über kontinuierliche Anpassung begründet.

Als ein maßgeblicher Faktor für die Hominisation und die Lebensweise des Menschen in seiner heutigen Form gilt neben der Vergrößerung des Gehirns der habituelle bipede alternierende Gang [3]. Dieser erfordert weitreichend anatomische Anpassungen des Achsskeletts des Menschen gegenüber anderen Primaten. Erste Nachweise für den bipeden Gang in der Familie der Hominidae werden durch Fußabdrücke sowie den Fund eines Mittelfußknochens, der bereits Hinweise auf ein Längs- und Quergewölbe aufweist und damit die notwendige Funktion einer Stoßdämpfung für den bipeden Gang erfüllt, auf mehr als drei Millionen Jahre zurückdatiert [4, 5]. Entsprechende Adaptationen an den aufrechten Gang durchziehen das gesamte Skelett des

Menschen, die es uns ermöglichen, mit langen, gestreckten Extremitäten große Schritte zu gehen und dabei unseren Körperschwerpunkt zentriert ohne größere kompensatorische Rumpfschwingungen zu halten, was ein Gehen mit hoher mechanischer Effizienz ermöglicht [6]. Ebenso zeigen das Becken sowie die Wirbelsäule mit dem lumbo-sacralen Übergang maßgebliche Adaptationen, welche die Vertikalisierung unseres Lebensstils ermöglichen und im Folgenden dargestellt werden [7, 8].

1.2 Evolutionäre Adaptationen des Achsskeletts sowie biomechanische Beanspruchung durch den vertikalisierten Lebensstil

Der lumbo-sacrale Übergang ist das Bindeglied der flexiblen Lendenwirbelsäule gegenüber dem Os sacrum, das einen Teil des Beckenrings darstellt. Für die Betrachtung der Entwicklung des lumbo-sacralen Übergangs ist deshalb das Verständnis der Adaptationsprozesse der Wirbelsäule sowie des Beckens unumgänglich.

Dem Becken kommt eine maßgebliche Rolle für den bipeden alternierenden Gang sowie für unsere sagittale Balancierung zu. Bereits seit mehr als einem halben Jahrhundert wird der Zusammenhang zwischen lumbaler sowie pelviner Lage und Bewegung für den Gang untersucht und beschrieben [9]. Eine sehr eindrückliche Formulierung entstammt der Arbeit Duboussets als ‚pelvic vertebra', der damit das Becken als Teil der Wirbelsäule definiert und die Bedeutung für die Haltung unterstreicht [10]. Jedoch erfüllt das Becken durch den aufrechten Gang einander entgegenstehenden Funktionen. Einerseits benötigt der Mensch eine möglichst stabile Stützfunktion für den Rumpf sowie die Eingeweide. Andererseits ist der für Mutter und Kind möglichst sichere Durchtritt des Kindes unter der Geburt von höchster evolutionärer Bedeutung und erfordert durch die Größe des Kindskopfes aufgrund der bereits bei Geburt relativ großen Gehirnmasse einen ausreichend weiten Geburtskanal [7].

Die daraus resultierenden anatomischen Adaptationen haben neben der evolutionären Relevanz ebenso einen maßgeblichen Einfluss auf die biomechanischen Eigenschaften des Beckens. Durch die anteriore Kippung des Os sacrum sowie die doppelte S-Form der Wirbelsäule mit lumbaler Lordose liegt der spino-pelvine

Übergang ventral des Iliosacralgelenks sowie dorsal des Hüftdrehzentrums (Abbildung 1a). Eine weitere anteriore Rotation des Os sacrum aufgrund der axialen Belastung durch unsere Rumpflast wird passiv durch die starken sacro-tuberalen Bänder gehemmt [11]. Die Hüftextension wird passiv durch die straffe Hüftkapsel mit dem Ligamentum iliofemorale gehemmt [12]. Durch die Verkürzung und die Verlagerung der Ossa ischiadica resultiert eine Verlängerung der ischiocruralen Muskulatur mit einer Optimierung des Hebelarms für das aufrechte Stehen [8]. Ebenso weist der Mensch eine Anpassung der Form des Os ilium an das aufrechte Stehen und Gehen auf. Die Schaufeln des Os ilium sind dabei ausladend erweitert mit einer dorso-lateralen Kurvatur, die mit einer Veränderung der Ursprünge für die gluteal Muskulatur einhergeht und die Funktion des Musculus gluteus medius als Abduktor der Hüfte ermöglicht, was maßgeblich zur Stabilisierung unseres Beckens in der einbeinigen Standphase beiträgt [13].

Für die Beschreibung des Sagittalprofils des Beckens haben sich die Parameter der Beckenkippung (pelvic tilt, PT) sowie der Orientierung der sacralen Deckplatte (sacral slope, SS) etabliert. Die Summe des PT sowie des SS ergeben einen die Beckengeometrie lageunabhängig beschreibenden Parameter, die pelvic incidence (PI) (Abbildung 1b) [14, 15]. Die Beckengeometrie beeinflusst die lumbale Lordose (LL), die für einen aufrechten Stand und somit eine sagittale Balancierung im Stehen notwendig ist, und bestimmt damit das Rückenprofil maßgeblich. Im Falle eines Ungleichgewichts mit einer PI, die die LL deutlich übersteigt, resultiert eine Verlagerung des Körperschwerpunkts nach ventral, sodass eine vermehrte Muskelkontraktion für das Stehen notwendig ist und damit ein erhöhter Energieaufwand sowie eine erhöhte mechanische Belastung der lumbalen Strukturen resultiert [16].

Abbildung 1 Übersicht über vertikale Schwerpunktlinie und pelvine Lageparameter

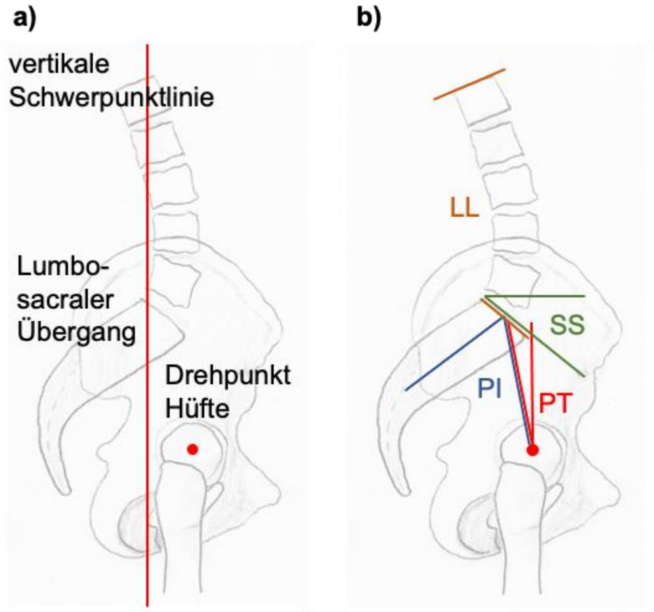


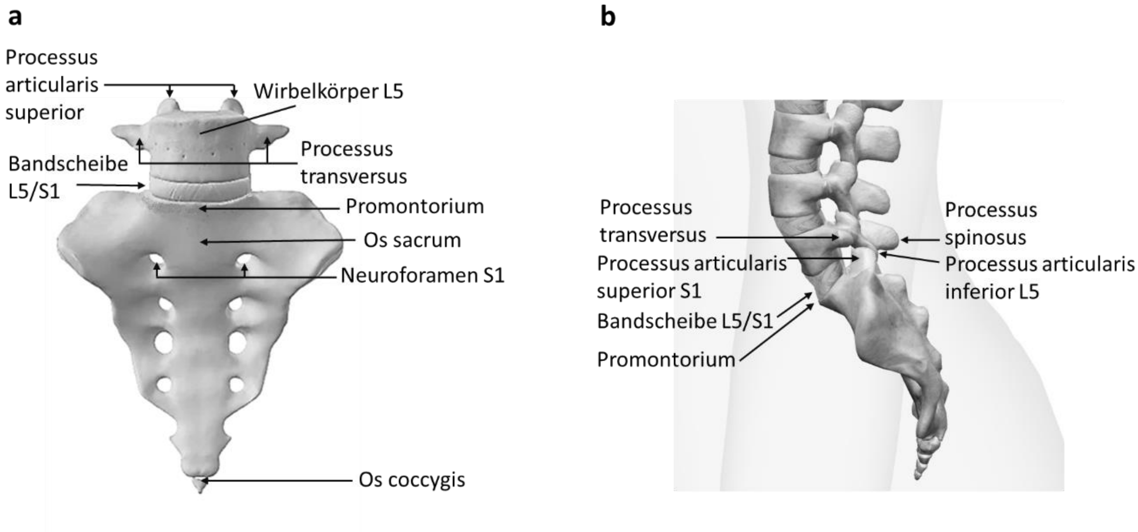
Abbildung 1a zeigt die vertikale Schwerpunktlinie des Rumpfes in aufrechter Haltung gegenüber der Lendenwirbelsäule sowie dem Hüftdrehzentrum. Abbildung 1b stellt die Beurteilung der Becken- sowie Lendenwirbelsäulen Haltungsparameter LL, PI, PT, SS dar. Bildquelle: Abbildung selbstständig erstellt.

Die Form und Funktion unsere Wirbelsäule hingegen unterliegt dem steten Konflikt zwischen einer Stützfunktion als zentraler Pfeiler unseres Oberkörpers sowie der Notwendigkeit von Flexibilität für das Einnehmen unterschiedlicher Körperpositionen wie dem Sitzen, der Rumpfbeugung oder dem Stehen [17, 18]. Unsere nächsten rezenten verwandten Primaten weisen eine im Sagittalprofil gerade oder leicht C-förmig gebogene Wirbelsäule auf, ebenso wird der Mensch mit einer geraden oder leicht C-förmig gebogenen Wirbelsäule geboren. Jedoch entwickeln wir in den ersten Lebensjahren während des Erlernens des Laufens eine doppelt S-förmige Wirbelsäulenkrümmung mit einer lumbalen und zervikalen Lordose sowie einer thorakalen und sacralen Kyphose [19, 20]. In der Lendenwirbelsäule liegt der Rumpfschwerpunkt bei einer sagittal balancierten Wirbelsäule ebenso dorsal der Lendenwirbelkörper, sodass die Schwerkraft ohne muskuläre Gegenspannung zu einer vermehrten Lordosierung führt (Abbildung 1a) [21]. Während unsere nächst verwandten Primaten, die Schimpansen, den thorako-lumbalen Übergang zumeist auf Höhe des 20. Wirbels und nur drei oder vier Lendenwirbel aufweisen, hat der Mensch im Regelfall fünf Lendenwirbel und damit eine verlängerte Lendenwirbelsäule, die größere Bewegungsumfänge erlaubt [22]. Gleichsam unterscheidet sich der Mensch durch eine veränderte Konfiguration der Dornfortsätze der Lendenwirbelsäule, die eine vermehrte lumbale Flexion und Extension ermöglicht [23]. Die berichteten Werte für die lumbale Lordose im aufrechten Stehen unterscheiden sich bei subjektiv rückengesunden Patientinnen und Patienten in Übersichtsarbeiten und Studien mit großen Fallzahlen von 19,3° – 76,8° erheblich, was die Varianz der Messmethoden, Haltungsvariationen und Körperformen eindrucksvoll unterstreicht [24-26]. Dabei ist die Beweglichkeit der Lendenwirbelsäule durch den aufrechten Lebensstil für viele unserer Alltagsaktivitäten elementar, was sich in mehr als 4,000 Bewegungen der Lendenwirbelsäule pro Tag widerspiegelt [27]. Analog zur lumbalen Lordose weisen Metaanalysen sehr heterogene Normwerte für lumbale Bewegungsumfänge aus: für die lumbale Flexion werden Normwerte von 23° – 73° berichtet, für die Extension 6° – 29°, für die Seitneigung 14° – 53° sowie für die Rotation 6° – 33° [25, 28-34]. Die Bewegungen der Lendenwirbelsäule resultieren insgesamt maßgeblich aus einer Bandscheibenverformung sowie einer Bewegung der kranialen und kaudalen Gelenkpartner im Facettengelenk, wobei dieser Komplex zuweilen historisch als „Articular triad“ für die lumbale Beweglichkeit definiert wird [35]. Die Bewegungsumfänge werden durch die Form und Orientierung der Facettengelenke, die Verformbarkeit der Bandscheibe ebenso wie durch die der Wirbelsäule anliegenden Bänder und der ansetzenden Muskulatur gehemmt.

Neben der reinen Gewichtsbelastung der Wirbelsäule durch die Rumpflast entstehen durch die Muskelaktivierung für die Stabilisierung des aufrechten Stehens eine zusätzliche Kompression der intervertebralen Strukturen, sodass eine Gesamtlast resultiert, die ungefähr der Last des Gesamtkörpergewichtes entspricht [16, 36, 37]. In dynamischen Prozessen wie dem Gehen kann die Belastung auf das 1,6-fache Körpergewicht ansteigen [38]. Bereits durch das Heben alltäglicher Lasten von 10kg können auf die lumbalen Bandscheiben aufgrund des langen Hebels der Rumpflänge große Kräfte einwirken, die sich mit *in-vivo* Belastungen von über 2.000 N niederschlagen können [39, 40]. Hierbei ist der lumbo-sacrale Übergang als Bindeglied zwischen der Dynamik der segmental gegliederten Wirbelsäule gegenüber dem Beckenring mit vorwiegend statischer Funktion und andererseits durch die Gewichtslast des Rumpfes besonders exponiert [41-43]. Daraus resultierend zeigt sich im Bereich des lumbo-sacralen Übergangs eine Facettengelenksorientierung, bei welcher die kraniale Facette die kaudale hakenförmig umgreift und somit ein ventrales Abgleiten durch die ventro-kaudale Neigung der sacralen Deckplatte verhindert

(Abbildung 2) [44]. Die große Interindividualität des Sagittalprofils, das gehäufte Auftreten der isthmischen Spondylolisthesis sowie die hohe Prävalenz von lumbo-sacralen Übergangsstörungen verdeutlichen den fortwährenden Anpassungsprozess des lumbo-sacralen Übergangs an unseren aufrechten Lebensstil eindrücklich.

Abbildung 2 Der lumbo-sacrale Übergang in frontaler (a) sowie sagittaler (b) Ansicht



Bildquelle: Abbildung selbstständig erstellt.

1.3 Variationen des lumbo-sacralen Übergangs

Im Bereich des lumbo-sacralen Übergangs weisen in Europa im Sagittalprofil ca. 6 % der Bevölkerung die anatomische Variation der isthmischen Spondylolisthesis auf [45, 46]. Diese resultiert im lumbo-sacralen Übergang zumeist aus einem knöchernen Defekt der Pars interarticularis des Wirbelbogens und ist mit einer Segmentinstabilität vergesellschaftet. Diese Veränderung kann mit einer frühzeitigen Segmentdegeneration sowie konsekutiver Nervenwurzelkompression vergesellschaftet sein [47]. Das lumbale Wirbelgleiten wurde in der Literatur zum Zeitpunkt der Erstellung dieser Arbeit mit über 5600 abrufbaren Artikeln in der Meta-Datenbank PubMed® des U.S. National Institutes of Health bereits extensiv beleuchtet.

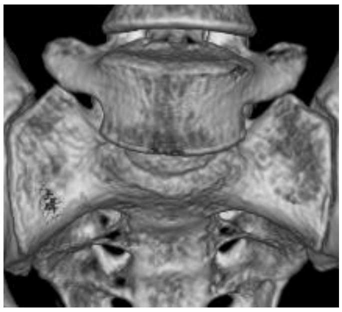
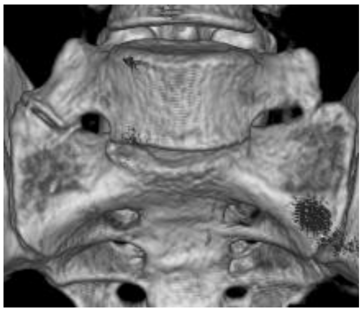
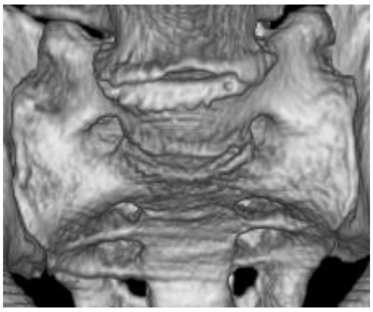
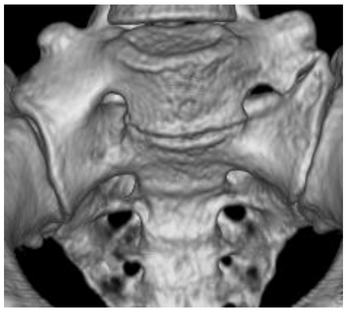
Demgegenüber weist der lumbo-sacrale Übergang in der Frontalebene in großen Kohortenstudien anatomische Variationen mit einer Prävalenz von 9,9 bis zu 29 % auf, über assoziierte Pathologien sowie Versorgungsstrategien ist jedoch bislang deutlich weniger bekannt [48-52]. Diese Veränderungen resultieren aus einer dysplastischen Vergrößerung des Processus transversus des kaudalsten Lumbalwirbels, einer Pseudarthrose des Processus transversus des kaudalsten Lumbalwirbels mit der Massa lateralis des Os sacrum oder einer ossären Verschmelzung des Processus transversus mit dem Ala ossis sacri bei persistierender intervertebraler Bandscheibe. Dabei weist die partielle Lumbalisation oder Sacralisation regulär fünf Lendenwirbel auf. Dem gegenüber steht die vollständige Sacralisation, die zu einer Reduktion der Anzahl freier Lendenwirbel auf vier freie Lendenwirbel resultiert und mit einer Reduktion der lumbalen Lordose assoziiert ist [53]. Im Rahmen der vollständigen Lumbalisation resultieren sechs freie Lendenwirbel, was ebenso mit einem Einfluss auf das Sagittalprofil und einer erhöhten lumbalen Lordose assoziiert ist [54]. Bereits 1977 wurde durch Tini et al. eine familiäre Häufung beobachtet und damit der Rückschluss auf eine genetische Ursache für lumbo-sacrale Übergangsstörungen detektiert. Damit einhergehend konnte in Tierversuchen der elementare Einfluss der homeobox Gene 10 und 11 auf die sacrale sowie lumbale Entwicklung nachgewiesen werden [55-57].

Die erstmalige Beschreibung von tieflumbalen Rückenschmerzen in Assoziation mit lumbo-sacralen Übergangswirbeln erfolgte 1917 durch Bertolotti, der somit namensgebend für das Bertolotti-Syndrom ist, das sich durch Rückenschmerzen oder Radikulopathien bei Vorhandensein einer lumbo-sacralen Übergangsstörung auszeichnet [58]. Trotz dieser Primärbeschreibung von lumbo-sacralen Übergangswirbeln im Zusammenhang mit Rückenschmerzen berichtet je nach untersuchtem Kollektiv ein relevanter Anteil an Personen mit lumbo-sacraler Übergangsstörung keine Symptomatik im Sinne von tieflumbalen Rückenschmerzen oder einer Radikulopathie, wobei die Literatur ein gehäuftes Auftreten von Rückenschmerzen in Assoziation zu lumbo-sacralen Übergangsstörungen aufzeigt [48, 49, 59-62].

Die klinisch gängigste Klassifikation entstammt der Beschreibung nach Castellvi et al. von 1984, die eine Einteilung in vier Kategorien beinhaltet, wovon die ersten drei Kategorien jeweilig zwei Unterkategorien umfassen (Tabelle 1) [63]. Weitere Klassifizierungsansätze entstammen Mahato, der eine mechanische Betrachtung sowie die Mitbeurteilung, ob eine Sacralisation oder Lumbalisation vorliegt, vorschlägt, sowie die von Tini et al. bereits sieben Jahre vor Castellvi et al. vorgeschlagene

Klassifikation, die jedoch beide einer weniger breiten klinischen Anwendung unterliegen [55, 64].

Tabelle 1 Klassifikation der lumbo-sacralen Übergangsstörung nach Castellvi

Castellvi Typ	Beschreibung	Beispiel
I	Ia: Unilateral dysplastischer Processus transversus >19 mm Ib: Bilateral dysplastischer Processus transversus	Ib 
II	IIa: Unilaterale Pseudarthrose zwischen Processus transversus und Ala ossis sacri IIb: Bilaterale Pseudarthrose zwischen Processus transversus und Ala ossis sacri	IIa 
III	IIIa: Unilaterale knöcherne Verschmelzung zwischen Processus transversus und Ala ossis sacri IIIb: Bilaterale knöcherne Verschmelzung zwischen Processus transversus und Ala ossis sacri	IIIb 
IV	Unilaterale knöcherne Verschmelzung, kontralaterale Pseudarthrose zwischen Processus transversus und Ala ossis sacri	IV 

Bildquelle: Becker et al. J. Clin. Med. 2022 [65]

1.4 Klinischer Kontext tieflumbaler Rückenschmerzen

Der lumbo-sacrale Übergang als Bindeglied zwischen der Dynamik der segmental gegliederten Wirbelsäule gegenüber dem Beckenring mit vorwiegend statischer Funktion stellt eine Prädilektionsstelle für Degenerationen dar [41, 42]. Die lumbo-sacrale Übergangsstörung ist mit einer vermehrten Degeneration der kranial angrenzenden Segmente assoziiert, dabei weisen lumbo-sacrale Übergangsstörungen entsprechend Castellvi Grad II und IV am häufigsten Rückenschmerzen bereits in jungem Patientenalter auf [48, 51, 66].

Die hohe Rate an Degenerationen und anatomischen Variationen verdeutlicht den biologischen Kompromiss einer Anpassung an das aufrechte Leben mit einer Optimierung des Körperschwerpunkts sowie einer erhöhten Wirbelsäulenmobilität gegenüber einer erhöhten biologischen Beanspruchung, der unser Körper bislang bei einer Prävalenz von chronischen Rückenschmerzen von 7,5 – 25 % in vielen Fällen nur eingeschränkt gewachsen zu sein scheint [67, 68].

Daraus resultierend stellt der Rückenschmerz eine der maßgeblichen Erkrankungen des 21. Jahrhunderts mit einer steigenden Prävalenz in unserer Gesellschaft dar, die ein hohes Maß an Invalidisierung und Verlust an Erwerbstätigkeit sowie einen Verlust an Lebensqualität bedeuten [67, 69]. Die Lebenszeitprävalenz von Rückenschmerzen liegt bei 70 – 85 % der Weltbevölkerung, von denen je nach Alter und Geschlecht ca. 4 – 25 % chronifizieren [70, 71]. Rückenbeschwerden sind dabei für weltweit 577 Millionen mit Invalidisierung gelebte Lebensjahre („years lived with disability") verantwortlich, und führen zu einer hohen Quote von Arbeitsausfällen, Produktivitätsverlusten und Krankenhauseinweisungen, die enorme direkte und indirekte Kosten für die Gesundheitssysteme und die Volkswirtschaften der Gesellschaften verursachen [67, 69]. Bereits im Jahr 2008 wurden die Gesamtkosten für Beschwerden der Wirbelsäule durch direkte und indirekte Krankheitskosten auf 49 Milliarden Euro jährlich allein in Deutschland mit steigender Tendenz geschätzt [72, 73]. Obwohl die Ursachen und die Behandlung von Beschwerden der Lendenwirbelsäule seit Jahrzehnten intensiv erforscht werden, sind das Verständnis von Rückenbeschwerden sowie die daraus resultierenden Behandlungserfolge nach wie vor mitunter begrenzt.

Dabei werden spezifische von unspezifischen Rückenschmerzen unterschieden, wobei diese Klassifizierung auf einer bildmorphologischen Diagnose beruht, welche mit den subjektiven Beschwerden vereinbar ist [74]. Durch Bildgebung wie Röntgendiagnostik, Computertomographie oder Magnetresonanztomographie wird nach anatomischen Variationen oder Pathologien wie Bandscheibendegenerationen, Wirbelbrüchen und arthritischen Veränderungen gesucht und diese in Konkordanz mit dem klinischen Beschwerdebild als Grundlage für die Festlegung von Behandlungsstrategien für Rückenschmerzpatientinnen und -patienten herangezogen [75].

Die Beeinträchtigung von Patientinnen und Patienten resultiert jedoch aus diverseren Dimensionen als dem lediglich röntgenologischen Nachweis einer Pathologie gepaart mit Rückenschmerz. Weitere Aspekte der Rückengesundheit, die für die Funktionalität des Menschen neben dem Schmerz relevant sind, stellt die Rückenfunktion im Sinne der Rückenbeweglichkeit dar ebenso wie psychosoziale Faktoren [76, 77]. Diesen Erkenntnissen trägt das bio-psycho-soziale Krankheitsmodell Rechnung, in welchem neben der Erfassung der Rückenform und -funktion und Vorerkrankungen als Risikofaktoren für einen potentiell gefährlichen Verlauf („red flags"), psychosoziale und verhaltensassoziierte Aspekte („yellow flags"), sozioökonomische („blue flags") und Arbeitsplatz bezogene Risikofaktoren („black flags") für die Diagnose sowie den Behandlungsalgorithmus herangezogen werden [78, 79].

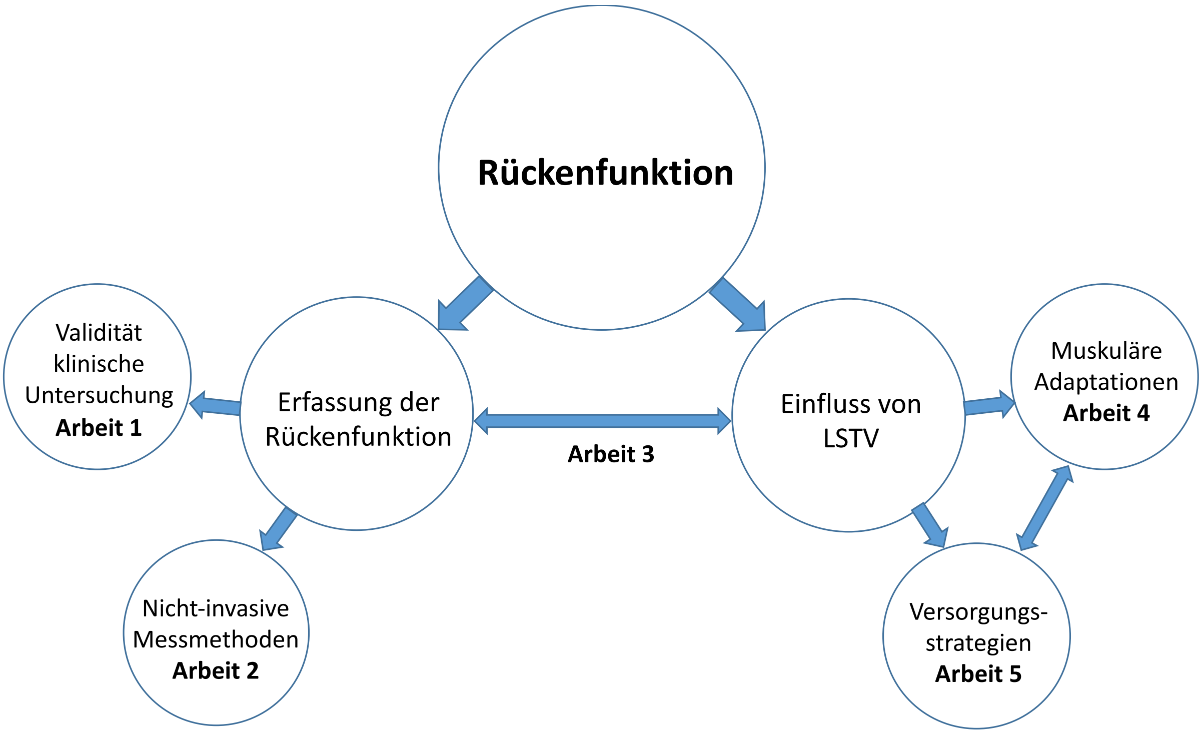
Entsprechend werden Einschränkungen der Rückengesundheit durch mannigfaltige Operatoren nachzuweisen versucht. Hierfür werden mitunter biomechanische Dimension wie die endgradige Bewegungsfähigkeit, Maximalkraftmessungen oder Bewegungsgeschwindigkeiten untersucht. Ebenso wird das subjektive Befinden und die Funktion von Patientinnen und Patienten („patient-reported outcome measures", PROMs) erfasst und psychosoziale Auswirkungen nachzuweisen versucht.

Für die biomechanische Beurteilung der Rückenfunktion steht eine große Variabilität an Untersuchungen von Bewegungsabläufen zur Verfügung, in der klinischen Routine wird häufig in Analogie zur Neutral-Null Methode die endgradige Bewegungsfähigkeit (range of motion) evaluiert [77, 80]. Entsprechend ist die Empfehlung zur Durchführung der körperlichen Untersuchung in den nationalen sowie internationalen Leitlinien als elementarer Punkt für die Beurteilung von Patientinnen und Patienten verankert. Dabei wird neben der Schmerzprovokation sowie der neurologischen Untersuchung ebenso die Evaluation der Beweglichkeit der Wirbelsäule empfohlen [80-83].

1.5 Ziele der Arbeit und wissenschaftliche Fragestellungen

Entsprechend der für das Fachgebiet der Orthopädie bahnbrechenden Befunde von Julius Wolff, der um die Jahrhundertwende des 19. in das 20. Jahrhundert die erste Professur der Charité für das Fachgebiet der Orthopädie innehatte, folgt die Form des Bewegungsapparates seiner Beanspruchung. Diese wegweisende Erkenntnis über die Knochenarchitektur wurde in der Arbeit „Das Gesetz der Transformation der Knochen" 1892 dargelegt [84]. Ebenso ist diese Erkenntnis auf muskuläre Hypertrophie, tendinöse Adaptationen oder eine Steigerung der kardio-respiratorischen Leistungsfähigkeit durch eine regelmäßige Beanspruchung übertragbar und wird im Rahmen von Trainingsprogrammen gezielt zum Verschieben des Leistungsmaximums herangezogen. Jedoch ist der Einfluss dieser Erkenntnis nicht nur auf medizinisch-biologische Bereiche begrenzt, so wurde das Grundprinzip vielfach abstrahiert und ist als Anglizismus „form follows function" als Leitmotiv ebenso in anderen Fachdisziplinen wie der Architektur oder Ingenieurwissenschaften implementiert. Entsprechend benötigt es neben der alleinigen anatomischen Beschreibung von Formveränderungen an der Wirbelsäule stets die Beurteilung der normalen Wirbelsäulenfunktion sowie assoziierter Funktionseinschränkungen um eine Aussage über den Einfluss auf unseren Alltag, Pathomorphologie sowie Versorgungsstrategien zu liefern. Daher stellt die Beurteilung der Funktion der Lendenwirbelsäule sowie des lumbo-sacralen Übergangs durch klinische und nicht-invasive Messverfahren (Arbeit 1 + Arbeit 2) in gesunden sowie Rückenschmerz-Kohorten den Grundstein dieser Arbeit dar. Darauf aufbauend erfolgt die Evaluation des Einflusses von anatomischen Variationen des lumbo-sacralen Übergangs auf die Rückenfunktion (Arbeit 3). Aus der Funktionsveränderung resultierende Adaptationsprozesse des Bewegungsapparates werden erfasst (Arbeit 4) und konsekutive Therapieimplikationen dargelegt (Arbeit 5) (Abbildung 3).

Abbildung 3 Übersicht der Zielsetzung der Arbeit



Bildquelle: Abbildung selbstständig erstellt.

1.5.1 Beurteilung der Erfassung der Funktion der Lendenwirbelsäule und des spino-pelvinen Übergangs

Als Fundament jeder ärztlichen Behandlung gilt, wie bereits von Hippokrates von Kos praktiziert, die körperliche Untersuchung, um Funktionsdefizite und Symptome zu erkennen, die einer Therapie bedürfen und zugänglich sind [85]. Die klinische Untersuchung der Wirbelsäule umfasst neben der neurologischen Prüfung, der Schmerzprovokationsprüfung und der Haltungsbeurteilung eine Bewegungsprüfung zur Beurteilung der dynamischen Wirbelsäulenfunktion. Für die Bewegungsprüfung haben sich vereinfachende Hilfsparameter wie der Finger-Boden-Abstand etabliert. Ob dieser jedoch einen validen Parameter zur Beurteilung der lumbalen Beweglichkeit sowie der Hüftbewegung in Patientinnen und Patienten mit und ohne chronische Rückenschmerzen darstellt wurde in **Arbeit 1** evaluiert.

1. Arbeit: “Is finger-floor distance a valid parameter for the assessment of lumbar flexion? An analysis of 523 participants“

Nicht-invasive objektivierbare Messinstrumente für die Beurteilung der Rückenfunktion können die Genauigkeit und Aussagekraft der klinischen Untersuchung erweitern. Diese weisen mitunter eine hohe Reliabilität und Validität auf. Bei zuvor postuliertem Zusammenhang zwischen Form und Funktion der Wirbelsäule stellt jedoch eine intermodale Vergleichbarkeit der Messwerte der Wirbelsäulenfunktion für eine konklusive Aussage bei Form- oder Funktionsänderungen ein maßgebliches Kriterium dar, bei der Anwendung unterschiedlicher Messinstrumente. In **Arbeit 2** wird deshalb die Frage beurteilt: Sind die resultierenden Messergebnisse von ausgewählten nicht-invasiven Messmethoden miteinander vergleichbar und damit die nicht-invasiven Messverfahren in der longitudinalen Verlaufsbeurteilung miteinander kompatibel?

2. Arbeit: "Comparison of three validated systems to analyse spinal shape and motion"

1.5.2 Einfluss von lumbo-sacralen Übergangsstörungen auf die Rückenfunktion und muskuläre Adaptation

Neben erworbenen anatomischen Veränderungen, die aus einer Überlastung resultieren, bestehen kongenitale Variationen, die reziprok die Rückenfunktion beeinflussen. Die in dieser Arbeit behandelte Veränderung des lumbo-sacralen Übergangs stellt eine entsprechende kongenitale Variation dar. **Arbeit 3** beurteiltet den Zusammenhang zwischen der lumbo-sacralen Übergangsstörung mit Funktionseinschränkungen sowie Kompensationsmechanismen in angrenzenden Segmenten und beantwortet die Frage: Inwieweit resultiert eine kranial kompensatorische Mehrbeweglichkeit aus lumbo-sacralen Übergangsstörungen und welchen Einfluss haben diese auf die Gesamtfunktion der lumbalen Wirbelsäule?

3. Arbeit: "Lumbosacral transitional vertebrae alter the distribution of lumbar mobility-Preliminary results of a radiographic evaluation"

Einhergehend mit Veränderungen der Rückenfunktion resultieren muskuläre Adaptationen. Diese ermöglichen bei spezifischen Degenerationsmustern die Möglichkeit einer zielgerichteten Intervention mittels funktioneller Beanspruchung, die konsekutiv eine Veränderung der muskulären Morphologie herbeiführen können im Sinne einer konservativen Therapie [86]. Entsprechend beurteilt **Arbeit 4** die Frage: Resultiert in Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen einhergehend mit Veränderungen der knöchernen Anatomie sowie der Rückenfunktion ebenso eine Adaptation der Muskulatur?

4. Arbeit: “Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients.”

1.5.3 Besonderheiten von Versorgungsstrategien des spino-pelvinen Übergangs bei lumbo-sacralen Übergangsstörungen

Mit anatomischen und Funktionsveränderungen des lumbo-sacralen Übergangs ist eine höhere Rate an Wirbelsäulendegenerationen und lumbalen Schmerzen assoziiert [51, 66], sodass operative Versorgungsformen bei fehlgeschlagener konservativer Therapie zu erwägen sind. Um das Risiko eines Implantatversagens oder Schraubenausrisses multisegmentaler Spondylodesen aufgrund der reduzierten Knochendichte des Kreuzbeines sowie eines langen Hebelarms multisegmentaler Spondylodesen zu reduzieren wird häufig die Verankerung langstreckiger Spondylodesen mittels S2-Ala-Ilium Schrauben gewählt [87, 88]. Diese weisen gegenüber Iliumschrauben den Vorteil auf, dass diese ohne Verwendung von Konnektoren an das Implantat System gekoppelt werden können und eine größere Weichgewebsdeckung besteht [89]. Zudem weisen sie eine höhere mechanische Stabilität durch die Verankerung in drei Knochenkortikalis-Schichten gegenüber der Iliumschraube, die lediglich eine Kortikalis fasst auf [90]. Gleichsam wie für die retroperitonealen Zugangswege [91] stellt die veränderte Gefäßanatomie [92] sowie die veränderte Beckengeometrie [93] einhergehend mit lumbo-sacralen Übergangsstörungen jedoch ein etwaiges Risiko bei der spino-pelvinen Verankerung mittels S2-Ala- sowie S2-Ala-Ilium Schrauben dar. Dementsprechend wird in **Arbeit 5** die Frage diskutiert, ob und wie ebenso in Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen spino-pelvine Verankerungsmöglichkeiten mit geringstem Risiko für eine neuro-vaskuläre Schädigung durch die Schraubenpositionierung durchführbar sind.

5. Arbeit: “Safe Zones for Spinopelvic Screws in Patients With Lumbosacral Transitional Vertebra”

2. Ergebnisse

2.1 Validität klinischer Untersuchungsmethoden für die Rückenfunktion

Becker L, Schömig F, Cordes LM, Duda GN, Pumberger M, Schmidt H

Finger-Floor Distance is not a Valid Parameter for the Assessment of Lumbar Mobility.

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Die Beurteilung der Rückenfunktion sowie der endgradigen Bewegungsfähigkeit stellt eine der maßgeblichen Säulen in der Therapieplanung sowie longitudinalen Untersuchung von Patientinnen und Patienten mit Formvariationen sowie Rückenbeschwerden dar [77]. Hierbei haben sich historisch Hilfsparameter wie der Finger-Boden-Abstand aufgrund einer hohen Reliabilität und einfachen Durchführbarkeit etabliert [94, 95]. Das Ziel der Arbeit war die Untersuchung der Validität des Finger-Boden-Abstands für die Beurteilung der lumbalen Mobilität in Patientinnen und Patienten mit chronischen Rückenschmerzen gegenüber einem asymptomatischen Kollektiv.

Im Rahmen dieser Arbeit wurde von 523 Probandinnen und Probanden (167 chronische Rückenschmerzen, 327 asymptomatisch) mittels des Epionic SPINE Systems die lumbale sowie pelvine Bewegung unter maximaler Rumpfbeugung sowie in einer Subkohorte von 12 Probandinnen und Probanden die graduelle Rumpfbeugung gegenüber dem Finger-Boden-Abstand evaluiert. Epionics SPINE besteht dabei aus zwei Dehnungsmessstreifen, die paravertebral mittels Hohlkammerpflaster auf die Haut appliziert werden und durch 12 Messsegmente die lumbale und die partielle thorakale Form und Bewegung sowie Formveränderungen in Alltagsbedingungen erfassen können. Für die Beurteilung der Beckenkippung weisen sie zudem zwei Akzelerometer auf, welche auf die Haut über der Spina iliaca posterior superior appliziert werden.

Der Finger-Boden-Abstand zeigte zu der lumbalen Flexion eine schwache Korrelation ($p<0,001$, $r=-0,442$), zur Hüftbeugung eine moderate ($p<0,001$, $r=-0,548$). In der Subkohorte von zwölf Probandinnen und Probanden zeigte die graduelle Rumpfbeugung eine starke Korrelation des Finger-Boden-Abstands mit der

Hüftbeugung (p<0,001, r=-0,895) und eine mäßige mit der lumbalen Flexion (p<0,001, r=-0,602).

Entsprechend können Unterschiede im Finger-Boden-Abstand in der longitudinalen Untersuchung eines individuellen Patienten, eine gleichbleibende Hüftfunktion vorausgesetzt, möglicherweise auf Unterschiede in der lumbalen Flexibilität zurückgeführt werden. Die absoluten Werte des Finger-Boden-Abstands eignen sich jedoch nicht als interindividuelles Maß für einen Vergleich der lumbalen Beweglichkeit.

diagnostics

Article

Finger-Floor Distance Is Not a Valid Parameter for the Assessment of Lumbar Mobility

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Abstract: Low back pain (LBP) could be associated with a reduced lumbar mobility. For the evaluation of lumbar flexibility, parameters such as finger-floor distance (FFD) are historically established. However, the extent of the correlation of FFD to lumbar flexibility or other involved joint kinematics such as pelvic motion, as well as the influence of LBP, is not yet known. We conducted a prospective cross-sectional observation study with 523 participants included (167 with LBP > 12 weeks, 356 asymptomatic). LBP-participants were matched for sex, age, height, and body-mass-index with an asymptomatic control cohort, resulting in two cohorts with 120 participants each. The FFD in maximal trunk flexion was measured. The Epionics-SPINE measurement-system was used to evaluate the pelvic and lumbar Range-of-Flexion (RoF), and the correlation of FFD to pelvic- and lumbar-RoF was evaluated. In an asymptomatic sub-cohort of 12 participants, we examined the individual correlation of FFD to pelvic- and lumbar-RoF under gradual trunk flexion. Participants with LBP showed a significantly reduced pelvic-RoF ($p < 0.001$) and lumbar-RoF ($p < 0.001$) as well as an increased FFD ($p < 0.001$) compared to the asymptomatic control cohort. Asymptomatic participants exhibited a weak correlation of FFD to pelvic-RoF and lumbar-RoF ($r < 0.500$). LBP patients revealed a moderate correlation of FFD to pelvic-RoF (male: $p < 0.001$, $r = -0.653$, female: $p < 0.001$, $r = -0.649$) and sex-dependent to lumbar-RoF (male: $p < 0.001$, $r = -0.604$, female: $p = 0.012$, $r = -0.256$). In the sub-cohort of 12 participants, gradual trunk flexion showed a strong correlation of FFD to pelvic-RoF ($p < 0.001$, $r = -0.895$) but a moderate correlation to lumbar-RoF ($p < 0.001$, $r = -0.602$). The differences in FFD in an individual patient, assuming consistent hip function, may be attributed partially to the differences in lumbar flexibility. However, the absolute values of FFD do not qualify as a measure for lumbar mobility. Rather, using validated non-invasive measurement devices should be considered.

Keywords: clinical examination; fingertip-to-floor distance; lbp; lumbar flexion; lumbar mobility; spinal mobility

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1. Introduction

Low back pain (LBP) is a global burden to society with a lifetime prevalence of up to 80 %, leading to a high rate of work absence, loss of productivity, and hospital admissions, resulting in tremendous direct and indirect costs for societies' healthcare systems and economies [1]. LBP could be accompanied by functional impairment [2–4], which is assessed by various outcome parameters. Hereby self-reported outcome measures are used to evaluate different dimensions such as function by the Oswestry Disability Index or the Roland-Morris Disability Questionnaire, the health-related quality of life by Short Form-36, or a pain assessment by different pain scales such as the Numerical rating scale or the Visual-analog scale [5–7]. However, LBP can not only be associated with reduced outcome in patient reported outcome measures, but also with detectable decrease in functional testing [6,8–11]. Therefore, a widespread heterogeneity of tasks for the functional assessment of LBP exists, and different findings might be associated with LBP such as a reduced movement velocity [8], changes in more complex motion sequences with increased flexion-relaxation time, or the most commonly used tool, the range-of-motion [6,9–11]. Under conservative treatment, an improvement of pain and function could be observed [3,9]. Therefore, a reproducible and undemanding detection of functional impairment for therapy planning and restoration of spinal function is required [12]. Accordingly, national guidelines for the management of patients with LBP include a clinical examination of the spine with motion analysis to detect functional impairments in spinal mobility [13].

In most cases, the evaluation of lumbar mobility is performed by non-radiological methods. Here, the finger-floor distance (FFD) in full trunk flexion has been established among others as a parameter for the examination of spinal mobility. The FFD is simple to assess, and it has a high responsiveness and a high reliability [14,15]. Additionally, the FFD has a high correlation to self-assessed impairment due to LBP measured by the Roland Morris Disability Questionnaire [15].

However, the extent to which lumbar and hip mobility correlate with the FFD is currently unknown. Considering that LBP influences the movement distribution of lumbar and hip flexion in forward bending [16], the aim of this study is to assess the validity of FFD as a parameter to represent both, lumbar and hip mobility, in participants with LBP over those without.

2. Materials and Methods

2.1. Study Design

We performed a prospective cross-sectional observation-study approved by the local ethics board (EA4/011/10). Participants gave written informed consent. The study was reported according to the STROBE guidelines.

2.2. Participants

We included 620 participants aged ≥18, with chronic LBP ≥ 12 weeks or without LBP. Chronic LBP was assessed with a questionnaire asking for the subjective condition of persistent LBP for at least 12 weeks, which was defined as chronic LBP. No minimal threshold for LBP on a pain scale, such as a numeric rating scale, was set. The exclusion criteria were acute LBP < 12 weeks, prior spinal surgery, neurological impairments such as paralysis, muscle weakness, radiculopathy, or movement disorders, malignancy, professional athletes, and pain exacerbation during examination, limiting the subjective performance in the range of motion. Therefore, 97 participants were excluded, resulting in 523 included participants, of which 167 stated to have chronic LBP for ≥12 weeks.

2.3. Epionics SPINE Measurement Device

The FFD and pelvic motion (pelvic-RoF), as well as the lumbar Range-of-Flexion (RoF) under maximal trunk-flexion, was observed. For the measurement of pelvic-RoF and lumbar-RoF during trunk flexion, the Epionics-SPINE (Epionics Medical GmbH, Potsdam, Germany) system was used. Epionics-SPINE is a validated, non-invasive measurement device [9,10] that can assess the lumbar back shape and motion via two sensor strips. The system is based on strain-gauge technology, consists of twelve 25-mm long sensor units and a three-dimensional accelerometer at the lower end for the assessment of pelvic version. The two sensor strips are attached to the back 7.5 cm paravertebrally in a standardized manner in hollow plasters. The lower end with the accelerometer is attached at the level of the posterior superior iliac spine. For upper orientation of sensor strips, 15 cm and 25 cm cranially to the spinae iliacae posteriores superiores, markings were attached on both sides 7.5 cm paravertebrally (Figure 1).

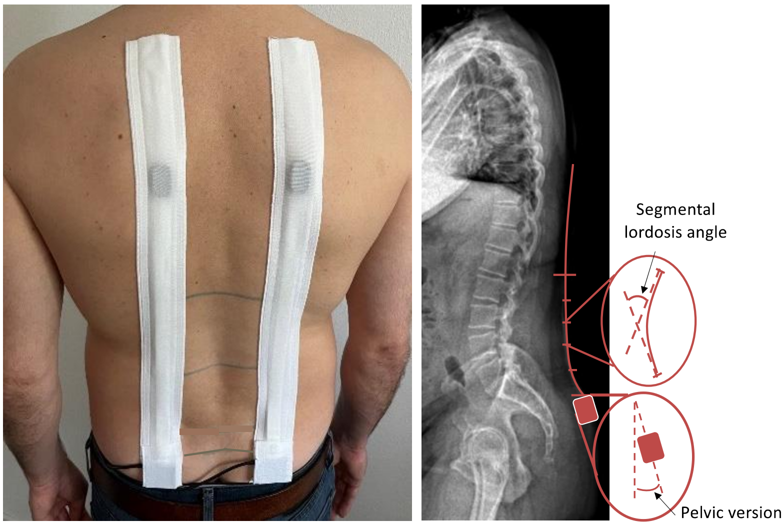

Figure 1. Epionics-SPINE measurement system.

To account for spine length discrepancies, the sensor units corresponding to the lumbar lordosis were determined for each study participant, defined by segmental lordosis angle. These sensor units served as reference units for further evaluations for lumbar-RoF. To determine lumbar lordosis in standing and lumbar curvature in maximum flexion, all local angles of the reference sensor units in standing and in maximum flexion were summed individually. The resulting RoF was then calculated as the angular difference from the standing reference. The values of the left and right sensor strips were averaged.

2.4. Measurement Protocol

Measurements were performed according to a standardized measurement protocol in all 523 participants. Anthropometrics were measured, body height via stadiometer and body weight via calibrated scale, and the body mass index (BMI) was calculated. This was followed by the application of the Epionics-SPINE measurement device. For standardized assessment of pelvic version and lumbar lordosis in upright standing, participants were asked to step on a platform of 30 cm height with marked foot positions of about 40 cm distance in between and asked to stand upright with fully extended knees. In this position, pelvic version and lumbar lordosis were recorded by the Epionics-SPINE system. Participants were asked to perform maximal trunk flexion with the aim to reach the floor with the fingertips while standing with the knees fully extended. In end position minimal vertical FFD was measured. As participants stood on a platform 30 cm high for measurements, a measured FFD of 30 cm was labeled and reported as 0 cm, referencing to standing on the ground floor, whereas the lowest reachable value for FFD was -30 cm. Pelvic-RoF and lumbar-RoF were assessed by the attached Epionics-SPINE system in end position. Differences of pelvic version and lumbar lordosis between upright standing and trunk flexion end position were calculated and defined as pelvic-RoF and lumbar-RoF.

2.5. Measurement Protocol "Gradual Trunk Flexion"

In a randomly chosen sub-group of 12 asymptomatic participants (four females, eight males) without LBP, the proportions of pelvic- and lumbar-RoF during stepwise trunk flexion was assessed. Therefore, a standardized measurement protocol with the same standardized standing and foot position as in the main protocol was established. Firstly, the FFD of participants was measured by measuring tape, and pelvic version and lumbar lordosis in upright standing were recorded. Subsequently, participants were instructed to perform a trunk flexion with extended knees so that the FFD was 60 cm and pelvic-RoF and lumbar-RoF were recorded by the Epionics-SPINE system. After trunk flexion, participants were instructed to return to the relaxed standing position and perform gradual trunk flexion to reach predefined finger-floor distances (60 cm, 52 cm, 44 cm, 36 cm, 28 cm, 19 cm, 10 cm, 0 cm) with intermitting rest periods in the relaxed upright standing position. If participants were unable to achieve a prescribed FFD, no further movement steps were performed.

2.6. Data Analysis

Data were tested for normal distribution using the Kolmogorow–Smirnow-test. For comparison of unpaired parametric parameters, the *t*-test, and for continuous data, the Mann–Whitney U-test was performed. For the comparison of two paired parametric samples, the paired *t*-test and for continuous samples, the Wilcoxon-rank sum-test was used. Correlations were observed by Spearman's correlation coefficient. A p-value < 0.05 was considered as statistically significant. Statistical analysis was performed using SPSS Version 27 (IBM Corporation, New York, NY, USA). As other aspects of this cohort were already published elsewhere [17], we performed a post-hoc power analysis with our effect size of 0.442, an α-error of 0.05, and a sample size of 523 participants; a test power of 1.000 was achieved for our cohort. Power analysis was performed using G*Power Version 3.1.9.6.

3. Results

3.1. Demographics

A total of 523 participants was analyzed. The demographics for the collective of 523 participants and for matched cohorts are given in Table 1.

Table 1. Demographics and anthropometrics of included participants in both the LBP and the control groups.

	Overall				
	LBP (n = 167)		Asymptomatic Control (n = 356)		
	Male Median (IQR)	Female Median (IQR)	Male Median (IQR)	Female Median (IQR)	
n	70	97	159	197	
Age [years]	49 (22)	51 (20)	36 (21)	37 (22)	
Height [cm]	178 (11)	167 (8)	179 (11)	168 (9)	
BMI [kg/m^2]	26.3 (6.0)	25.8 (6.1)	24.0 (2.0)	22.0 (3.0)	
	Matched Groups				
	LBP (n = 120)		Asymptomatic Control (n = 120)		p-value
	Male Median (IQR)	Female Median (IQR)	Male Median (IQR)	Female Median (IQR)	
n	49	71	49	71	1.000
Age [years]	49 (23)	50 (22)	48 (18)	49 (22)	0.804
Height [cm]	178 (12)	168 (9)	178 (14)	168 (7)	0.802
BMI [kg/m^2]	24.9 (3.8)	24.1 (5.1)	25.0 (2.0)	24.0 (4.0)	0.380

IQR = Interquartile range; LBP = low back pain; BMI = body-mass index. Wilcoxon rank-sum test was performed for intergroup comparison between the LBP and the matched asymptomatic control group.

3.2. Sex Differences in Pelvic Version, Lumbar Lordosis, Pelvic- and Lumbar-RoF

The Kolmogorow–Smirnow test showed for the collective of 523 participants the normal distribution for lumbar lordosis and pelvic-RoF, whereas the pelvic version, lumbar-RoF, and FFD did not follow normal distribution. For the whole sample, female and male participants differed significantly in their pelvic version and lumbar lordosis in upright standing (Table 2). The pelvic-RoF, but not the lumbar-RoF, was significantly associated with sex.

Table 2. Sex differences in pelvic version, lumbar lordosis, pelvic- and lumbar-RoF between male and female participants.

	All Median (IQR) (*n* = 523)	Male Median (IQR) (*n* = 229)	Female Median (IQR) (*n* = 294)	*p*-Value
Pelvic version [°]	17.9 (11.7)	16.0 (11.8)	19.0 (10.9)	**<0.001**
Lumbar lordosis [°]	30.8 (14.4)	28.3 (16.0)	32.1 (13.4)	**<0.001**
Pelvic-RoF [°]	72.9 (30.1)	69.5 (28.4)	76.2 (27.7)	**<0.001**
Lumbar-RoF [°]	48.5 (17.8)	48.0 (19.4)	49.5 (16.6)	0.277
FFD [cm]	1.0 (20.0)	5.0 (19.5)	0.0 (20)	**<0.001**

IQR = Interquartile range; FFD = Finger-floor distance; Statistically significant *p*-values are marked in bold.

3.3. Influence of LBP

In the matched cohorts of 120 participants, each pelvic version, lumbar lordosis, pelvic-RoF, and lumbar-RoF followed the normal distribution according to the Kolmogorow–Smirnow test, although the FFD did not follow normal distribution. LBP patients had a significantly reduced pelvic version and lumbar lordosis in upright standing ($p < 0.001$) and significantly reduced pelvic-RoF ($p < 0.001$) and lumbar-RoF ($p < 0.001$) accompanied by a significant increase in FFD ($p < 0.001$) compared to the asymptomatic control-group (Table 3).

Table 3. Differences in pelvic version and lumbar lordosis, as well as pelvic- and lumbar-RoF, between matched LBP participants and the control group.

	LBP Median (IQR) (*n* = 120)	Control Median (IQR) (*n* = 120)	*p*-Value
Pelvic version [°]	13.5 (11.0)	17.7 (11.9)	**<0.001**
Lumbar lordosis [°]	23.7 (11.9)	30.5 (16.2)	**<0.001**
Pelvic-RoF [°]	61.2 (29.4)	74.2 (26.3)	**<0.001**
Lumbar-RoF [°]	37.7 (15.8)	50.7 (14.6)	**<0.001**
FFD [cm]	16.5 (33.3)	0.0 (15.0)	**<0.001**

IQR = Interquartile range; FFD = Finger-floor distance; Statistically significant *p*-values are marked in bold.

3.4. Correlation between Lumbar and Pelvic-RoF and FFD

For all study participants, the FFD had a moderate negative correlation with pelvic-RoF ($p < 0.001$, $r = -0.548$) and a weak negative correlation with lumbar-RoF ($p < 0.001$, $r = -0.442$). However, individuals with and without chronic LBP differed in the correlations.

For the asymptomatic population, a weak negative correlation ($p < 0.001$, $r = -0.348$) between FFD and pelvic-RoF and no correlation with lumbar-RoF ($p < 0.001$, $r = -0.184$) was observed. Participants with LBP had a moderate negative correlation between pelvic-RoF and FFD ($p < 0.001$, $r = -0.663$) and a weak correlation of FFD with lumbar-RoF ($p < 0.001$, $r = -0.432$). Sex influenced the correlation between FFD and pelvic-RoF and lumbar-RoF. Females and males differed significantly in FFD ($p < 0.001$). In asymptomatic females, pelvic-RoF showed a weak negative ($p < 0.001$, $r = -0.353$), and in asymptomatic males, it showed a negligible negative correlation ($p < 0.001$, $r = -0.295$) with FFD. Lumbar-RoF in asymptomatic females ($p = 0.022$, $r = -0.163$) and males ($p = 0.012$, $r = -0.256$) also had negligible correlations with FFD. In contrast, for LBP participants, males presented a moderate negative correlation of both pelvic-RoF ($p < 0.001$, r = −0.653) and lumbar-RoF ($p < 0.001$, r = −0.604). However, females showed a moderate negative correlation for pelvic-RoF ($p < 0.001$, r = −0.649) but negligible correlation for lumbar-RoF ($p = 0.012$, r = −0.256) with FFD (Figure 2).

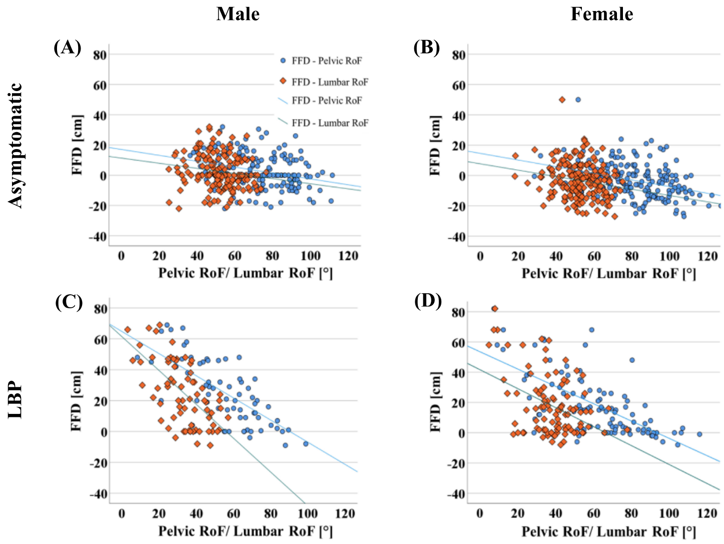

Figure 2. Correlation of lumbar-RoF and pelvic-RoF with finger-floor distance in asymptomatic males (**A**), asymptomatic females (**B**), symptomatic males (**C**), and symptomatic females (**D**).

3.5. Relationship between Pelvic-RoF, Lumbar-RoF, and Gradual FFD

For the subcohort of 12 asymptomatic participants in which FFD was measured stepwise from 60 cm to 0 cm, four females and eight males with a median (interquartilrange) age of 33.0 (10.8) years, median height of 180.0 (15) cm, and median BMI of 22.1 (10.8) kg/m^2 were analyzed. The subgroup analyses showed that pelvic-RoF had a strong negative correlation with gradual FFD ($p < 0.001$, r = −0.895), whereas lumbar-RoF yielded a moderate negative correlation with gradual FFD ($p < 0.001$, r = −0.602) (Figure 3).

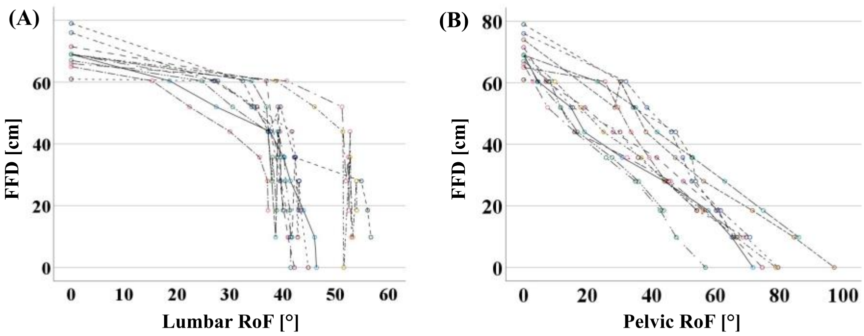

Figure 3. Relationship between gradual FFD and lumbar-RoF (**A**) and pelvic-RoF (**B**) with linear interpolation lines in the subcohort of 12 asymptomatic participants. For each participant the values were depicted in circles of one color.

4. Discussion

This study aimed to evaluate the validity of FFD as a measure of lumbar mobility. Our results demonstrate that in a population without LBP, FFD has a weak correlation to both pelvic- and lumbar-RoF. However, in participants with LBP, a moderate correlation of FFD to pelvic-RoF and a sex-dependent correlation to lumbar-RoF was observed. Males with LBP had a moderate correlation of FFD to lumbar-RoF, whereas females presented a weak correlation of FFD to lumbar-RoF. For gradual trunk flexion in 12 individuals, a strong correlation of FFD to pelvis and a moderate to lumbar-RoF was shown.

The obtained values for pelvic-RoF and lumbar-RoF are in the range of those reported elsewhere for maximum trunk flexion [18–23]. Consistent with a meta-analysis, we detected sex differences for lumbar lordosis in upright standing with increased lumbar lordosis in females [24]. In agreement, females in our study concomitantly showed an increased pelvic version [18,25–27]. Females performed a significantly increased pelvic-RoF during trunk flexion compared to males, due to an increased hip flexion as described in the literature [28]. Lumbar flexion did not differ significantly between sexes [24]. This resulted in a significantly decreased FFD in females compared to males.

Chronic LBP significantly influenced posture. As in our collective, Chun et al. demonstrated an association of LBP with flattening of the lumbar spine [29]. Concomitantly, LBP patients in an upright standing exhibited a significantly reduced pelvic version in line with the results of Schmidt et al. [17]. The association of LBP with restricted RoF is controversially discussed [2,3,30,31]. However, according to a meta-analysis by Laird et al., our results show reduced lumbar mobility in subjects with LBP [2]. Similarly, subjects with LBP presented a significantly reduced pelvic-RoF, which has also previously been described by Wong et al. [16]. The task-related avoidance behavior of subjects with LBP [32] and the reduced hip-spine kinematics with hamstring affection in the context of LBP could possibly have contributed to these findings [33]. The reduced pelvic-RoF and reduced lumbar-RoF resulted in a greater FFD in participants with LBP.

In addition to the outlined differences of posture and RoF between male and female participants, as well as participants with and without LBP, varying correlations between FFD and pelvic-RoF and lumbar-RoF were observed. For asymptomatic participants, a weak correlation was observed for pelvic- and lumbar-RoF. The weak correlation may be due to the complexity of the movement resulting from the numerous movement components such as hip, lumbar, and thoracic flexion, as well as shoulder, elbow, wrist, and finger extension. Perret et al. reported a strong correlation between the FFD and the radiographic evaluation of the tilting of the fifth thoracic vertebra between the standing and trunk flexion [14]. However, these results are comparable with our data only to a limited extent due to the evaluation of a combined movement of hip, lumbar, and thoracic flexion by Perret et al. [14]

The FFD is influenced by anthropometric data such as arm-to-leg length ratio and trunk length. These parameters show a significant correlation with height but a considerable interindividual variability [34], possibly resulting in an influence on the assessment of FFD. This was also observed in our subcohort of 12 participants who were examined with gradual FFD. In these participants, the values of FFD in upright standing differed by as much as 10 cm in individuals of the same height. Accordingly, the individual examination of the FFD versus the gradual trunk flexion, which is resistant against anthropometric differences by patient-specific examination, showed a strong correlation of the FFD to pelvic-RoF, as well as a moderate correlation to lumbar-RoF. As a result, a relevant influence of the body proportions on the FFD could be assumed. Furthermore, the different motion patterns of the trunk flexion in the whole cohort might be too heterogeneous between participants to obtain a strong correlation between the FFD and lumbar-RoF.

However, in participants with LBP, a stronger correlation of FFD to pelvic-RoF was observed. This finding could possibly be attributed to a change in kinematics with a relative reduction in lumbar-RoF in participants with LBP, as described by Wong et al. [16]. In our LBP cohort, males demonstrated a stronger correlation of FFD and lumbar-RoF compared to females. This may result from a greater FFD of males with an LBP of 21.5 cm compared to females with an FFD of 14.0 cm.

In line with our results, the literature shows that in the initial phase of trunk flexion, lumbar-RoF predominates, but in advanced trunk flexion, further hip flexion with concomitant pelvic-RoF occurs almost exclusively [18]. However, these findings have never been considered in relation to FFD. These effects are evident considering the results presented in Figure 3, illustrating that lumbar flexion occurs especially in the initial phase of trunk flexion and, accordingly, the reduction of FFD shows a higher correlation with lumbar flexion, especially in the initial phase of trunk flexion.

This study has limitations that need to be mentioned. Even though this study included a large collective of subjects with and without chronic LBP, a further evaluation of pain intensity based on the available data is not possible, which may also have influenced the presented results. The presumed underlying cause of LBP was not considered, as no imaging data of the participants was available. Therefore, no allocation to specific- or non-specific LBP was performed. Hip–spine interaction could be influenced by hip osteoarthritis, which was not evaluated in our study due to lacking imaging data [35]. In our cohort for patients with a pain increase in trunk flexion, the examination was stopped and the participants were excluded to prevent an elevated FFD caused by pain avoidance behavior. However, this could have resulted in a selection bias and influenced the FFD in the cohort of LBP patients as only participants without subjective pain-related movement restrictions were included. The side deviation and lateral shift in forward bending were not recorded, although the side differences between the left and right side were averaged. Therefore, our results do not take trunk or kinematic asymmetries into account. Even though measuring back shape by Epionics-SPINE is validated against radiographic imaging for the detection of spinal shape [36] differences in soft tissue, the anatomy due to sex or BMI could have influenced our results.

5. Conclusions

Based on our results, it could be concluded that the differences in the FFD in an individual patient in longitudinal measurements under consistent hip function may be attributed partially to differences in lumbar flexibility. For the patient-specific examination of stepwise trunk flexion, which is not subject to differences in anthropometrics or to heterogeneity in movement patterns, a strong correlation between FFD and pelvic-RoF and a moderate correlation to lumbar-RoF were found in asymptomatic participants. Based on our results, absolute values of FFD should not be used as a comparative parameter between patients with the purpose of evaluating lumbar flexibility for both asymptomatic and patients with LBP. Instead, the measurement of lumbar RoM by non-invasive measurement devices might be considered a viable option with a high reliability and validity.

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References

1. Wu, A.; March, L.; Zheng, X.; Huang, J.; Wang, X.; Zhao, J.; Blyth, F.M.; Smith, E.; Buchbinder, R.; Hoy, D. Global low back pain prevalence and years lived with disability from 1990 to 2017: Estimates from the Global Burden of Disease Study 2017. *Ann. Transl. Med.* **2020**, *8*, 299. [CrossRef] [PubMed]
2. Laird, R.A.; Gilbert, J.; Kent, P.; Keating, J.L. Comparing lumbo-pelvic kinematics in people with and without back pain: A systematic review and meta-analysis. *BMC Musculoskelet. Disord.* **2014**, *15*, 229. [CrossRef] [PubMed]
3. Wernli, K.; Tan, J.S.; O'Sullivan, P.; Smith, A.; Campbell, A.; Kent, P. Does Movement Change When Low Back Pain Changes? A Systematic Review. *J. Orthop. Sport. Phys. Ther.* **2020**, *50*, 664–670. [CrossRef] [PubMed]
4. Agnus Tom, A.; Rajkumar, E.; John, R.; Joshua George, A. Determinants of quality of life in individuals with chronic low back pain: A systematic review. *Health Psychol. Behav. Med.* **2022**, *10*, 124–144. [CrossRef]
5. de Luca, K.; Anderson, D.; Dutt, A.; Magennis, L.; Parrello, T.; Ferreira, M.L.; Chiarotto, A. Outcome Domain and Measurement Instrument Reporting in Randomized Controlled Trials of Interventions for Lumbar Spinal Stenosis: A Systematic Review. *J. Orthop. Sport. Phys. Ther.* **2022**, *52*, 446-A2. [CrossRef]
6. Chapman, J.R.; Norvell, D.C.; Hermsmeyer, J.T.; Bransford, R.J.; DeVine, J.; McGirt, M.J.; Lee, M.J. Evaluating common outcomes for measuring treatment success for chronic low back pain. *Spine* **2011**, *36*, S54–S68. [CrossRef]
7. Garg, A.; Pathak, H.; Churyukanov, M.V.; Uppin, R.B.; Slobodin, T.M. Low back pain: Critical assessment of various scales. *Eur. Spine J.* **2020**, *29*, 503–518. [CrossRef]
8. Poitras, S.; Loisel, P.; Prince, F.; Lemaire, J. Disability measurement in persons with back pain: A validity study of spinal range of motion and velocity. *Arch. Phys. Med. Rehabil.* **2000**, *81*, 1394–1400. [CrossRef]
9. Shahvarpour, A.; Henry, S.M.; Preuss, R.; Mecheri, H.; Lariviere, C. The effect of an 8-week stabilization exercise program on the lumbopelvic rhythm and flexion-relaxation phenomenon. *Clin. Biomech.* **2017**, *48*, 1–8. [CrossRef]
10. Ge, L.; Pereira, M.J.; Yap, C.W.; Heng, B.H. Chronic low back pain and its impact on physical function, mental health, and health-related quality of life: A cross-sectional study in Singapore. *Sci. Rep.* **2022**, *12*, 20040. [CrossRef]
11. Abd Rahman, N.A.; Li, S.; Schmid, S.; Shaharudin, S. Biomechanical factors associated with non-specific low back pain in adults: A systematic review. *Phys. Ther. Sport* **2023**, *59*, 60–72. [CrossRef]
12. Fritz, J.M.; Cleland, J.A.; Childs, J.D. Subgrouping patients with low back pain: Evolution of a classification approach to physical therapy. *J. Orthop. Sport. Phys. Ther.* **2007**, *37*, 290–302. [CrossRef]
13. Enix, D.; Cho, C.; Sembrano, J.; Easa, J.; Annaswamy, T.; Meagher, R.; Cassidy, R.; O'Toole, J.; Matz, P.; Asgari, M.; et al. Evidence-Based Clinical Guidelines for Multidisciplinary Spine Care: Diagnosis & Treatment of Low Back Pain. *N. Am. Spine Soc.* **2020**, 1–217.
14. Perret, C.; Poiraudeau, S.; Fermanian, J.; Colau, M.M.; Benhamou, M.A.; Revel, M. Validity, reliability, and responsiveness of the fingertip-to-floor test. *Arch. Phys. Med. Rehabil.* **2001**, *82*, 1566–1570. [CrossRef]
15. Ekedahl, H.; Jonsson, B.; Frobell, R.B. Fingertip-to-floor test and straight leg raising test: Validity, responsiveness, and predictive value in patients with acute/subacute low back pain. *Arch. Phys. Med. Rehabil.* **2012**, *93*, 2210–2215. [CrossRef]
16. Wong, T.K.; Lee, R.Y. Effects of low back pain on the relationship between the movements of the lumbar spine and hip. *Hum. Mov. Sci.* **2004**, *23*, 21–34. [CrossRef]
17. Schmidt, H.; Bashkuev, M.; Weerts, J.; Altenscheidt, J.; Maier, C.; Reitmaier, S. What does the shape of our back tell us? Correlation between sacrum orientation and lumbar lordosis. *Spine J.* **2018**, *18*, 655–662. [CrossRef]
18. Pries, E.; Dreischarf, M.; Bashkuev, M.; Putzier, M.; Schmidt, H. The effects of age and gender on the lumbopelvic rhythm in the sagittal plane in 309 subjects. *J. Biomech.* **2015**, *48*, 3080–3087. [CrossRef]
19. Mayer, T.G.; Tencer, A.F.; Kristoferson, S.; Mooney, V. Use of noninvasive techniques for quantification of spinal range-of-motion in normal subjects and chronic low-back dysfunction patients. *Spine* **1984**, *9*, 588–595. [CrossRef]
20. Esola, M.A.; McClure, P.W.; Fitzgerald, G.K.; Siegler, S. Analysis of lumbar spine and hip motion during forward bending in subjects with and without a history of low back pain. *Spine* **1996**, *21*, 71–78. [CrossRef]
21. Porter, J.L.; Wilkinson, A. Lumbar-hip flexion motion. A comparative study between asymptomatic and chronic low back pain in 18- to 36-year-old men. *Spine* **1997**, *22*, 1508–1513, discussion 1513–1504. [CrossRef] [PubMed]
22. Kim, M.H.; Yi, C.H.; Kwon, O.Y.; Cho, S.H.; Cynn, H.S.; Kim, Y.H.; Hwang, S.H.; Choi, B.R.; Hong, J.A.; Jung, D.H. Comparison of lumbopelvic rhythm and flexion-relaxation response between 2 different low back pain subtypes. *Spine* **2013**, *38*, 1260–1267. [CrossRef] [PubMed]
23. Tafazzol, A.; Arjmand, N.; Shirazi-Adl, A.; Parnianpour, M. Lumbopelvic rhythm during forward and backward sagittal trunk rotations: Combined in vivo measurement with inertial tracking device and biomechanical modeling. *Clin. Biomech.* **2014**, *29*, 7–13. [CrossRef] [PubMed]

24. Arshad, R.; Pan, F.; Reitmaier, S.; Schmidt, H. Effect of age and sex on lumbar lordosis and the range of motion. A systematic review and meta-analysis. *J. Biomech.* **2019**, *82*, 1–19. [CrossRef] [PubMed]
25. Nguyen, A.D.; Shultz, S.J. Sex differences in clinical measures of lower extremity alignment. *J. Orthop. Sport. Phys. Ther.* **2007**, *37*, 389–398. [CrossRef]
26. Medina McKeon, J.M.; Hertel, J. Sex differences and representative values for 6 lower extremity alignment measures. *J. Athl. Train.* **2009**, *44*, 249–255. [CrossRef]
27. Merrill, R.K.; Kim, J.S.; Leven, D.M.; Kim, J.H.; Meaike, J.J.; Bronheim, R.S.; Suchman, K.I.; Nowacki, D.; Gidumal, S.S.; Cho, S.K. Differences in Fundamental Sagittal Pelvic Parameters Based on Age, Sex, and Race. *Clin. Spine Surg.* **2018**, *31*, E109–E114. [CrossRef]
28. Czuppon, S.; Prather, H.; Hunt, D.M.; Steger-May, K.; Bloom, N.J.; Clohisy, J.C.; Larsen, R.; Harris-Hayes, M. Gender-Dependent Differences in Hip Range of Motion and Impingement Testing in Asymptomatic College Freshman Athletes. *PM R* **2017**, *9*, 660–667. [CrossRef]
29. Chun, S.W.; Lim, C.Y.; Kim, K.; Hwang, J.; Chung, S.G. The relationships between low back pain and lumbar lordosis: A systematic review and meta-analysis. *Spine J.* **2017**, *17*, 1180–1191. [CrossRef]
30. Laird, R.A.; Kent, P.; Keating, J.L. How consistent are lordosis, range of movement and lumbo-pelvic rhythm in people with and without back pain? *BMC Musculoskelet. Disord.* **2016**, *17*, 403. [CrossRef]
31. Parks, K.A.; Crichton, K.S.; Goldford, R.J.; McGill, S.M. A comparison of lumbar range of motion and functional ability scores in patients with low back pain: Assessment for range of motion validity. *Spine* **2003**, *28*, 380–384. [CrossRef]
32. Matheve, T.; De Baets, L.; Bogaerts, K.; Timmermans, A. Lumbar range of motion in chronic low back pain is predicted by task-specific, but not by general measures of pain-related fear. *Eur. J. Pain* **2019**, *23*, 1171–1184. [CrossRef]
33. Shum, G.L.; Crosbie, J.; Lee, R.Y. Effect of low back pain on the kinematics and joint coordination of the lumbar spine and hip during sit-to-stand and stand-to-sit. *Spine* **2005**, *30*, 1998–2004. [CrossRef]
34. Reeves, S.L.; Varakamin, C.; Henry, C.J. The relationship between arm-span measurement and height with special reference to gender and ethnicity. *Eur. J. Clin. Nutr.* **1996**, *50*, 398–400.
35. Haffer, H.; Adl Amini, D.; Perka, C.; Pumberger, M. The Impact of Spinopelvic Mobility on Arthroplasty: Implications for Hip and Spine Surgeons. *J. Clin. Med.* **2020**, *9*, 2569. [CrossRef]
36. Consmuller, T.; Rohlmann, A.; Weinland, D.; Druschel, C.; Duda, G.N.; Taylor, W.R. Comparative evaluation of a novel measurement tool to assess lumbar spine posture and range of motion. *Eur. Spine J.* **2012**, *21*, 2170–2180. [CrossRef]

2.2 Vergleichbarkeit der Analyse der Rückenform und -funktion durch drei validierte nicht-invasive Messinstrumente

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Comparison of three validated systems to analyze spinal shape and motion.

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Aufgrund der in Arbeit 1 gezeigten eingeschränkten interindividuellen Validität der klinischen Beurteilung der Rückenfunktion durch die klinische Testung gewinnen für die Beurteilung der Wirbelsäulenform und -beweglichkeit objektive, nicht-invasive Messverfahren zunehmend an Bedeutung. Auch wenn die jeweiligen Methoden eine hohe Messreliabilität aufweisen, ist jedoch die Vergleichbarkeit der Messwerte untereinander und damit die Kompatibilität der Messverfahren im longitudinalen Verlauf bislang unzureichend beschrieben.

Drei nicht-invasive Messinstrumente wurden miteinander verglichen: Idiag M360, Rasterstereographie und Epionics SPINE. Die Idiag M360 erfasst die Rückenform durch das Abfahren der Processi spinosi vom 7. Halswirbel bis zum 2. Sacralwirbel. Dabei wird die Länge der Gesamtstrecke sowie die Rückenform durch drei Lagesensoren erfasst. Dies ermöglicht Bewegungsanalysen durch die Beurteilung von Endpositionen und somit Bewegungsumfängen. Die Rasterstereographie ermöglich die digitale Formerfassung der Wirbelsäule im aufrechten Stand durch die Projektion von Lichtstreifen auf den Rücken und eine anschließende digitale Aufarbeitung der Linien, diese ist insbesondere in der Verlaufsbeurteilung von Patientinnen und Patienten mit Skoliose bereits klinisch etabliert [96]. Die Messmethode von Epionics SPINE ist im vorherigen Abschnitt erläutert. Dreißig Probandinnen und Probanden (15 weiblich / 15 männlich) wurden mit jedem der drei Systeme untersucht. Dabei wurden die Lendenlordose, die Brustkyphose und der Bewegungsumfang der Wirbelsäule in der Sagittalebene analysiert.

Die Lendenlordose unterschied sich signifikant ($p<0{,}001$) zwischen den Messgeräten, zeigte jedoch eine signifikante Korrelation untereinander (Pearson's r 0,5 – 0,6). Bei der thorakalen Kyphose wurden keine signifikanten Unterschiede in der Rückenform sowie eine hohe Korrelation ($r=0{,}78$) zwischen Idiag M360 und der

Rasterstereographie nachgewiesen. In der Beurteilung der lumbalen Bewegung unterschieden sich die Messinstrumente signifikant voneinander und korrelierten nur mäßig zwischen Idiag M360 und Epionics SPINE (r=0,47).

Obwohl die verschiedenen Messinstrumente miteinander mäßig bis hoch korrelierende Werte für die lumbale Lordose sowie die lumbale Beweglichkeit aufweisen, ist ihre absolute Übereinstimmung begrenzt. Dies könnte auf Unterschiede in der Definition der lumbalen Lordose, dem Messort oder Messmethoden (statische vs. dynamische Messungen) beruhen. Daher sollte für die longitudinale Beurteilung des Rückenprofils ein intermodaler Vergleich von Werten zwischen verschiedenen nicht-invasiven Geräten vermieden werden.

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Comparison of three validated systems to analyse spinal shape and motion

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The assessment of spinal shape and mobility is of great importance for long-term therapy evaluation. As frequent radiation should be avoided, especially in children, non-invasive measurements have gained increasing importance. Their comparability between each other however stays elusive. Three non-invasive measurement tools have been compared to each other: Idiag M360, raster stereography and Epionics SPINE. 30 volunteers (15 females/15 males) have each been assessed by each system, investigating lumbar lordosis, thoracic kyphosis and spinal range-of-motion in the sagittal plane. Lumbar lordosis differed significantly (p < 0.001) between measurement devices but correlated significant to each other (Pearson's r 0.5–0.6). Regarding thoracic kyphosis no significant difference and a high correlation (r = 0.8) could be shown between Idiag M360 and raster stereography. For lumbar mobility resulting measurements differed significantly and correlated only moderate between Idiag M360 and Epionics SPINE. Although the different measurement systems are moderate to high correlated to each other, their absolute agreement is limited. This might be explained by differences in their angle definition for lordotic and kyphotic angle, their measurement placement, or their capturing of mobility (static vs. dynamic assessment). Therefore, for long-term evaluation of the back profile, inter-modal comparison of values between different non-invasive devices should be avoided.

As the prevalence and incidence of low back pain (LBP) constantly rise[1], the number of clinical examinations and the costs for healthcare due to LBP are tremendously increasing[2]. In cases of chronic LBP, X-rays are often performed serially, contrary to international guidelines[3]. Especially in children and adolescents, whereas a prevalence of LBP of up to 40% is reported, the use of ionizing radiation raises ethical questions for sequential documentation[4,5]. Therefore, in recent years, alternative—radiation-free—methods have been developed to track and monitor postural deformities and thus, claim to replace at least some of the follow-up radiological measurements. These methods focus mainly on assessing lumbar spinal shape and mobility (range of motion, RoM), which are common measures in clinical examinations to determine spinal dysfunction and serve as indicators in monitoring changes of patients pre-, during and post- therapy over time[6].

Apart from systems that are in use in sports medicine like Vicon[7], Zebris[8], 3D SpineMoveGuard[9] or X-Sens sensors[10], or those used for workplace analyses such as Lumbar Motion Monitor[11] or CUELA system[12], some measurement tools have been implemented in the clinical setting, for example, the Idiag M360 (MediMouse, Idiag AG, Fehraltorf, Switzerland)[13–15], the Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany)[16] or the Formetric III raster sterography (Diers International GmbH, Schlangenbad, Germany)[17,18]. All three systems track patient's spinal shape (lordosis and kyphosis) and mobility in the sagittal plane (RoM in flexion (RoF) and extension (RoE)) by measuring postural changes over time. However, the measuring instruments differ in several aspects. Idiag M360 measures sagittal along the processi spinose in a static position using photoelectric sensors. Raster Sterography (Formetric III) captures through a 3-dimensional image of the body surface in a static position using photoelectric sensors. Epionics SPINE measures the back shape by resistive sensors attached paravertebrally to the skin. The system is able to evaluate dynamic movements. To what extent these technical differences lead to differences in the measurement outcome has not yet been investigated. For all three systems, the literature reports moderate to good inter- and intra-rater reliability. For Idiag M360, reliability in the sagittal plane with an intra-class correlation coefficients (ICC) of 0.57 up to 0.95[15,19] and a correlation to radiographic imaging with Spearman coefficient of r = 0.86[13] is reported. For raster sterography, ICC ranges from 0.79 to

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0.99[20–22] with a correlation to radiographic imaging of $r^2 > 0.5$[23]. For Epionics SPINE, an ICC of 0.79–0.87 is reported[16], a direct comparison to radiographic imaging does not exist. For the clinical examination parameter fingertip to floor distance (MFTF), the literature reports an ICC reliability of up to 0.99[24]. However, even if the obtained results of some of the devices are already compared against radiographic imaging and presented good correlation, the comparability of the output data between the devices for the back shape stays elusive.

Therefore, the aim of this study was to examine the correlation and the absolute agreement of three currently used devices with a reported high reliability: the Idiag M360, the raster stereography and the Epionics SPINE system. The identification of possible measurement differences should contribute to the further development of radiation-free back measurement methods and consequently to clinical quality assurance.

Methods

Study participants. A total of 30 asymptomatic volunteers (15 females, 15 males) were included. The participants had no low back pain or previous spinal surgery. The mean volunteer's age was 30.9 ± 4.6 years (females: 30.6 ± 4.0, males: 31.2 ± 5.4), mean height 174.0 ± 9.1 cm (females: 166.6 ± 5.4 cm, males: 181.4 ± 5.2 cm), mean weight 68.7 ± 12.9 kg (females: 58.9 ± 7.2 kg, males: 78.5 ± 9.4 kg) and mean body mass index (BMI) 22.5 ± 2.8 kg/m^2 (females: 21.2 ± 2.7 kg/m^2, males: 23.8 ± 2.2 kg/m^2).

Study design. All participants completed a measurement protocol that included measurements with three different devices: Idiag M360 (MediMouse, Idiag AG, Fehraltorf, Switzerland), Formetric III raster sterography (Diers International GmbH, Schlangenbad, Germany) and Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany) in upright standing as well as in upper body flexion and extension (functional analyses).

In standing, all three devises allow the measurement of the lumbar lordosis (LL), whereas Idiag M360 and raster stereography further allow the assessment of the thoracic kyphosis (TK) during relaxed standing. For the functional spinal motion analysis, Idiag M360 and Epionics SPINE allow the assessment of RoF, RoE and full sagittal range of motion (RoM; sum of RoF and RoE) during maximal upper body bending.

Measurement protocol. All three measurement-systems were employed at the same day within in protocol of approximately 90 min to exclude diurnal variations. The measurements were performed by one of the authors with an experience of 3 years with the used measurement devices. To assess intra-rater reliability, all measurements were repeated five times. The protocol started with the Epionics SPINE measurements. For this, the patients were asked to undress the upper body as well as the feet, and to stand upright with the feet shoulder-width apart and the knees extended. This was defined as the standard leg position and standardized for inter-device comparisons by using two markers on the floor for foot positioning. After that relevant landmarks were identified and the hollow plasters were attached, according to the description in the subsection Epionics SPINE. This was followed by a two-minute rest period in relaxed sitting position. The measurement with Epionics SPINE was performed in five consecutive cycles starting with neutral upright standing and standard leg position, a subsequent maximum ventral flexion with the task to touch the ground with the fingertips or hands, when even possible while holding knees fully extended. This was followed by a maximum reclination with loosely hanging arms, head reclination and with persistent knee extension ending with a return to the neutral position. These procedure where performed five times consequently. After completion of five cycles, the plasters were removed and the patient rested for five minutes in sitting position. After this rest period, the patient was asked to return to the standardized neutral position; the markings were made according to the description of the subsection Idiag M360. After marking a two-minute resting period was taken in a sitting position. Afterwards the Idiag M360 measurements were performed in upright standing, ventral flexion and dorsal extension. Patients were asked to hold end position for about 30 s for measurement. This cycle was repeated five times. The measurements with Idiag M360 were followed by a rest period of five minutes in a relaxed sitting position. This was followed by five measurements using raster sterography (Formetric III). For this, patients had to step onto a measurement platform and position himself in an upright neutral position with his knees extended, whereupon the measurements were performed. After each measurement, the subject had to step off the measurement platform and step onto the platform again for the next measurement cycle. Five measurement cycles with Raster sterography were performed. Additionally the modified fingertip to floor distance (MFTF) was assessed once 25. For inter-device and sex comparisons, the mean values of the five measurements with each device were reported and taken into account.

Employed measurement devices. *Idiag M360.* The Idiag M360 is a hand-held computer-assisted electro-mechanical device that allows the assessment of the spinal shape using two rolling wheels that transfer the spinal contour via Bluetooth to a computer. For this, the tool is guided along the spine on the spinous processes starting at the C7 and ending at the caudal reference point or the top of the anal crease, respectively[15,19]. For the Idiag M360 measurements, the spinous process of C7, a reference point 2 cm below the connection line of the left and right PSIS and the top of the anal crease (approximately S3) were measured by cloth tape and marked by a skin pen. The Idiag M360 records the back length in step length of 1.3 mm. The 3D orientation of the measuring device is assigned to the specific location with a frequency of 150 Hz. By detecting the shape of each spinous processes, an imaginary line is drawn perpendicular to skin surface along each midline of the vertebrae, calculating lordotic angles between vertebrae as depicted in Fig. 1. In accordance with the measurement-guidelines, maximum upper body flexion and extension were performed with extended knees. During extension the arms were crossed in front of the body. The system's reliability was investigated previously. A more detailed description of the system can be found elsewhere[26,27].

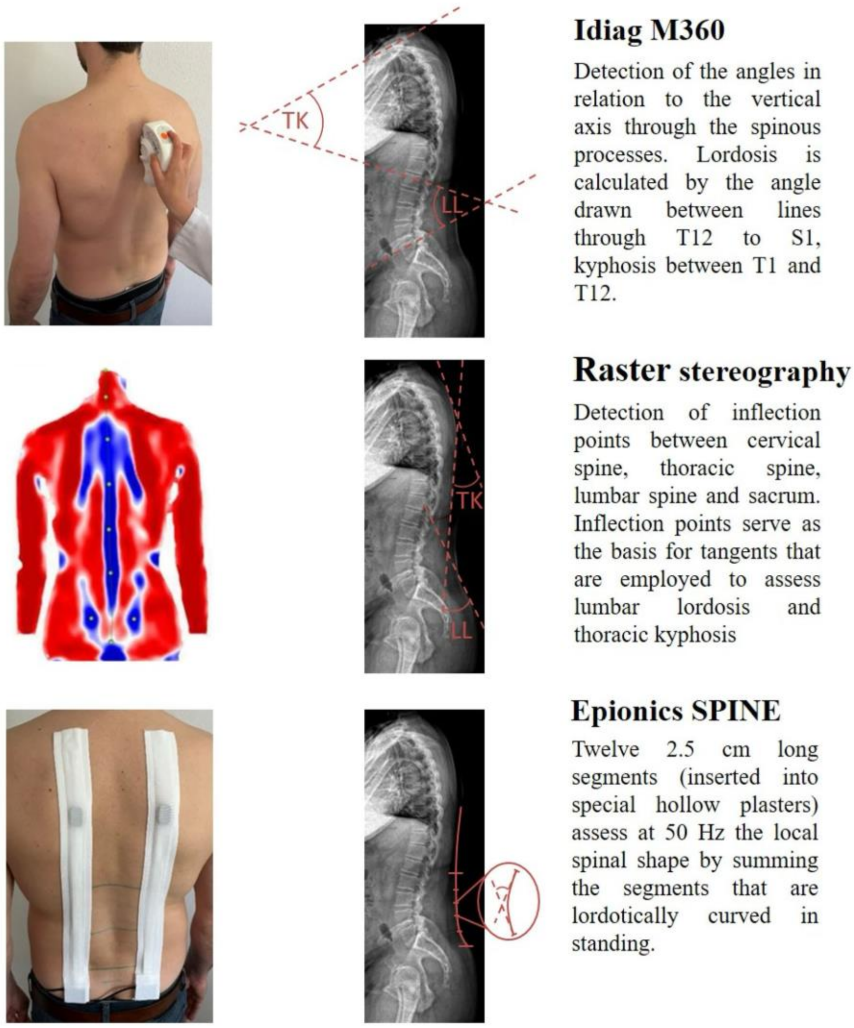

Figure 1. Comparison of the measurement devices and their definition for the lordosis and kyphotic angles.

Raster sterography (Formetric III). The raster stereography is a non-radiological photogrammetric method that bases on the principles of triangulation. A system of light-lines is projected onto the subject's back and subsequently distorted as a function of the three-dimensional back surface, with the aim to reconstruct the individual spinal shape[28,29]. The system is able to determine the inflection points between cervical spine, thoracic spine, lumbar spine and sacrum in the median sagittal plane as well as specific back surface landmarks such as the spinous process automatically. Therefore the spinous processus C7 is detected as the spinous process closest to the inflection point between thoracic kyphosis and cervical lordosis. These inflection points serve as the basis for tangents, which are employed to assess LL and TK as seen in Fig. 1. The system does not allow the determination of maximal range of flexion or range of extension during maximal upper body bending. In the present study, the measurement mode "3D-Average" was employed, which averages 30 measurements in 5 s to account for small posture variations. The system's reliability in particular for sagittal plane parameters was investigated previously[20–22] and a detailed description of the system can be found elsewhere[30,31].

Epionics SPINE. The Epionics SPINE uses strain-gauge measurement technology for the detection of back shape and motion. Two flexible sensor strips that consist of each twelve 2.5 cm long segments (inserted into

	Lordosis (95% CI)	Kyphosis (95% CI)	RoF (95% CI)	RoE (95% CI)	RoM (95% CI)
MediMouse	0.986 (0.976–0.993)	0.986 (0.976–0.993)	0.968 (0.946–0.983)	0.951 (0.916–0.974)	0.982 (0.969–0.991)
Raster stereography	0.989 (0.982–0.994)	0.968 (0.949–0.983)	–	–	–
Epionics Spine	0.988 (0.979–0.994)	–	0.999 (0.999–1.000)	0.988 (0.979–0.994)	0.993 (0.988–0.997)

Table 1. Intraclass correlation (ICC) between the five single measurements of each device for the investigated parameters. *CI* confidence interval, *RoM* range of motion, *RoF* range of flexion, *RoE* range of extension.

	Idiag M360	Raster stereography	Epionics SPINE	RM-ANOVA	Post hoc Bonferroni		
	Mean (SD)	Mean (SD)	Mean (SD)	p value	ID vs. RS	RS vs. ES	ES vs. ID
Lordosis (overall)	30.1 (8.7)	40.3 (8.4)	37.9 (7.9)	**< 0.001**	**< 0.001**	0.277	**< 0.001**
Male	25.9 (9.4)	37.6 (8.9)	34.6 (8.4)	**< 0.001**	**0.001**	0.559	**0.006**
Female	34.2 (5.6)	43.0 (7.1)	41.2 (5.9)	**< 0.001**	**0.001**	0.931	**0.001**
	Idiag M360	Raster stereography		t-test			
Kyphosis (overall)	43.3 (9.8)	44.4 (6.5)	–	0.343	–	–	–
Male	47.2 (10.1)	47.1 (6.1)	–	0.928	–	–	–
Female	39.4 (8.1)	41.7 (5.8)	–	0.131			

Table 2. Lumbar lordosis and thoracic kyphosis in upright standing for the entire study population (overall) as well as males and females separately. Significant differences (p value < 0.05) are marked in bold. *ID* Idiag M360, *RS* Raster stereography, *ES* epionics SPINE.

special hollow plasters) are placed standardized at a distance of 7.5 cm from the mid-sagittal plane with the lowest sensor segment positioned relative to the PSIS (approximately S1). Therefore, in agreement with the systems' measurement guidelines for Epionics SPINE the left and right posterior superior iliac spines (PSIS) were marked and horizontally connected. A distance of 7.5 cm from the mid-sagittal plane was measured by cloth tape at the connecting line between the PSIS as well as 10 and 25 cm more cranial from this connecting line on each side, to which the application of the hollow plasters were adjusted. The system assesses at 50 Hz the local spinal shape in each sensor segment of 2.5 cm length, from which the lordotically curved segments in standing are individually summed up to assess the LL as shown in Fig. 1. In accordance with the measurement-guidelines, the volunteers performed maximal upper body flexion and extension keeping the knees extended. The system's reliability was investigated previously[16] and a more detailed description of the system can be found elsewhere[32,33].

Statistical analysis. The intra-rater reliability (IRR) was evaluated by ICCs for each device to quantify the degree of agreement and was evaluated following Cicchetti[34–36]. Data were tested for normal distribution using the Kolmogorov–Smirnow test. The repeated measures analysis of variance (RM-ANOVA) with Bonferroni post hoc test and sex as a between-subjects factor was used to examine the influence of the three different devices and sex for LL. To detect statistical differences in each sex in LL a RM-ANOVA were performed in male and female separately. For comparison of TK between Idiag M360 and Raster stereography as well as comparison between RoM, RoF, RoE between Idiag M360 and Epionics SPINE paired samples t-test was used. For detection of sex differences for LL and TK unpaired t-test was performed. Correlations were observed by Pearson's correlation coefficient. A p value < 0.05 was considered as statistically significant.

Ethics approval. The Charité University Berlin Ethics Board (EA1/204/16) approved this study. Each participant gave written informed consent, for publication of images informed consent was obtained. All methods were performed in accordance with the Declarations of Helsinki.

Results

The Kolmogorov-Smirnow test demonstrated that LL, TK, RoF, RoE and RoM followed normal distribution for the entire cohort and for males and females separately.

Intra-rater reliability analysis and comparison with reference values. The intra-rater reliability for the five repetitions for all investigated parameters in each measurement device separately demonstrated excellent reliability, with ICC greater than 0.951 (range 0.951–0.999) (Table 1).

Lumbar lordosis. For the entire study population as well as for males and females separately, the assessed LL differed significantly between the three employed systems, with significantly smaller values determined by the Idiag M360 compared to the two other systems (Table 2). In RM-ANOVA accounting for different measurement devices and sex as a between-subjects factor, both measurement device ($p < 0.001$, ηp^2 (effect size) = 0.659) and sex ($p = 0.006$, ηp^2 (effect size) = 0.239) presented significant influence on LL, however no significant interaction between sex and measurement device on LL was observed ($p = 0.593$, ηp^2 (effect size) = 0.018). In agreement,

	Idiag M360 r (p value)	Raster stereography r (p value)	Epionics SPINE r (p value)	MFTF r (p value)
Lordosis				
Idiag M360	–	**0.54** (.002)	**0.61** (<.001)	–
Raster stereography	**0.54** (.002)	–	**0.56** (.001)	–
Epionics SPINE	**0.61** (<.001)	**0.56** (.002)	–	–
Kyphosis				
Idiag M360	–	**0.78** (<.001)	–	–
Raster stereography	**0.78** (<.001)	–	–	–
Epionics SPINE	–	–	–	–
RoF				
Idiag M360	–	–	**0.48** (.008)	0.05 (.815)
Raster stereography	–	–	–	–
Epionics SPINE	**0.48** (.008)	–	–	**0.42** (.022)
RoE				
Idiag M360	–	–	**0.53** (.002)	0.30 (.113)
Raster stereography	–	–	–	
Epionics SPINE	**0.53** (.002)	–	–	**0.54** (.002)
RoM				
Idiag M360	–	–	**0.47** (.009)	0.24 (.197)
Raster stereography	–	–	–	–
Epionics SPINE	**0.47** (.009)	–	–	**0.62** (<.001)

Table 3. Correlation (Pearson) between measurement data (mean values) obtained by the different devices and modified fingertip-to-floor distance; r = correlation coefficient; MFTF = fingertip to floor distance; all correlations that are statistically significant (p value < 0.05) are marked in bold.

all systems detected a larger lordosis in women compared to men. The absolute differences in lordosis between sexes differed between systems (Idiag M360: 8.8°; Raster stereography: 5.4°; Epionics SPINE: 6.6°) resulting in significant differences between sexes only for the Idiag M360 ($p = 0.007$, Cohen's $d = 1.072$) and Epionics SPINE ($p = 0.019$, Cohen's $d = 0.906$). Correlation analysis revealed a moderate correlation for the LL between systems with correlation coefficients between 0.54 and 0.61 (Table 3).

Thoracic kyphosis. The assessment of the thoracic kyphosis resulted in non-significant differences between Idiag M360 and raster stereography for the entire cohort as well as for males and females separately (Table 2). Consistently in both systems, the thoracic kyphosis was significantly larger in males than in females and differed significantly between sexes as detected by both systems ($p = 0.026$, Cohen's $d = 0.892$ for Idiag M360; $p = 0.021$, Cohen's $d = 0.859$ for raster stereography). Correlation between both systems revealed a high and significant correlation ($r = 0.78$) for the assessed kyphosis values (Table 3).

Lumbar range of flexion, range of extension, range of motion. For the entire study population, as well as for both sexes, the absolute values for RoF and RoE obtained with the Idiag M360 and Epionics Spine significantly differed from each other (Fig. 2, Table 4). The RoF was significantly larger, when obtained with the Idiag M360, whereas the RoE was significantly smaller, when measured with the Idiag M360. For the RoM, non-significant difference was obtained between systems. Consistently, both systems measured non-significant differences between males and females for the RoF ($p = 0.946$ Idiag M360, $p = 0.288$ Epionics SPINE), RoE ($p = 0.523$ Idiag M360, $p = 0.393$ Epionics SPINE) and RoM ($p = 0.616$ Idiag M360, $p = 0.229$ Epionics SPINE). For all three motion-parameters, a significant correlation between both systems was observed, ranging between $r = 0.47$ for the RoM to $r = 0.53$ for the RoE (Table 3).

Fingertip to floor distance (MFTF). The modified fingertip to floor distance was also correlated to the mobility values RoF, RoE and RoM. Moderate to good correlations ranging from 0.42 to 0.62 could be detected between the MFTF distance and the Epionics SPINE results, whereas correlations between MFTF distance and Idiag M360 were poor and non-significant (Table 3).

Discussion

The current gold standard for analysing patients' spinal shape and mobility are radiological x-rays. As during the documentation of patients' therapy progress, several repeated measurements are required, non-invasive measurement methods have become more and more significant, as they have the advantage of being radiation-free, enabling several measurements without any harm for the patient. However, the comparability of the measurement results of the devices against each other—even if a high intra- and interrater reliability is provided stays

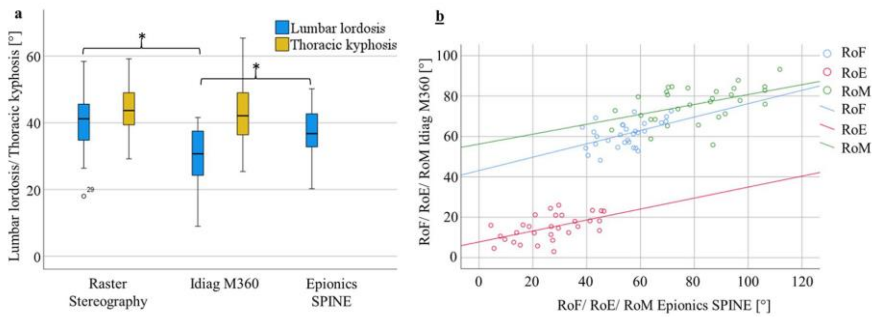

Figure 2. Plotted data for lumbar lordosis, thoracic kyphosis, RoF, RoE and RoM for each measurement device. (**a**) The measured lumbar lordosis (blue) and thoracic kyphosis (yellow) for each measurement device. (**b**) The range of flexion (RoF), extension (RoE) and range of motion (RoM) of the Idiag M360 and the Epionics SPINE. Significante differences are marked by asterisk.

	Idiag M360	Epionics SPINE	t-test
	Mean (SD)	Mean (SD)	p value
RoF (overall)	61.0 (6.3)	54.1 (9.2)	**<0.001**
Male	60.9 (7.4)	52.3 (11.1)	**0.002**
Female	61.1 (5.3)	55.9 (6.7)	**0.018**
RoE (overall)	14.9 (6.3)	26.4 (12.4)	**<0.001**
Male	14.2 (7.2)	24.4 (11.5)	**0.001**
Female	15.7 (5.4)	28.4 (13.3)	**0.001**
RoM (overall)	76.0 (8.9)	80.5 (16.9)	0.106
Male	75.1 (9.5)	76.7 (16.8)	0.691
Female	76.8 (8.4)	84.3 (16.8)	0.063

Table 4. Descriptive statistics (mean, standard deviation) for lumbar flexion and extension for the whole study population (overall) as well as males and females separately for Idiag M360 and Epionics SPINE. p values base on paired t-test.

elusive. The present study therefore aimed to analyze three commonly used non-invasive measurement systems, to investigate their correlation to each other and to test their comparability regarding resulting angles.

The results of the present study show that in general the results of the single devices are significantly correlated. However, significant differences in total values were detected for LL, RoF, RoE and RoM between Idiag M360 and Epionics SPINE as well as for TK between Idiag M360 and raster stereography. The obtained results for the lumbar lordosis in upright standing between Idiag M360 and raster stereography differed up to 33.8%. Therefore the measured angles obtained with one of the devices could be compared to the measurements of another one in a clinical setting just to a limited extent.

The three devices differed from each other in several factors which might have led to differences between the total values. For example, the Idiag M360 measures the spinal curvature directly on the mid-sagittal plane follow the spinous processes[37], while the Epionics SPINE system measures paravertebrally the muscle contour[16]. Moreover, the measured RoMs are not directly comparable as the Idiag M360, for example, examines flexion and extension in a static, full bended position where the subject has to hold the position for several seconds[37]. In contrast, Epionics SPINE captures movements while subjects perform the motion[16]. In addition, the devices differ in their definition of the lordotic and kyphotic angles[16,37].

One of the three above mentioned differences might also be responsible for the fact, that the Idiag M360 and the Epionics SPINE system detect absolute differences in lordosis and kyphosis between both sexes while the raster-stereography does not account for these sex specifics. Whereas the literature reports sex differences in LL, TK, RoF, RoE and RoM[38,39]. Moreover, the Idiag M360 detected significantly higher values for the RoF and significantly lower values for RoE compared to Epionics SPINE. These differences diminished when comparing the sum of RoF and RoE (= RoM). This result emphasizes that it is important to examine not only the total range of motion, which is often used in clinical assessment as the predominant parameter of spinal function, but to also investigate the amount of flexion and extension separately.

Differences between Idiag M360 and Epionics SPINE become also very obvious when correlating both measurements to the commonly used MFTF distance, which is a current clinical orientating parameter for assessing patients' flexibility[24]. Measurements of Epionics SPINE correlate quite well to MFTF, while those of Idiag M360 do not, emphasizing again differences in the measurement technique or the definition of the measured angle. However, the MFTF is dependent not only on trunk flexion but also on hip flexion and body proportions such as arm, hand and trunk length[25]. The obtained measurements for LL, flexion and extension by the Idiag M360[13,15,19] as by Epionics SPINE[20] were within the range of those reported in the literature. The results for thoracic kyphosis and LL in upright standing from raster stereography are also in line with the results reported for that device[40].

The measurement devices presented an excellent ICC of 0.951–0.999 in our study. While in the literature for the Idiag M360 an ICC of 0.57 up to 0.95 is reported[15,19], in our study an ICC of 0.951–0.986 was obtained. For the raster stereography the literature reports an ICC of 0.79–0.99 while we examined values of 0.968–0.989[20–22]. For the Epionics SPINE, we obtained an ICC of 0.993–0.999 while the literature reports values of 0.79–0.87[16]. The excellent ICC shown in our study compared to the literature could possibly have resulted from the execution in our study by a single investigator experienced with each of the measurement devices, the close time interval of our measurements with persistent skin markers (Idiag M360) or the remaining of the measurement instrument on the body between measurement cycles (Epionics SPINE) as well as the standardization of the body position between the measurements cycles of each measurement device. Additionally, the literature reports a strong relationship to radiographic measurements for the Idiag M360 as well as for raster stereography. Despite the good reliability the literature reports a strong relationship to radiographic imaging for Idiag M360[13,14] as well as for raster stereography[23].

The presented study had several limitations. To keep the influence of soft tissue on the measurement results low, only subjects were included who had a BMI < 27. The measurement differences between the systems, would possibly increase at higher BMIs, as Epionics SPINE measures directly on soft tissue and is thus stronger BMI influenced, while the Idiag M360 measures on the spinous processes and is thus lower BMI influenced. Furthermore, the order of measurements could not be randomized because, due to regular patient examinations, we had limited access to raster stereography. Age may also have an effect on the differences in measurement, as skin aging, and increased skin movability may have affected the procedures. We performed our analysis on patients without known spinal pathology, structural abnormalities or back pain, which might result in limited transferability to the evaluation of patients with low back pain. The measurements in our study were performed by a single rater with repeated measurements. Despite the high ICC for intra- and inter-rater reliability reported in the literature, this may limit the transferability of our study to repeated diagnostics by different investigators. Although a good reliability was shown for each single measurement devise, differences in the measurement outcome can be caused by the different measurement techniques when using several devices on one patient making therapy progress hard to evaluate or falsify the therapy effects altogether.

It can be concluded that the three used measurement devices with the advantage over X-ray not to expose the subjects to radiation differ to some extent in their exact outcome. Therefore, the interpretation and comparability of the results stays challenging. A significant correlation of total values against radiological imaging is described for both Idiag M360 and raster stereography measurements, however, analyses of the total statistical agreement between radiographic imaging and non-radiographic measurement tools are lacking[13,23]. Accordingly, the non-radiological measurement instruments should be used less as an instrument for the primary detection of pathologies but X-ray measurements can be supplemented by one of the three described methods, which, due to their high reliability, may reduce the frequency of radiographic follow-up examinations. The choice, which measurement method should be used, depends on the individual indication for the follow-up examinations. The Idiag M360 and raster stereography are static measurements that are well suited for monitoring the back profile and scoliosis progression. The Idiag M360 can also be used to assess the RoM. Epionics SPINE allow statements to be made about the long- and short-term back functionality as well as the back profile in daily activities. Due to the dynamic measurement, the movement sequence can be described precisely. However, for long-term evaluation of the back profile, inter-modal comparison of values between different non-invasive devices should be avoided.

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References

1. Freburger, J. K. *et al.* The rising prevalence of chronic low back pain. *Arch. Intern. Med.* **169**, 251–258. https://doi.org/10.1001/archinternmed.2008.543 (2009).
2. Dieleman, J. L. *et al.* US health care spending by payer and health condition, 1996–2016. *JAMA* **323**, 863–884. https://doi.org/10.1001/jama.2020.0734 (2020).
3. Foster, N. E. *et al.* Prevention and treatment of low back pain: Evidence, challenges, and promising directions. *Lancet* **391**, 2368–2383. https://doi.org/10.1016/S0140-6736(18)30489-6 (2018).
4. Taimela, S., Kujala, U. M., Salminen, J. J. & Viljanen, T. The prevalence of low back pain among children and adolescents. A nationwide, cohort-based questionnaire survey in Finland. *Spine (Phila Pa 1976)* **22**, 1132–1136. https://doi.org/10.1097/00007632-199705150-00013 (1997).
5. Calvo-Munoz, I., Gomez-Conesa, A. & Sanchez-Meca, J. Prevalence of low back pain in children and adolescents: A meta-analysis. *BMC Pediatr.* **13**, 14. https://doi.org/10.1186/1471-2431-13-14 (2013).
6. Nattrass, C. L., Nitschke, J. E., Disler, P. B., Chou, M. J. & Ooi, K. T. Lumbar spine range of motion as a measure of physical and functional impairment: An investigation of validity. *Clin. Rehabil.* **13**, 211–218. https://doi.org/10.1177/026921559901300305 (1999).
7. Tsushima, H., Morris, M. E. & McGinley, J. Test-retest reliability and inter-tester reliability of kinematic data from a three-dimensional gait analysis system. *J. Jpn. Phys. Ther. Assoc.* **6**, 9–17. https://doi.org/10.1298/jjpta.6.9 (2003).
8. Cagnie, B., Cools, A., De Loose, V., Cambier, D. & Danneels, L. Reliability and normative database of the Zebris cervical range-of-motion system in healthy controls with preliminary validation in a group of patients with neck pain. *J. Manipulative Physiol. Ther.* **30**, 450–455. https://doi.org/10.1016/j.jmpt.2007.05.003 (2007).
9. Wunderlich, M. *et al.* A new approach to assess movements and isometric postures of spine and trunk at the workplace. *Eur. Spine J.* **20**, 1393–1402. https://doi.org/10.1007/s00586-011-1777-7 (2011).

10. Hamacher, D., Bertram, D., Folsch, C. & Schega, L. Evaluation of a visual feedback system in gait retraining: A pilot study. *Gait Posture* **36**, 182–186. https://doi.org/10.1016/j.gaitpost.2012.02.012 (2012).
11. Gill, K. P. & Callaghan, M. J. Intratester and intertester reproducibility of the lumbar motion monitor as a measure of range, velocity and acceleration of the thoracolumbar spine. *Clin. Biomech. (Bristol, Avon)* **11**, 418–421. https://doi.org/10.1016/0268-0033(96)00031-9 (1996).
12. Schiefer, C. *et al.* Optimization of inertial sensor-based motion capturing for magnetically distorted field applications. *J. Biomech. Eng.* **136**, 121008. https://doi.org/10.1115/1.4028822 (2014).
13. Guermazi, M. *et al.* Validity and reliability of Spinal Mouse to assess lumbar flexion. *Ann. Readapt. Med. Phys.* **49**, 172–177. https://doi.org/10.1016/j.annrmp.2006.03.001 (2006).
14. Livanelioglu, A., Kaya, F., Nabiyev, V., Demirkiran, G. & Firat, T. The validity and reliability of "Spinal Mouse" assessment of spinal curvatures in the frontal plane in pediatric adolescent idiopathic thoraco-lumbar curves. *Eur. Spine J.* **25**, 476–482. https://doi.org/10.1007/s00586-015-3945-7 (2016).
15. Post, R. B. & Leferink, V. J. Spinal mobility: Sagittal range of motion measured with the SpinalMouse, a new non-invasive device. *Arch. Orthop. Trauma Surg.* **124**, 187–192. https://doi.org/10.1007/s00402-004-0641-1 (2004).
16. Consmuller, T. *et al.* Comparative evaluation of a novel measurement tool to assess lumbar spine posture and range of motion. *Eur. Spine J.* **21**, 2170–2180. https://doi.org/10.1007/s00586-012-2312-1 (2012).
17. Degenhardt, B. F., Starks, Z. & Bhatia, S. Reliability of the DIERS formetric 4D spine shape parameters in adults without postural deformities. *Biomed. Res. Int.* **2020**, 1796247. https://doi.org/10.1155/2020/1796247 (2020).
18. Ohlendorf, D. *et al.* Standard reference values of the upper body posture in healthy male adults aged between 41 and 50 years in Germany. *Sci. Rep.* **10**, 3823. https://doi.org/10.1038/s41598-020-60813-w (2020).
19. Mannion, A. F., Knecht, K., Balaban, G., Dvorak, J. & Grob, D. A new skin-surface device for measuring the curvature and global and segmental ranges of motion of the spine: Reliability of measurements and comparison with data reviewed from the literature. *Eur. Spine J.* **13**, 122–136. https://doi.org/10.1007/s00586-003-0618-8 (2004).
20. Guidetti, L. *et al.* Intra- and interday reliability of spine rasterstereography. *Biomed. Res. Int.* **2013**, 745480. https://doi.org/10.1155/2013/745480 (2013).
21. Mohokum, M. *et al.* Reproducibility of rasterstereography for kyphotic and lordotic angles, trunk length, and trunk inclination: A reliability study (vol 35, pg 1353, 2010). *Spine* **35**, 1738–1738. https://doi.org/10.1097/BRS.0b013e3181eeb243 (2010).
22. Betsch, M. *et al.* Reliability and validity of 4D rasterstereography under dynamic conditions. *Comput. Biol. Med.* **41**, 308–312. https://doi.org/10.1016/j.compbiomed.2011.03.008 (2011).
23. Schulte, T. L. *et al.* Raster stereography versus radiography in the long-term follow-up of idiopathic scoliosis. *J. Spinal Disord. Tech.* **21**, 23–28. https://doi.org/10.1097/BSD.0b013e318057529b (2008).
24. Perret, C. *et al.* Validity, reliability, and responsiveness of the fingertip-to-floor test. *Arch. Phys. Med. Rehabil.* **82**, 1566–1570. https://doi.org/10.1053/apmr.2001.26064 (2001).
25. Gauvin, M. G., Riddle, D. L. & Rothstein, J. M. Reliability of clinical measurements of forward bending using the modified fingertip-to-floor method. *Phys. Ther.* **70**, 443–447. https://doi.org/10.1093/ptj/70.7.443 (1990).
26. Topalidou, A., Tzagarakis, G., Souvatzis, X., Kontakis, G. & Katonis, P. Evaluation of the reliability of a new non-invasive method for assessing the functionality and mobility of the spine. *Acta Bioeng. Biomech. Wroclaw Univ. Technol.* **16**, 117–124 (2014).
27. Barrett, E., McCreesh, K. & Lewis, J. Reliability and validity of non-radiographic methods of thoracic kyphosis measurement: A systematic review. *Man. Ther.* **19**, 10–17. https://doi.org/10.1016/j.math.2013.09.003 (2014).
28. Drerup, B. & Hierholzer, E. Objective determination of anatomical landmarks on the body-surface—measurement of the vertebra prominens from surface curvature. *J. Biomech.* **18**, 467. https://doi.org/10.1016/0021-9290(85)90282-9 (1985).
29. Drerup, B. & Hierholzer, E. Automatic localization of anatomical landmarks on the back surface and construction of a body-fixed coordinate system. *J. Biomech.* **20**, 961–970. https://doi.org/10.1016/0021-9290(87)90325-3 (1987).
30. Drerup, B. & Hierholzer, E. Objective determination of anatomical landmarks on the body surface: Measurement of the vertebra prominens from surface curvature. *J. Biomech.* **18**, 467–474 (1985).
31. Frobin, W. & Hierholzer, E. Analysis of human back shape using surface curvatures. *J. Biomech.* **15**, 379–390 (1982).
32. Consmuller, T. *et al.* Velocity of lordosis angle during spinal flexion and extension. *PLoS One* **7**, e50135. https://doi.org/10.1371/journal.pone.0050135 (2012).
33. Taylor, W. R., Consmuller, T. & Rohlmann, A. A novel system for the dynamic assessment of back shape. *Med. Eng. Phys.* **32**, 1080–1083. https://doi.org/10.1016/j.medengphy.2010.07.011 (2010).
34. McGraw, K. O. & Wong, S. P. Forming inferences about some intraclass correlation coefficients. *Psychol. Methods* **1**(1), 30–46. https://doi.org/10.1037/1082-989X.1.1.30 (1996).
35. Shrout, P. E. & Fleiss, J. L. Intraclass correlations: Uses in assessing rater reliability. *Psychol. Bull.* **86**, 420–428. https://doi.org/10.1037//0033-2909.86.2.420 (1979).
36. Cicchetti, D. V. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol. Assess.* **6**, 284–290. https://doi.org/10.1037/1040-3590.6.4.284 (1994).
37. Seichert, N., Baumann, M., Senn, E. & Zuckriegl, H. Die Rückenmaus - Ein analog-digitales Meßgerät zur Erfassung der sagittalen Rückenkontur. *Phys. Med. Rehabil. Kurortmedizin* **04**, 35–43 (1994).
38. Arshad, R., Pan, F., Reitmaier, S. & Schmidt, H. Effect of age and sex on lumbar lordosis and the range of motion. A systematic review and meta-analysis. *J. Biomech.* **82**, 1–19. https://doi.org/10.1016/j.jbiomech.2018.11.022 (2019).
39. Asai, Y. *et al.* Sagittal spino-pelvic alignment in adults: The Wakayama Spine Study. *PLoS One* **12**, e0178697. https://doi.org/10.1371/journal.pone.0178697 (2017).
40. Schroeder, J., Reer, R. & Braumann, K. M. Video raster stereography back shape reconstruction: A reliability study for sagittal, frontal, and transversal plane parameters. *Eur. Spine J.* **24**, 262–269. https://doi.org/10.1007/s00586-014-3664-5 (2015).

Author contributions

B.D. (conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing original draft).E.K. (data curation, formal analysis, investigation, methodology, writing original draft). M.D. (conceptualization, data curation, formal analysis, investigation, methodology, writing original draft). H.S. (conzeptualization, project administration, resources, writing—review and editing). M.P. (project administration, resources, writing—review and editing). L.B. (project administration, writing—review and editing).

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2.3 Einfluss von lumbo-sacralen Übergangsstörungen auf die Rückenfunktion

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Lumbosacral transitional vertebrae alter the distribution of lumbar mobility-Preliminary results of a radiographic evaluation.

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Die Rückenfunktion wird sowohl durch Degeneration als auch Formveränderungen beeinflusst [97-101]. Lumbo-sacrale Übergangsstörungen sind mit einer erhöhten Degenerationshäufigkeit im kranialen Nachbarsegment verbunden [52, 66]. Hypermobilität und damit einhergehende erhöhte Belastungen werden als mögliche Ursache für die segmentale Degeneration diskutiert.

In einer retrospektiven nach Alter und Geschlecht gematchten Analyse beurteilten wir daher die lumbale sowie segmentale Bewegung von 17 Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung gegenüber einem Kontrollkollektiv anhand von Flexions- sowie Extensionsaufnahmen der Lendenwirbelsäule. Dabei wurden die Bewegung der lumbalen Lordose, der Segmentwinkel sowie der Bandscheibenwinkel aller lumbalen Segmente bestimmt.

Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung wiesen keine signifikant verringerte Bewegung der Gesamtlendenwirbelsäule auf (p=0,065). Lumbo-sacrale Übergangsstörungen verringerten die segmentale Bewegung im Übergangssegment jedoch signifikant (p=0,003). Die Verteilung der lumbalen Bewegung unterschied sich signifikant: während die relative Bewegung im Übergangssegment vermindert war (p=0,002), war sie im kranialen Anschlusssegment signifikant erhöht (p=0,007).

Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung zeigen in Flexions- und Extensions-Röntgenaufnahmen eine reduzierte Bewegung im Übergangssegment und eine signifikant erhöhte Bewegungsverteilung auf das kraniale Nachbarsegment. Der erhöhte Anteil der Mobilität im kranialen Nachbarsegment trägt möglicherweise zu höheren Degenerationsraten innerhalb des Segments bei.

PLOS ONE

RESEARCH ARTICLE

Lumbosacral transitional vertebrae alter the distribution of lumbar mobility–Preliminary results of a radiographic evaluation

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Abstract

Background

Lumbo-sacral transitional vertebrae (LSTV) are one of the most common congenital variances of the spine. They are associated with an increased frequency of degeneration in the cranial adjacent segment. Hypermobility and concomitant increased loads are discussed as a possible reason for segmental degeneration. We therefore examined the lumbar and segmental motion distribution in patients with LSTV with flexion-extension radiographs.

Methods

A retrospective study of 51 patients with osteochondrosis L5/S1 with flexion and extension radiographs was performed. Of these, 17 patients had LSTV and were matched 1:1 for age and sex with patients without LSTV out of the collective of the remaining 34 patients. The lumbar and segmental range of motion (RoM) by segmental lordosis angle and the segmental wedge angle were determined. Normal distribution of parameters was observed by Kolmogorov-Smirnov-test. Parametric data were compared by paired T-test. Non-parametric data were compared by Wilcoxon-rank-sum-test. Correlations were observed using Spearman's Rank correlation coefficient. A p-value <0.05 was stated as statistically significant.

Results

Patients with LSTV had mean age of 52.2±10.9, control group of 48.9±10.3. Both groups included 7 females and 10 males. Patients with LSTV presented with reduced RoM of the lumbar spine (LSTV 37.3˚±19.2˚, control 52.1˚±20.5˚, p = 0.065), however effects were statistically insignificant. LSTV significantly decreased segmental RoM in the transitional segment (LSTV 1.8˚±2.7˚, control 6.7˚±6.0˚, p = 0.003). Lumbar motion distribution differed significantly; while RoM was decreased in the transitional segment, (LSTV 5.7%, control 16.2%, p = 0.002), the distribution of lumbar motion to the cranial adjacent segment was increased (LSTV 30.7%, control 21.6%, p = 0.007).

Conclusion

Patients with LSTV show a reduced RoM in the transitional segment and a significantly increased motion distribution to the cranial adjacent segment in flexion-extension radiographs. The increased proportion of mobility in the cranial adjacent segment possibly explain the higher rates of degeneration within the segment.

Introduction

Lumbo-sacral transitional vertebrae (LSTV) are one of the most common congenital anomalies of the spine with a reported prevalence of 9.9–29% in large scale studies of general population [1–4]. LSTV are classified according to Castellvi, assessing the enlargement and fusion of the processus transversus with the sacral ala [5]. The association between LSTV and back pain was first reported by Bertolotti probably caused by a pseudarthrosis between the widened processus transversus and the sacral bone and a consecutive irritation at the contact area [6]. In addition, extraspinal nerve compression through the widened processus transversus has been described [7]. An increased degeneration of the cranially adjacent segment to the LSTV is also suspected to be a reason for back pain in patients with LSTV. There is a consensus in the literature regarding increased disc degeneration [8–12] and a higher incidence of facet joint degeneration and neuroforaminal stenosis in the cranial segment adjacent to LSTV [11, 12] may be caused by an altered load transfer [6, 10, 13]. A possible instability of the vertebral segment above the transitional vertebra caused by a weak iliolumbar ligament could lead to subsequent disc degeneration. A reduced mobility between the transitional vertebra and the sacrum could be preserved by the formation of either an articulation or by bony union between the vertebra and the sacrum through its transverse process [10]. Furthermore, a reduced mobility of the transitional segment is discussed and attributed to an increased osseous connectivity of the transversal process of the LSTV with the sacral ala with a compensatory hypermobility of the cranially adjacent segment [6, 13]. The results are mainly based on in vitro analyses, whose used protocols have never been validated against in vivo kinematic data. Whereas in vitro studies before and after segmental fusion presume the same overall mobility of the lumbar spine, in vivo studies show that patients after spinal fusion rather decreased the motion of the whole lumbar spine, and thus protect the adjacent segment to fusion from increased mobility [14, 15].

To date, there is a lack of motion analyses of patients with LSTV describing the mobility in the LSTV segment as well as the cranially adjacent segments in vivo. Therefore, the aim of this study was to investigate the mobility of the lumbar spine and segmental motion distribution of patients with LSTV in flexion-extension radiographs.

Methods

Patient cohort

This study was performed as retrospective matched-pair analysis. The institutional ethics committee of the Charité University Berlin (EA4/155/21) approved the study. Informed consent from the patients was waived due to the retrospective study design according to ethics committee approval. The study was carried out according to the declaration of Helsinki. We included patients who were evaluated as part of the preoperative preparation for anterior lumbar interbody fusion from 01/2016 to 05/2021 with flexion and extension imaging of the lumbar spine as a consecutive case series due to osteochondrosis L5/S1. We included patients older than 18 years of age. Exclusion criteria were scoliosis with a Cobb angle >20˚, spondylolisthesis, previous spondylodesis, suspected spondylodiscitis, lack of preoperative full spine radiographs in the standing position or flexion and extension radiographs. Fifty-one patients were finally included, 17 had LSTV (33.3%). These were matched 1:1 for age and sex with a control group without LSTV out of the remaining 34 patients.

Classification

LSTV were classified according to Castellvi by both an orthopedic resident surgeon with three years of experience as well as a spine surgeon with eleven years of experience. Classification according to Castellvi is given in Table 1. Phönix-PACS software (Phönix-PACS GmbH, Freiburg im Breisgau, Germany) was used for measurements. The number of lumbar vertebral bodies was classified by counting caudally from C1 in whole-spine images. For the cervical spine, seven vertebrae were assumed, and twelve for the thoracic spine. L1 was defined as the 20th vertebra. We assumed six lumbar vertebrae if we counted 25 vertebrae with an at least rudimentary disc in between. Therefore, in cases of six lumbar vertebrae the transitional segment was level L6/S1, in all other cases the transitional segment was L5/S1. The cranially adjacent segment was consequently in patients with six lumbar vertebrae segment L5/6, in all other patients L4/5.

Image acquisition and measurements

Full spine radiographs were obtained using biplanar low dose stereoradiography (EOS, Paris, France) from lateral and anterior posterior in standing position. Functional images were obtained with lateral X-ray trajectory as ventral flexion and dorsal extension. Ventral flexion and dorsal extension were acquired in standing position and the patient was instructed to fully flex/extend the spine, while a bar limited tilting of the pelvis.

All parameters were measured by two of the authors. Lumbar lordosis (LL) was measured as the angle of the L1 upper endplate to the S1 upper endplate. Segmental wedge angles were measured between the upper endplate of the lower vertebral body and the lower endplate of the upper vertebral body as depicted in Fig 1A. Segmental lordosis angles were measured between the upper endplate of the upper vertebral body and the lower endplate of the lower vertebral body as shown in Fig 1B. For the lowest segment, segmental lordosis angle was measured between S1 upper endplate and upper endplate L5 or L6. Measurements were performed independently by two orthopedic resident surgeons with three years and two years of experience, after being trained by a spine surgeon with eleven years of experience. The range of motion was calculated as the sum of kyphosis in flexion and increased lordosis in extension. The segmental contribution to the total lumbar motion was determined by the percentages of the total sum of the range of motion of all lumbar segments.

Table 1. Radiographic classification for lumbosacral transitional vertebrae (LSTV) according to Castellvi [5].

Castellvi Type	Definition
Type I: dysplastic transverse process	Uni- (A) or bilateral (B) transverse process with a height >19 mm
Type II: incomplete lumbarization/ sacralization	Uni- (A) or bilateral (B) pseudarthrosis of the enlarged transverse process with the sacral ala
Type III: complete lumbarization/ sacralization	Uni- (A) or bilateral (B) bony fusion of the enlarged transverse process with the sacral ala
Type IV: mixed	Unilateral pseudarthrosis and contralateral bony fusion of the enlarged transversal process with the sacral ala

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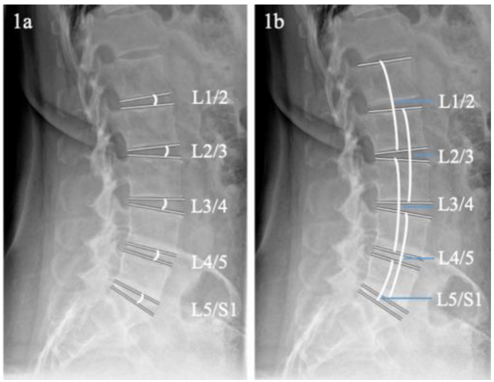

Fig 1. Measurement of segmental wedge angle and segmental lordosis angle. a. shows the measurement of the segmental wedge angle of the lumbar segments. b. depicts the measurement of the segmental lordosis angle.

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In Fig 2 an example of flexion-extension radiographs of a participant with Castellvi IIb and reduced mobility in transitional segment and enhanced mobility in the cranial adjacent segment is given.

Statistics

Statistical analyses were performed using SPSS Version 27 (IBM Corporation, New York, USA). The Kolmogorov-Smirnov test was used to test the data for normal distribution. For statistical analysis of parametric paired data, the paired T test was used. For nonparametric paired data, the Wilcoxon rank sum test was used. For testing correlations, Pearson's correlation

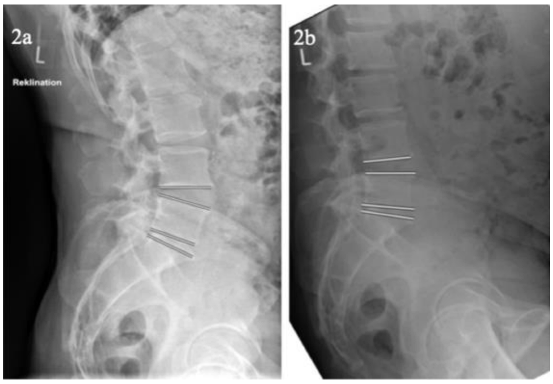

Fig 2. Example of a patient with reduced mobility in transitional segment L5/S1 and compensatory enhanced mobility in the cranial adjacent segment. a. depicts the dorsal trunk extension with increased segmental and lumbar lordosis, which results mostly of the cranially adjacent segment to the transitional segment L5/S1 in this participant. b. depicts the ventral trunk flexion with reduced segmental and lumbar lordosis.

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coefficient was used for parametric data. Spearman's correlation coefficient was used for non-parametric data. The significance level was set at $p < 0.05$ for all tests. Interrater reliability between the two raters for quantitative data was tested using intraclass coefficient, for categorial data by Cohens kappa.

Results

Demographics

The cohort of patients with LSTV had a mean age of 52.2 years (range 29–74 years), matched control group 48.9 years (range 36–71 years). Both groups included seven females and ten males. Four patients of the 17 patients with LSTV had six lumbar vertebrae (6LV). One of the 17 patients with LSTV had four free lumbar vertebrae (4LV). Four out of the 17 patients with LSTV had a transitional vertebra Castellvi I, nine had an LSTV Castellvi II, three had an LSTV Castellvi III and one patient had an LSTV Castellvi IV. An excellent interrater reliability for the grading of LSTV according to Castellvi with kappa of 0.924 ($p<0.001$) was observed. A high degree of reliability was found for the measurements of lumbar lordosis, segmental wedge angles and segmental lordosis between the two observers. The resulting interclass correlation coefficient was 0.971 with a 95% confidence interval from 0.968 to 0.975 ($p<0.001$).

Lumbar motion

Patients with LSTV and the control group did not differ significantly in lumbar lordosis in the upright standing position (p = 0.875). No significant differences were found between patients with LSTV and the control group for lumbar RoM (p = 0.065) if it was evaluated as Cobb angle from L1 upper endplate to S1-endplate. Also when looking separately to ventral flexion (p = 0.083) and dorsal extension (p = 0.426) no differences could be detected for measurement from L1 upper endplate to S1 upper endplate. Considering the motion resulting from disc deformation measured by summed segmental wedge angles, patients with LSTV presented reduced lumbar RoM (p = 0.022) resulting from reduced lumbar flexion (p = 0.017). However, lumbar extension was not reduced compared to the control group (p = 0.535). Lumbar movement is presented in Table 2.

In Table 2 the mean and standard deviation of lumbar lordosis in upright standing position, ventral flexion, dorsal extension is presented of patients with LSTV and control group. The lumbar range of motion was calculated as the sum of extension and flexion. The lumbar lordosis, flexion and extension of the lumbar wedge angles was calculated as the sum of movement in each lumbar disc. SD = standard deviation, RoM = range of motion. Level of significance was set at 0.05.

Segmental mobility

Patients with LSTV showed significantly reduced motion between the transitional segment and the segment L5/S1 (RoM L5/S1) compared to the control group looking at the movement

Table 2. Lumbar lordosis and range of motion in patients with LSTV and control group.

	S1-endplate to L1 upper endplate			Segmental wedge angle		
	LSTV Mean (SD)	**Control Mean (SD)**	**p-value**	**LSTV Mean (SD)**	**Control Mean (SD)**	**p-value**
Lumbar lordosis [˚]	43.7 (±7.2)	43.8 (±11.6)	0.875	43.7 (±7.2)	43.8 (±11.6)	0.875
RoM flexion [˚]	32.0 (±16.5)	44.1 (±19.2)	0.083	20.5 (±9.4)	30.7 (±13.5)	**0.017**
RoM extension [˚]	5.3 (±8.2)	8.0 (±8.6)	0.426	13.4 (±5.0)	15.0 (±6.8)	0.535
Lumbar RoM [˚]	37.3 (±19.2)	52.1 (±20.5)	0.065	33.9 (±11.0)	45.8 (±14.8)	**0.022**

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from disc deformation measured as the segmental wedge angle (p<0.001). This reduced segmental RoM resulted for segmental wedge angle from significantly reduced ventral flexion (p = 0.007) as well as dorsal extension (p = 0.001).

Looking at the segmental lordosis angle a reduced RoM in the transitional segment compared to control group was also detected (p = 0.035). For segmental lordosis angle the reduced RoM mainly resulted of significantly reduced dorsal extension (p = 0.043) whereas ventral flexion (p = 0.068) presented insignificant differences.

In the two cranial segments adjacent to the transitional segment, patients with LSTV did not differ significantly in their range of motion from the control group in segmental wedge angle (L4/5 p = 0.666, L3/4 p = 0.210) as well as in segmental lordosis angle (L4/5 p = 0.117, L3/4 p = 0.096). In the two most cranial lumbar segments, patients with LSTV showed significantly reduced range of motion for both segmental wedge angle (L2/3 p = 0.025, L1/2 p = 0.015) and segmental lordosis angle (L2/3 p = 0.028, L1/2 p = 0.004). The segmental mobility is shown in Table 3, segmental range of motion is presented in Fig 3.

Table 3 gives the segmental movement in flexion and extension with the segmental wedge angles and the segmental lordosis angles of the lumbar spine. In the segment L5/S1-LSTV the motion of the transitional segment or in the absence of LSTV the motion of the segment L5/S1 was shown. The range of motion of each segment was determined based on the sum of the flexion and extension. LSTV = lumbo-sacral transitional vertebra, SD = standard deviation, RoM = range of motion, Flex. = ventral flexion, Ext. = dorsal extension. Level of significance was set at 0.05. Significant values are marked in bold.

Distribution of lumbar mobility

Patients with LSTV differed significantly from the control group in the distribution of segmental mobility. While in patients without LSTV 16.2% of the total lumbar RoM–measured as a sum of all segmental wedge angles occurred in the segment L5/S1, in patients with LSTV 5.7% of the lumbar mobility resulted from the transitional segment (p = 0.002) as shown in Table 4. In contrast, in patients with LSTV 30.7% of lumbar motility resulted from the cranial adjacent segment to the LSTV, whereas in the control group, 21.6% of the lumbar flexibility resulted

Table 3. Segmental lumbar lordosis range of motion in patients with LSTV and control group.

	Segmental wedge angle			Segmental lordosis angle		
	LSTV mean (SD)	**Control mean (SD)**	**p-value**	**LSTV mean (SD)**	**Control mean (SD)**	**p-value**
Flex. Trans. Seg./ L5/S1 [˚]	0.8 (±2.0)	3.2 (±3.3)	**0.007**	2.3 (±3.5)	5.0 (±5.4)	0.068
Ext. Trans. Seg./ L5/S1 [˚]	0.8 (±1.0)	4.0 (±2.9)	**0.001**	2.2 (±2.2)	4.1 (±2.8)	**0.043**
RoM Trans. Seg./ L5/S1 [˚]	1.7 (±1.9)	7.2 (±5.1)	**<0.001**	4.5 (±5.0)	9.1 (±6.4)	**0.035**
Flex. L4/5 [˚]	6.1 (±3.4)	7.4 (±4.1)	0.382	8.8 (±5.5)	10.7 (±5.5)	0.316
Ext. L4/5 [˚]	3.3 (±2.1)	2.7 (±2.1)	0.530	3.1 (±2.7)	4.3 (±3.3)	0.243
RoM L4/5 [˚]	9.4 (±2.7)	10.1 (±4.6)	0.666	11.9 (±4.8)	15.0 (±5.7)	0.117
Flex. L3/4 [˚]	5.0 (±4.1)	6.9 (±4.0)	0.210	7.1 (±3.9)	9.9 (±6.0)	0.162
Ext. L3/4 [˚]	2.8 (±2.5)	2.6 (±1.7)	0.981	1.8 (±2.4)	2.2 (±3.4)	0.660
RoM L3/4 [˚]	7.7 (±4.1)	9.5 (±4.2)	0.210	8.9 (±3.3)	12.1 (±6.7)	0.096
Flex. L2/3 [˚]	4.2 (±3.8)	6.9 (±4.3)	**0.047**	6.1 (±3.1)	8.3 (±4.6)	0.081
Ext. L2/3 [˚]	2.7 (±2.3)	2.9 (±2.3)	0.801	2.6 (±2.8)	3.3 (±2.1)	0.309
RoM L2/3 [˚]	6.9 (±2.8)	9.9 (±3.5)	**0.025**	8.7 (±3.6)	11.6 (±4.1)	**0.035**
Flex. L1/2 [˚]	3.1 (±2.6)	6.1 (±3.6)	**0.015**	4.7 (±3.0)	6.4 (±3.4)	0.177
Ext. L1/2 [˚]	2.8 (±2.0)	3.2 (±2.4)	0.643	2.6 (±3.2)	5.4 (±2.2)	**0.006**
RoM L1/2 [˚]	5.9 (±2.6)	9.3 (±4.2)	**0.015**	7.3 (±3.6)	11.7 (±4.6)	**0.004**

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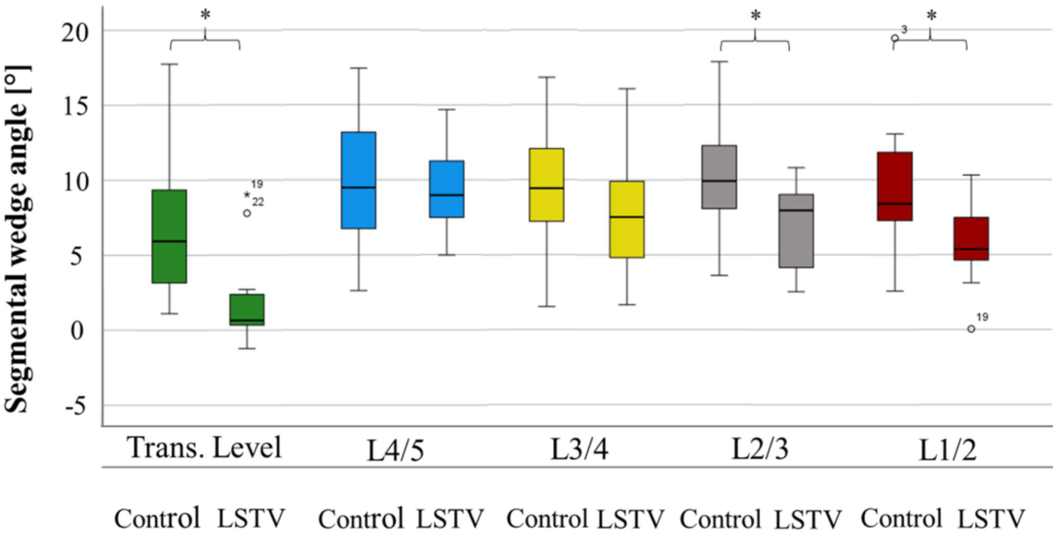

Fig 3. Segmental range of motion. Fig 3 compares the segmental range of motion based on the difference between segmental wedge angles in maximum ventral flexion and dorsal extension (Δ) of patients with LSTV and the control group. In the transitional segment, the range of motion between patients with LSTV and the control group differs significantly as well as in the L1/2 and L2/3 segment. Trans. Level = transitional vertebra level or level L5/S1 in patients without LSTV, Control = control group, LSTV = patient group with lumbosacral transitional vertebrae. The significance level was set at 0.05. Significant values are marked with an asterisk.

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from the segment L4/5 (p = 0.007). In the upper lumbar segments L1/2 (p = 0.943), L2/3 (p = 0.723) and L3/4 (p = 0.266) patients with LSTV and the control group did not differ significantly in distribution of lumbar mobility.

Table 4 shows the relative segmental lordosis based on the segmental wedge angle. Patients with LSTV have significantly reduced proportion of lumbar flexibility in the transitional segment and increased mobility in the cranial adjacent segment compared to the control group, whereas no differences was detected for the other lumbar segments.

Influence of Castellvi grading of LSTV on segmental mobility

Expression and grading of LSTV, classified according to Castellvi, did not correlate significantly with a reduced absolute mobility in the transitional segment (p = 0.862, r = -0.046) nor with extended motion in the cranial adjacent segment (p = 0.674, r = -0.110).

Table 4. Distribution of lumbar mobility to lumbar segments.

	LSTV	Control group	p-value
Transitional Segment/ L5/S1	5.7%	16.2%	**0.002**
Cranial adjacent segment/ L4/5	30.7%	21.6%	**0.007**
L3/4	23.4%	20.4%	0.266
L2/3	21.4%	21.7%	0.723
L1/2	18.7%	20.1%	0.943

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Discussion

This is the first study to investigate the segmental distribution of lumbar mobility in vivo in patients with LSTV with flexion-extension radiographs. Our results show that LSTV significantly alter the distribution of motion in the lumbar spine in vivo. While movement in the transitional segment was significantly reduced in patients with LSTV compared to segment L5/S1 of the control group, there was a significantly increased distribution of movement to the cranially adjacent segment.

In our cohort, 33.3% of patients presented with LSTV. The prevalence of LSTV in our study was therefore within the range of 5–36% prevalence reported in the literature [16–18]. The reported prevalence of LSTV differs, pending on the selected patients collective and to be dependent on regional factors [2, 12, 19–21]. Dzupa et al. reported a comparable prevalence of 27.6% in their study of a caucasian patients collective based on pelvic x-rays, unconnected to back pain [19]. While Hanhivaara et al. detected a prevalence of 21.1% in a Swedish collective of patients with back pain [12]. Haffer et al. reported a prevalence of 6.5% in a collective of patients without back pain from a central european collective [20]. Whereas Tang et al detected a prevalence of 15.8% in a Chinese Han population without pre-selection for back pain [2]. The study of Sekharappa et al. indicates the association between back pain and the presence of LSTV. In a study of an urological collective without back pain, he detected a prevalence of 8.1% whereas he reported a prevalence of 14% in a spine outpatient care department of the same hospital [21].

Patients with LSTV differed not significantly in lumbar lordosis compared to the control collective. There is no consensus in the literature regarding the effect of LSTV on lumbar lordosis [22–24]. While Chalian et al. and Mahato reported increased lumbar lordosis in patients with LSTV [22, 23], Abbas et al. reported no significant change in lumbar lordosis [24]. In our study, patients with LSTV showed a tendency towards a reduced lumbar range of motion compared with the control group, with statistical effects not reaching statistical significance. Whereas the summed segmental wedge angle showed significantly reduced lumbar flexion and lumbar RoM. These differences between the two measurement methods could result from the relatively small collective size and few patients with high-grade LSTV.

While lumbar flexion and lumbar RoM measured from the L1-S1 upper endplates did not differ significantly between patients with LSTV and the control group, significant differences were seen in the cumulated segmental wedge angle. Differences between the motion generated by intervertebral discs deformation and the motion of the completely lumbar spine, which includes a slight bony deformation of the vertebrae, have already been described by Been et al. [25]. Consequently, increased bony deformation may have occurred throughout the lumbar spine in patients with LSTV, compensating for decreased RoM as well as flexion by the intervertebral discs.

Looking into segmental movement, patients with LSTV had significantly reduced mobility of the transitional segment compared to segment L5/S1 of the control group, which is in line with the results of the cadaveric-study of Golubovsky et al. [13]. However, this investigation found a reduced range of motion in patients with LSTV, especially for axial torsion and side bending in vitro, but not for flexion or extension [13]. These differences may result from a tissue alteration in the cadaveric study of Golubovsky et al., the analysis of asymmetric LSTV only, and an isolated view on the osteo-ligamentous structures without inclusion of the musculature in their study. At the same time, the literature reports significant muscular adaptions in patients with LSTV [26, 27]. Recent evidence also indicates significant differences for the spinopelvic anatomy between LSTV and a control group, which might also affect the mutual interaction between the pelvis and lumbar spine [20].

No increased absolute range of motion compared to patients without LSTV was detected in the cranial adjacent segment to the transitional segment in patients with LSTV. Likewise, no significant differences in the range of motion of the segment L3/4 were seen. This is consistent with the findings of Golubovsky et al. [13]. In the upper segments of the lumbar spine L1/2 and L2/3, however, patients with LSTV showed a significantly reduced range of motion compared to the control group. Lee et al. reported a significant increased range of motion in the upper lumbar spine in the presence of degeneration of lower lumbar segment [28]. Accordingly, the differences in range of motion in the upper lumbar spine may result from compensatory increased motion in the upper lumbar spine due to the presence of osteochondrosis in the L5/S1 segment whereas in patients with LSTV this compensatory mechanism is possibly not sufficient due to the altered soft-tissue and osseous anatomy and accompanying changes in mobility of the transitional and adjacent segment.

Considering the relative proportions of the individual segments in the total lumbar motion, patients with LSTV and the control group showed significant differences. In accordance with the literature, the control group as well as patients with LSTV had the lowest mobility in the transitional segment and segment L5/S1 [29]. In both groups, this effect may have been further enhanced by the presence of osteochondrosis in segment L5/S1, as the degeneration could lead to a reduced range of motion [28]. However, patients with LSTV had significantly decreased mobility with a motion distribution in this segment of only 6.8% of total lumbar range of motion compared with 17.3% in the control group. Significant differences between patients with LSTV and the control group were also demonstrated in the cranial adjacent segment compared to the L4/5 segment. In patients with LSTV, 29.0% of the lumbar range of motion derived from the segment L4/5, whereas in the control group only 22.3% derived from this segment. In the upper lumbar spine, no differences in the distribution of the lumbar range of motion were observed between patients with LSTV and the control group. These changes in the distribution of the lumbar motion with a relative hypermobility of the cranial adjacent segment may be attributed to two causes, the anatomical variance with a weak iliolumbar ligament [10], and to a compensatory increased relative mobility due to the decreased mobility of the LSTV. Despite significantly higher distribution of the lumbar motion in the cranial adjacent segment, no differences in absolute range of motion were observed compared with segment L4/5 of the control group. This effect is might be influenced by the in tendency decreased overall lumbar range of motion in LSTV patients. No significant correlation between LSTV grading according to Castellvi and motion in the transitional segment or the cranial adjacent segment could be detected. However, reduced motion in the transitional segment and increased motion in the cranial adjacent segment would be expected due to the increased osseous connectivity of transversal process with sacral ala in higher Castellvi grading. These effects may could be not detected in our study due to the sample sizes with higher Castellvi gradings as well as the osteochondrosis in the transitional segment may could have diminished these expected effects.

Besides presenting the first analysis of the mobility of the lumbar spine in patients with LSTV in flexion-extension radiographs, the relatively small number of patients included need to be stated as a limitation of the study. The degree of degeneration of the lumbar spine was not compared between the groups, which may could have affected lumbar mobility. Apart from ventral flexion and dorsal extension, LSTV may also influence side-bending and rotation, which were not included in the analysis due to the retrospective study design and the lack of side-bending radiographs [30]. Detection of patients with LSTV in this study was performed using plain anterior posterior radiographs. However, the method with the highest sensitivity for the detection of LSTV is computed tomography or Ferguson radiographs [31].

Conclusion

This is the first study to demonstrate that LSTV have a significant effect on lumbar spinal motion patterns with the use of flexion-extension radiographs. Patients with LSTV have reduced range of motion in the transitional segment. This is reflected in a reduced proportion to lumbar motion of only 6.8%. Consecutively, patients with LSTV have a significantly increased proportion of 29% of total lumbar motion in the cranial adjacent segment to the transitional segment. Thus, the reduced motion in the transitional segment as well as the increased proportion of mobility in the cranial adjacent segment can be considered as influencing factors for increased degeneration rates in the cranial adjacent segment to LSTV.

Supporting information

S1 Dataset. Minimal-data set of Fig 3 and Tables 2–4.
(DOCX)

Author Contributions

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References

1. Nardo L, Alizai H, Virayavanich W, Liu F, Hernandez A, Lynch JA, et al. Lumbosacral transitional vertebrae: association with low back pain. Radiology. 2012; 265(2):497–503. Epub 20120905. https://doi.org/10.1148/radiol.12112747 PMID: 22952380; PubMed Central PMCID: PMC3480814.
2. Tang M, Yang XF, Yang SW, Han P, Ma YM, Yu H, et al. Lumbosacral transitional vertebra in a population-based study of 5860 individuals: prevalence and relationship to low back pain. Eur J Radiol. 2014; 83(9):1679–82. Epub 20140605. https://doi.org/10.1016/j.ejrad.2014.05.036 PMID: 24935139.
3. French HD, Somasundaram AJ, Schaefer NR, Laherty RW. Lumbosacral transitional vertebrae and its prevalence in the Australian population. Global Spine J. 2014; 4(4):229–32. Epub 20140910. https://doi.org/10.1055/s-0034-1387808 PMID: 25396103; PubMed Central PMCID: PMC4229381.
4. Hanhivaara J, Maatta JH, Niinimaki J, Nevalainen MT. Lumbosacral transitional vertebrae are associated with lumbar degeneration: retrospective evaluation of 3855 consecutive abdominal CT scans. Eur Radiol. 2020; 30(6):3409–16. Epub 20200219. https://doi.org/10.1007/s00330-020-06691-2 PMID: 32072261; PubMed Central PMCID: PMC7248049.
5. Castellvi AE, Goldstein LA, Chan DP. Lumbosacral transitional vertebrae and their relationship with lumbar extradural defects. Spine (Phila Pa 1976). 1984; 9(5):493–5. https://doi.org/10.1097/00007632-198407000-00014 PMID: 6495013.
6. McGrath K, Schmidt E, Rabah N, Abubakr M, Steinmetz M. Clinical assessment and management of Bertolotti Syndrome: a review of the literature. Spine J. 2021; 21(8):1286–96. Epub 20210303. https://doi.org/10.1016/j.spinee.2021.02.023 PMID: 33676018.

7. Porter NA, Lalam RK, Tins BJ, Tyrrell PN, Singh J, Cassar-Pullicino VN. Prevalence of extraforaminal nerve root compression below lumbosacral transitional vertebrae. Skeletal Radiol. 2014; 43(1):55–60. Epub 20131025. https://doi.org/10.1007/s00256-013-1750-0 PMID: 24310344.
8. Luoma K, Vehmas T, Raininko R, Luukkonen R, Riihimaki H. Lumbosacral transitional vertebra: relation to disc degeneration and low back pain. Spine (Phila Pa 1976). 2004; 29(2):200–5. https://doi.org/10.1097/01.BRS.0000107223.02346.A8 PMID: 14722415.
9. Lee CS, Ha JK, Kim DG, Hwang CJ, Lee DH, Cho JH. The clinical importance of lumbosacral transitional vertebra in patients with adolescent idiopathic scoliosis. Spine (Phila Pa 1976). 2015; 40(17): E964–70. https://doi.org/10.1097/BRS.0000000000000945 PMID: 25909352.
10. Aihara T, Takahashi K, Ogasawara A, Itadera E, Ono Y, Moriya H. Intervertebral disc degeneration associated with lumbosacral transitional vertebrae: a clinical and anatomical study. J Bone Joint Surg Br. 2005; 87(5):687–91. https://doi.org/10.1302/0301-620X.87B5.15727 PMID: 15855373.
11. Vergauwen S, Parizel PM, van Breusegem L, Van Goethem JW, Nackaerts Y, Van den Hauwe L, et al. Distribution and incidence of degenerative spine changes in patients with a lumbo-sacral transitional vertebra. Eur Spine J. 1997; 6(3):168–72. https://doi.org/10.1007/BF01301431 PMID: 9258634; PubMed Central PMCID: PMC3454625.
12. Hanhivaara J, Maatta JH, Karppinen J, Niinimaki J, Nevalainen MT. The Association of Lumbosacral Transitional Vertebrae with Low Back Pain and Lumbar Degenerative Findings in MRI: A Large Cohort Study. Spine (Phila Pa 1976). 2022; 47(2):153–62. https://doi.org/10.1097/BRS.0000000000004244 PMID: 34610612.
13. Golubovsky JL, Colbrunn RW, Klatte RS, Nagle TF, Briskin IN, Chakravarthy VB, et al. Development of a novel in vitro cadaveric model for analysis of biomechanics and surgical treatment of Bertolotti syndrome. Spine J. 2020; 20(4):638–56. Epub 20191025. https://doi.org/10.1016/j.spinee.2019.10.011 PMID: 31669612.
14. Malakoutian M, Volkheimer D, Street J, Dvorak MF, Wilke HJ, Oxland TR. Do in vivo kinematic studies provide insight into adjacent segment degeneration? A qualitative systematic literature review. Eur Spine J. 2015; 24(9):1865–81. Epub 20150609. https://doi.org/10.1007/s00586-015-3992-0 PMID: 26055273.
15. Volkheimer D, Malakoutian M, Oxland TR, Wilke HJ. Limitations of current in vitro test protocols for investigation of instrumented adjacent segment biomechanics: critical analysis of the literature. Eur Spine J. 2015; 24(9):1882–92. Epub 20150603. https://doi.org/10.1007/s00586-015-4040-9 PMID: 26038156.
16. Erken E, Ozer HT, Gulek B, Durgun B. The association between cervical rib and sacralization. Spine (Phila Pa 1976). 2002; 27(15):1659–64. https://doi.org/10.1097/00007632-200208010-00013 PMID: 12163729.
17. Quinlan JF, Duke D, Eustace S. Bertolotti's syndrome. A cause of back pain in young people. J Bone Joint Surg Br. 2006; 88(9):1183–6. https://doi.org/10.1302/0301-620X.88B9.17211 PMID: 16943469.
18. Konin GP, Walz DM. Lumbosacral transitional vertebrae: classification, imaging findings, and clinical relevance. AJNR Am J Neuroradiol. 2010; 31(10):1778–86. Epub 20100304. https://doi.org/10.3174/ajnr.A2036 PMID: 20203111; PubMed Central PMCID: PMC7964015.
19. Dzupa V, Slepanek M, Striz M, Krbec M, Chmelova J, Kachlik D, et al. Developmental malformations in the area of the lumbosacral transitional vertebrae and sacrum: differences in gender and left/right distribution. Surg Radiol Anat. 2014; 36(7):689–93. Epub 20131227. https://doi.org/10.1007/s00276-013-1250-x PMID: 24370578.
20. Haffer H, Becker L, Putzier M, Wietholter M, Ziegeler K, Diekhoff T, et al. Changes of Fixed Anatomical Spinopelvic Parameter in Patients with Lumbosacral Transitional Vertebrae: A Matched Pair Analysis. Diagnostics (Basel). 2021; 11(1). Epub 20210102. https://doi.org/10.3390/diagnostics11010059 PMID: 33401698; PubMed Central PMCID: PMC7824527.
21. Sekharappa V, Amritanand R, Krishnan V, David KS. Lumbosacral transition vertebra: prevalence and its significance. Asian Spine J. 2014; 8(1):51–8. Epub 20140206. https://doi.org/10.4184/asj.2014.8.1.51 PMID: 24596605; PubMed Central PMCID: PMC3939369.
22. Chalian M, Soldatos T, Carrino JA, Belzberg AJ, Khanna J, Chhabra A. Prediction of transitional lumbosacral anatomy on magnetic resonance imaging of the lumbar spine. World J Radiol. 2012; 4(3):97–101. https://doi.org/10.4329/wjr.v4.i3.97 PMID: 22468190; PubMed Central PMCID: PMC3314934.
23. Mahato NK. Disc spaces, vertebral dimensions, and angle values at the lumbar region: a radioanatomical perspective in spines with L5-S1 transitions: clinical article. J Neurosurg Spine. 2011; 15(4):371–9. Epub 20110708. https://doi.org/10.3171/2011.6.SPINE11113 PMID: 21740126.
24. Abbas J, Peled N, Hershkovitz I, Hamoud K. Is Lumbosacral Transitional Vertebra Associated with Degenerative Lumbar Spinal Stenosis? Biomed Res Int. 2019; 2019:3871819. Epub 20190610. https://doi.org/10.1155/2019/3871819 PMID: 31281838; PubMed Central PMCID: PMC6590608.

25. Been E, Barash A, Pessah H, Peleg S. A new look at the geometry of the lumbar spine. Spine (Phila Pa 1976). 2010; 35(20):E1014–7. https://doi.org/10.1097/BRS.0b013e3181ddd433 PMID: 20802392.

26. Becker L, Ziegeler K, Diekhoff T, Palmowski Y, Pumberger M, Schomig F. Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients. Skeletal Radiol. 2021; 50(8):1697–704. Epub 20210203. https://doi.org/10.1007/s00256-021-03722-x PMID: 33533964; PubMed Central PMCID: PMC8208907.

27. Bahadir Ulger FE, Illeez OG. The Effect of Lumbosacral Transitional Vertebrae (LSTV) on Paraspinal Muscle Volume in Patients with Low Back Pain. Acad Radiol. 2020; 27(7):944–50. Epub 20191202. https://doi.org/10.1016/j.acra.2019.09.030 PMID: 31806558.

28. Lee SH, Daffner SD, Wang JC, Davis BC, Alanay A, Kim JS. The change of whole lumbar segmental motion according to the mobility of degenerated disc in the lower lumbar spine: a kinetic MRI study. Eur Spine J. 2015; 24(9):1893–900. Epub 20140328. https://doi.org/10.1007/s00586-014-3277-z PMID: 24676853.

29. Wong KW, Leong JC, Chan MK, Luk KD, Lu WW. The flexion-extension profile of lumbar spine in 100 healthy volunteers. Spine (Phila Pa 1976). 2004; 29(15):1636–41. https://doi.org/10.1097/01.brs.0000132320.39297.6c PMID: 15284509.

30. Mahato NK. Complexity of neutral zones, lumbar stability and subsystem adaptations: probable alterations in lumbosacral transitional vertebrae (LSTV) subtypes. Med Hypotheses. 2013; 80(1):61–4. Epub 20121115. https://doi.org/10.1016/j.mehy.2012.10.013 PMID: 23159743.

31. Hou L, Bai X, Li H, Gao T, Li W, Wen T, et al. Lumbar plain radiograph is not reliable to identify lumbosacral transitional vertebra types according to Castellvi classification principle. BMC Musculoskelet Disord. 2020; 21(1):333. Epub 20200529. https://doi.org/10.1186/s12891-020-03358-3 PMID: 32471475; PubMed Central PMCID: PMC7260820.

2.4 Anpassungen der Rumpfmuskulatur auf lumbo-sacrale Übergangsstörungen

Becker L, Ziegeler K, Diekhoff T, Palmowski Y, Pumberger M, Schömig F

Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients.

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Lumbo-sacrale Übergangsstörungen führen zu einer Veränderung der knöchernen Anatomie [93] sowie zu einer lumbalen Funktionsveränderung wie in Arbeit 3 gezeigt wurde. Die Adaptationsvorgänge auf den Bewegungsapparat aus lumbo-sacralen Übergangsstörungen zu detektieren war das Ziel dieser Arbeit.

In dieser Arbeit wurde anhand von CT-Schnittbildgebung von 46 Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung insa einer retrospektiven matched-pair analyse nach Alter und Geschlecht die Muskelquerschnittsfläche, das Muskelvolumen sowie die Muskeldegeneration bestimmt.

Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung zeigten ein signifikant reduziertes Volumen der paraspinalen- und Rumpfmuskulatur verglichen mit der Kontrollgruppe ($p<0{,}001$). Sie wiesen einen signifikant höheren Degenerationsgrad in allen untersuchten Muskeln auf (M. psoas $p<0{,}040$, M. quadratus lumborum $p<0{,}001$, paravertebrale Muskeln $p=0{,}011$, M. rectus abdominis $p<0{,}001$, M. obliquus abdominis $p<0{,}001$). Ebenso zeigte sich eine signifikant negative Korrelation zwischen dem Ausprägungsgrad der lumbo-sacralen Übergangsstörung sowie dem Muskelvolumen ($p=0{,}001$; $r=-0{,}227$).

Lumbo-sacrale Übergangsstörungen sind mit einer Verringerung des Muskelvolumens und einer Zunahme der Muskeldegeneration sowohl der Lenden- als auch der Rumpfmuskulatur verbunden. Dies resultiert möglicherweise aus einer reduzierten Mobilität im Übergangssegment sowie die sich kranial anschließende kompensatorische relative Hypermobilität.

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SCIENTIFIC ARTICLE

Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients

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Abstract

Objective Even though lumbosacral transitional vertebrae (LSTV) are one of the most common congenital anomalies of the spine, their effect on surrounding soft tissues is not well-studied. We therefore aimed at analyzing the association between LSTV and changes in volume, mass, symmetry, and degeneration of lumbar and trunk muscles.

Materials and methods Abdomen–pelvis CT scans were analyzed in patients with LSTV and a matched control group. LSTV were classified according to the Castellvi classification. Muscles were segmented from the remaining soft tissue and their cross-sectional area and volume were examined at five defined levels. Threshold segmentation was used to differentiate between muscle fibers and fat tissue. Matched pairs were compared using Wilcoxon rank sum tests. For comparison of categorical data, chi-squared tests were performed and for associations between the degree of fusion and muscle size and degeneration, Spearman's correlation coefficients were calculated. Inter- and intrarater reliabilities were evaluated by computing intraclass correlation coefficients.

Results Forty-six patients with LSTV and 46 controls were included. Muscle volume of the paraspinal and trunk muscles was significantly lower (707.0 cm^3 vs. 809.7 cm^3, $p < 0.001$) and fatty muscle changes were significantly increased in all but the caudal paravertebral muscles of LSTV patients (M. psoas $p < 0.04$, M. quadratus lumborum $p < 0.001$, paravertebral muscles $p = 0.011$, M. rectus abdominis $p < 0.001$, M. obliquus abdominis $p < 0.001$). Correlations between the degree of Castellvi classification and muscle volume were significant ($p = 0.001$).

Conclusion LSTV are associated with a reduction in muscle volume and an increase in muscle degeneration of both lumbar and trunk muscles.

Keywords Transitional · Adaptation · Atrophy · Asymmetry

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Introduction

Lumbosacral transitional vertebrae (LSTV) are one of the most common congenital anomalies of the spine, with a reported prevalence of 4–36%, and are defined as either a sacralization of the lowest lumbar segment or a lumbarization of the superior sacral segment [1, 2]. Castellvi et al. introduced a radiographic classification system for LSTV in 1984, defining four different types of LSTV: Type I includes unilateral (Ia) or bilateral (Ib) dysplastic transverse processes; type II is an incomplete unilateral (IIa) or bilateral (IIb) lumbarization or sacralization with an enlarged transverse process with a diarthrodial joint between itself and the sacrum; type III is a unilateral (IIIa) or bilateral (IIIb) lumbarization or sacralization with complete osseous fusion of the transverse process to the sacrum; and type IV is defined as a unilateral type II transition with a type III transition on the contralateral side [3]. Diagnosis of LSTV classically includes lateral and

Ferguson radiographs but characterization of LSTV is best performed by computed tomography (CT) [1].

Despite some controversies in the literature, there appears to be an association between LSTV and the occurrence of low back pain (LBP) caused by various etiologies, such as disc or spinal canal pathology at the level above transition, degeneration of the anomalous articulation, facet joint arthrosis, and stenosis secondary to a broadened transverse process [1]. However, other studies reported no correlation between LBP and LSTV and no increased incidence of structural pathologies in patients with LSTV [4, 5].

Core trunk and low back muscle atrophy has been shown to be associated with LBP and, with less strong evidence, with degenerative disc disease and spinal stenosis [6–9]. As the posterior muscles of the lumbar spine provide stability to the lumbar vertebral segments and control movement of the lumbar spine, muscular integrity plays an important role in the maintenance of global spinal alignment [10, 11]. Previous studies have shown that atrophy of paraspinal muscles may lead to altered thoracic kyphosis, lumbar lordosis, and sacral–vertebral angles both in adults with and without degenerative spinal disease [12–14]. Due to this important role trunk and lumbar muscles play in spinal integrity and pain development, physiotherapy has been shown to significantly improve functionality and positively alter the course of LBP [15].

To determine whether the occurrence of LSTV is associated with changes in the psoas muscle, quadratus lumborum muscle, rectus abdominis muscle, abdominal oblique muscle, and paraspinal muscles, we analyzed muscle volume, mass, symmetry, and degeneration at five defined levels of CT scans of patients with and without LSTV using the image processing software Amira.

Materials and methods

Patients and ethics approval

A retrospective matched-pair analysis of the abdomen–pelvis CT scans was performed. The study was approved by the local ethics board (ethics proposal number EA1/300/19). Included patients underwent abdomen–pelvis CT scans in our department of radiology from 2016 to 2019. The CT scans were high-resolution abdomen–pelvis CT images with an image section at least from level L1 to the greater trochanter and were acquired due to reasons other than LBP. Exclusion criteria were metastatic and primary malignancy of the musculoskeletal system, previous spinal or pelvic fusion surgery, incomplete image data, and insufficient image quality for software evaluation. Eight-hundred nineteen patients were included. Fifty-two patients had LSTV, six of which had to be excluded due to insufficient image quality. The resulting 46 patients were matched with control patients from the cohort described above, using propensity score matching with a tolerance of 0.01, matching for age, gender, weight category, and indication for CT.

Image acquisition and radiographic classification

Images were taken by an 80-row or a 320-row CT scanner (Canon Aquillon Prime and Canon Aquillon One Vision, Canon Medical Systems, Otawara, Japan). The chosen isometric slice thickness was 1.0 mm in a medium soft tissue core. CT images were reconstructed with the image visualization and analysis software Amira for Life & Biomedical Sciences certified by the Food and Drug Administration (Thermo Fisher Scientific Materials & Structural Analysis c/o Zuse-Institut Berlin, Germany). Image analysis, muscle segmentation, and measurements were performed by a spine surgeon with experience in measuring radiological spinal parameters, who was trained by a spinal-attending surgeon. LSTV were classified by a radiological resident with specialized training in musculoskeletal radiology (5 years of experience in clinical musculoskeletal imaging and research). A random sample of 50 patients of the original study cohort was additionally classified by an experienced board-certified musculoskeletal radiologist and scored a second time by the primary reader to calculate inter- and intrareader reliabilities.

In each patient, LSTV were classified according to the Castellvi classification for both the left and the right side as shown in Fig. 1. We then divided all vertebral sides into the following groups: no transition (I), enlarged transverse process (II), pseudarticulation of the transverse process with the sacral bone (III), and fusion of the transverse process with the sacrum (IV).

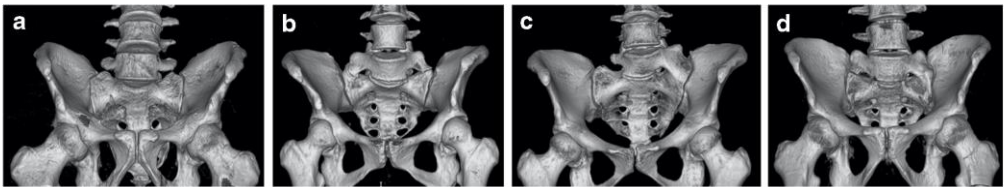


Fig. 1 CT scans of different LSTV types in our patient population. **a**. Castellvi Ib, **b**. Castellvi IIb, **c**. Castellvi IIIa, **d**. Castellvi IV. CT = computed tomography, LSTV = lumbosacral transitional vertebrae

Muscle segmentation and measurement

For image analysis, we used the image processing software Amira. We segmented the muscles from the remaining soft tissue by semi-automated procedures using threshold segmentation tools and manual muscle contouring. We examined muscle cross-sectional area and the muscle volume of the psoas muscle, quadratus lumborum muscle, and paraspinal muscles (erector spinae, multifidus). To verify the accuracy of the measurements, 24 of the 92 patients were remeasured. Twelve patients were randomly selected from both the cohorts of patients with and without LSTV. We differentiated between muscle fibers and fat tissue by using threshold segmentation and assessed the mean muscle density as well as the proportion between muscle mass and fat as signs of muscle degeneration [16]. We determined the muscles' cross-sectional area in axial sectional imaging at five defined levels. For standardization of our measurements, we determined each measuring level at the center of the anterior edge of the intervertebral disc between the two vertebrae. The uppermost measurement level was between the first and second vertebra below the rib-bearing vertebrae. The other measurement levels were between the second and third, third and fourth, fourth and fifth, and fifth and sixth vertebrae as shown in Fig. 2. Muscle degeneration as expressed by visual fat content was assessed using a classification adapted to the Goutallier grading (Fig. 3): grade 0 shows no fatty infiltration, grade 1 some fatty streaks, grade 2 less than 50% fat, grade 3 50% fat, and grade 4 more than 50% fat [16–18].

Data analysis

All statistical analyses were performed using SPSS Version 25 (IBM Corporation, New York, USA). Controls were identified from the same study cohort using propensity score matching with a tolerance of 0.01, matching for age, gender, weight category, and indication for CT. The Wilcoxon rank sum test for the comparison of paired samples was used due to the study design as a matched pair analysis. Categorical data were compared using chi-squared test. The associations between the degree of fusion (none, enlarged transverse process, pseudoarticulation, fusion) and muscle size and degeneration were investigated using Spearman's correlation coefficients. Intra-class correlation coefficients (ICCs) were calculated for inter- and intrareader reliabilities using a two-way mixed model. A significance level of $p < 0.05$ was assumed for all tests.

Results

Patients

A total of 46 patients with transitional vertebrae matched with 46 controls. As per study design, LSTV patients did not differ from their matched controls regarding median age (51.5, interquartile range, IQR 37.0–68.0, vs. 50.0, IQR 31.0–70.0; $p = 0.872$), proportion of female patients (23/46 vs. 19/46; $p = 0.236$) or proportion of normal weight patients (29/46 vs. 25/46; $p = 0.585$). CT scans were acquired with query of malignancy (27/46 vs. 25/46), infection (11/46 vs. 20/46),

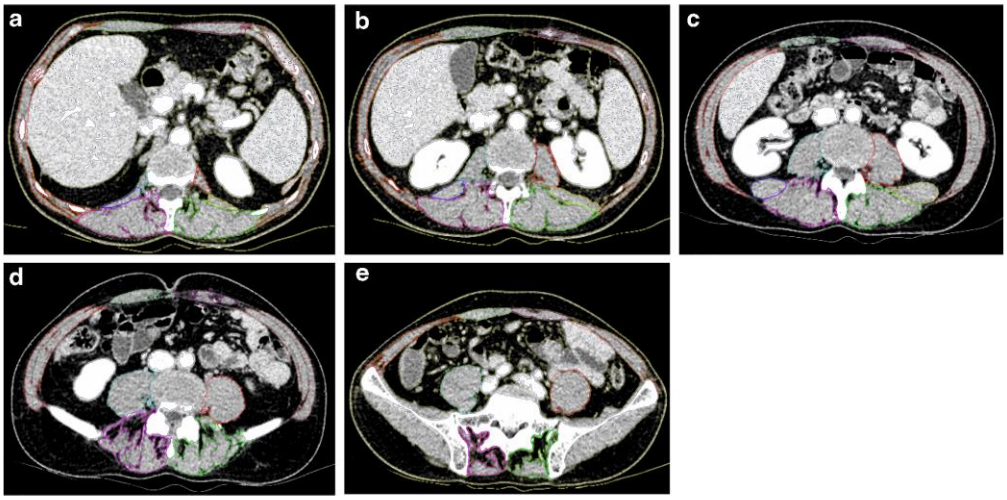


Fig. 2 Measurements of the psoas, paraspinal, rectus abdominis, and obliquus abdominis muscles at five levels and the quadratus lumborum muscle at three levels in a patient with Castellvi type IIb. **2a**. Level L1/2, **2b**. level L2/3, **2c**. level L3/4, **2d**. level L4/5, **2e**. level L5/S1

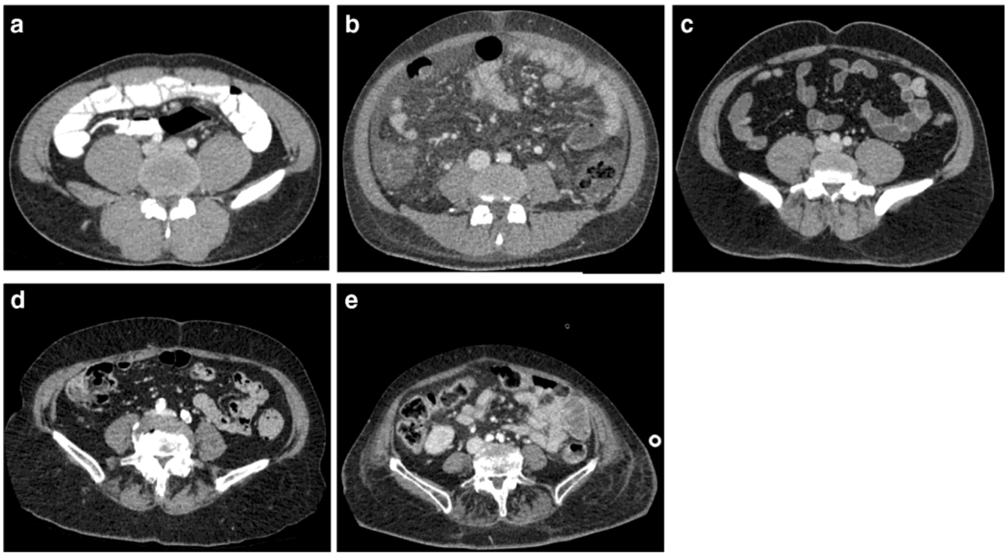


Fig. 3 CT scans showing different Goutallier gradings of the paravertebral muscles at level L4/5. **a**. Grade 0: no fatty infiltration. **b**. Grade 1: some fatty streaks. **c**. Grade 2: less than 50% fatty infiltration. **d**. Grade 3: 50% infiltration. **e**. Grade 4: more than 50% fatty infiltration

bleeding (2/46 vs. 0/46) or other (7/46 vs. 6/46)—the distribution did not differ significantly between groups ($p = 0.126$). Frequencies of Castellvi grades are shown in Table 1. For classification of LSTV, interreader reliability was good with ICCs of 0.832 (95%CI 0.705–0.904) for the right and 0.712 (95%CI 0.493–0.836) for the left side. Intrareader reliability was very good with ICCs of 0.958 (95%CI 0.925–0.976) for the right and 0.905 (95%CI 0.833–0.946) for the left side.

Muscle — volume

For muscle volume measurements, the intrareader reliability was very good with an ICC of 0.995 (95%CI 0.994–0.996). Total muscle volume was calculated by adding the volumes of all individual muscles of one side. We found a statistically significant ($p < 0.001$) lower total muscle volume for patients with LSTV (mean 707.0 cm^3, IQR 632.9 cm^3–1006.4 cm^3) in relation to our control group (mean 809.7 cm^3, IQR 689.9 cm^3–1035.5 cm^3). Similar findings were found for total muscle volume for M. psoas ($p = 0.028$), paraspinal musculature ($p < 0.001$), M. rectus abdominis ($p < 0.001$), and M. obliquus abdominis ($p < 0.001$). No differences were seen in total muscle volume for M. quadratus lumborum. The cross-sectional area of the individual muscles examined at the five levels is shown in Table 2. An example of muscular atrophy in an LSTV patient is presented in Fig. 4.

Table 1 Frequencies of Castellvi grades

Type	I	II	III	IV
n (%)	14 (30.4%)	22 (47.8%)	6 (13.0%)	4 (8.7%)

Muscle — symmetry

Asymmetry of muscle mass, defined as the median difference in the cross-sectional area between the left and right side at different levels, did not differ significantly in single levels or in total muscle volume between patients with asymmetrical LSTV (Castellvi Ia, IIa and IIIa; $n = 31$) and controls ($n = 31$).

Goutallier grading and density

We found significantly more fatty muscle changes for all analyzed muscles in patients with LSTV (M. psoas $p < 0.04$, M. quadratus lumborum $p < 0.001$, paravertebral muscles $p = 0.011$, M. rectus abdominis $p < 0.001$, M. obliquus abdominis $p < 0.001$). Patients with LSTV showed more fatty degeneration at every examined level except the paravertebral muscles at L2/3 and L4/5. Table 3 summarizes the grading by presenting frequencies of modified Goutallier grades. Quantitative analysis of radiodensity as a parameter for fatty degeneration of the muscle as whole did not reveal significant differences between both groups.

Table 2 Muscle cross-sectional area in cm^2 at the five measured levels as well as the muscle volume in cm^3. Significant values are marked in bold

	M. psoas		M. quad. lumborum		Paraspinal m.		M. rect. abd.		M. obliquus abd.	
	LSTV	Control	LSTV	Control	LSTV	Control	LSTV	Control	LSTV	Control
L1/2	3.15	2.72	2.96	3.01	**21.86**	**22.90**	**5.25**	**5.55**	**23.75**	**24.81**
	p=0.457		*p*=0.635		***p* =0.015**		***p* =0.005**		***p* =0.027**	
L2/3	6.56	6.87	4.01	4.05	**22.17**	**23.19**	5.07	5.26	**23.37**	**24.69**
	p=0.309		*p*=0.717		***p* =0.001**		*p*=0.082		***p* =0.019**	
L3/4	10.21	10.28	5.12	4.93	**21.40**	**22.42**	**5.47**	**5.89**	**23.36**	**24.89**
	p=0.058		*p*=0.163		***p* =0.003**		***p* =0.003**		***p* =0.003**	
L4/5	**11.79**	**12.24**	–	–	**16.96**	**18.96**	**5.50**	**5.81**	**17.51**	**19.83**
	***p* =0.006**				***p* <0.001**		***p* =0.014**		***p* <0.001**	
L5/S1	9.21	9.33	–	–	**8.14**	**10.07**	**5.61**	**6.29**	**8.55**	**9.59**
	p=0.256				***p* <0.001**		***p* =0.004**		***p* =0.027**	
Volume	121.57	124.95	26.63	27.25	**278.99**	**292.07**	**78.81**	**82.26**	**274.68**	**298.63**
	p=0.028		*p*=0.217		***p* <0.001**		***p* =0.001**		***p* <0.001**	

Muscle mass and degeneration pending on the degree of expression of LSTV

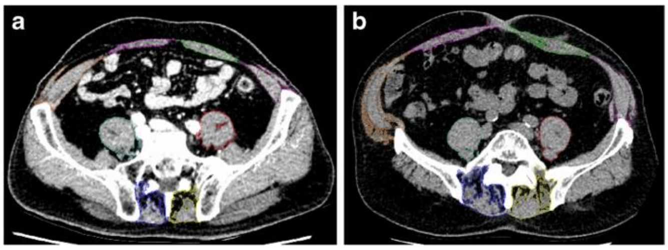
We found weak but significant negative correlations between the degree of fusion and muscle cross-sectional area for paraspinal muscles ($r = -0.230$; $p = 0.001$), M. rectus abdominis ($r = -0.211$; $p = 0.002$) and M. obliquus abdominis ($r = -0.2541$; $p < 0.001$). In terms of overall muscle volume, we found a significant negative correlation between volume and degree of fusion ($r = -0.227$; $p = 0.001$). Our results show a weak but significant negative correlation between the degree of expression of LSTV and fatty degeneration of M. psoas ($r = -0.221$; $p = 0.003$), M. quadratus lumborum ($r = -0.381$; $p < 0.001$), paraspinal muscles ($r = -0.320$; $p < 0.001$), M. rectus abdominis ($r = -0.320$; $p < 0.001$), and M. obliquus abdominis ($r = -0.252$; $p = 0.001$).

Discussion

Our results show a significant reduction of total muscle volume in patients with LSTV compared with our control group (707.0 cm^3 vs. 809.7 cm^3, $p < 0.001$) as well as a significant reduction of muscle volumes of the paraspinal musculature, M. rectus abdominis, and M. obliquus abdominis. Furthermore, we found significantly more fatty muscle changes in the M. psoas ($p < 0.04$), M. quadratus lumborum ($p < 0.001$), paravertebral muscles ($p = 0.011$), M. rectus abdominis ($p < 0.001$), and M. obliquus abdominis ($p < 0.001$) in patients with LSTV.

As changes in lumbar muscles have been shown to not only affect global sagittal alignment of the spine but also contribute to the development of LBP, we performed this retrospective study to analyze whether there is an association between the occurrence of LSTV and changes in muscle volume, mass, and degeneration. Multiple studies have analyzed the correlation between LSTV and LBP, but evidence on the exact mechanisms of pain development is still lacking.

In patients with LSTV, we found total muscle volume to be significantly reduced. Additionally, paraspinal muscles, psoas muscle as well as both the M. rectus abdominis and M. obliquus abdominis showed significantly lower muscle masses compared to the control group. This reduction of muscle volume and mass in LSTV patients may be caused by



c	LSTV [cm²]	Control [cm²]
M. psoas	23.4	35.6
Paraspinal m.	13.3	38.5
Rectus abd.	8.3	22.7
Obliquus abd.	19.0	46.8

Fig. 4 Measurements of the cross-sectional area of the psoas, paraspinal, rectus abdominis and obliquus abdominis muscles at level 5 in a patient with an LSTV Castellvi type IIIb (**a**.) and in a patient without an LSTV (**b**.). **c**. shows the resulting cross-sectional areas

Table 3 Frequencies of modified Goutallier grades per level. *P* values are derived from chi-square test. Significant values are marked in bold

		LSTV (*n*=46)				Controls (*n*=46)				p
Modified Goutallier		I	II	III	IV	I	II	III	IV	
L1/2	M. psoas	89.13%	10.87%	0.00%	0.00%	73.91%	4.35%	0.00%	0.00%	**<0.001**
	M. quad. lumb.	95.65%	4.35%	0.00%	0.00%	70.65%	5.43%	0.00%	0.00%	**<0.001**
	Paraspinal m.	47.83%	52.17%	0.00%	0.00%	60.87%	31.52%	1.09%	0.00%	**0.004**
	M. rectus abd.	61.96%	31.52%	6.52%	0.00%	54.35%	21.74%	2.17%	1.09%	**<0.001**
	M. obliquus abd.	9.78%	88.04%	2.17%	0.00%	35.87%	61.96%	2.17%	0.00%	**<0.001**
L2/3	M. psoas	89.13%	10.87%	0.00%	0.00%	71.74%	8.70%	0.00%	0.00%	**<0.001**
	M. quad. lumb.	86.96%	11.96%	1.09%	0.00%	78.26%	2.17%	0.00%	0.00%	**<0.001**
	Paraspinal m.	48.91%	51.09%	0.00%	0.00%	46.74%	46.74%	2.17%	0.00%	0.101
	M. rectus abd.	51.09%	48.91%	0.00%	0.00%	50.00%	31.52%	0.00%	2.17%	**<0.001**
	M. obliquus abd.	15.22%	84.78%	0.00%	0.00%	30.43%	69.57%	0.00%	0.00%	**0.014**
L3/4	M. psoas	92.39%	7.61%	0.00%	0.00%	80.43%	1.09%	0.00%	0.00%	**<0.001**
	M. quad. lumb.	83.70%	13.04%	3.26%	0.00%	72.83%	3.26%	0.00%	0.00%	**<0.001**
	Paraspinal m.	26.09%	70.65%	3.26%	0.00%	42.39%	51.09%	3.26%	0.00%	**0.024**
	M. rectus abd.	58.70%	40.22%	1.09%	0.00%	57.61%	16.30%	1.09%	4.35%	**<0.001**
	M. obliquus abd.	20.65%	79.35%	0.00%	0.00%	56.52%	40.22%	1.09%	0.00%	**<0.001**
L4/5	M. psoas	90.22%	9.78%	0.00%	0.00%	89.13%	4.35%	0.00%	0.00%	**0.019**
	Paraspinal m.	5.43%	70.65%	23.91%	0.00%	8.70%	61.96%	21.74%	2.17%	0.124
	M. rectus abd.	54.35%	45.65%	0.00%	0.00%	59.78%	27.17%	0.00%	2.17%	**0.001**
	M. obliquus abd.	18.48%	81.52%	0.00%	0.00%	43.48%	56.52%	0.00%	0.00%	**<0.001**
L5/S1	M. psoas	91.30%	8.70%	0.00%	0.00%	93.48%	2.17%	0.00%	0.00%	**0.022**
	Paraspinal m.	0.00%	85.87%	9.78%	4.35%	2.17%	59.78%	35.87%	1.09%	**<0.001**
	M. rectus abd.	59.78%	36.96%	3.26%	0.00%	73.91%	10.87%	0.00%	1.09%	**<0.001**
	M. obliquus abd.	22.83%	77.17%	0.00%	0.00%	45.65%	54.35%	0.00%	0.00%	**0.001**

restrictions in mobility and a higher degree of connection through osseous fusion [8]. A possible explanation for this may be that biomechanical changes caused by LSTV affect paravertebral muscles as well as abdominal muscles. LSTV therefore is not only a change in bony structure of the spine but may also cause changes in soft tissue anatomy. To the authors' knowledge, this is the first study showing that with increasingly pronounced disturbances of the lumbo-sacral transition, a significant decrease in the muscle volume of paraspinal and trunk muscles occurs.

Furthermore, we show significantly greater total muscle degeneration of all analyzed muscles in LSTV patients compared to the control group. As mentioned above, morphological changes in LSTV patients lead to altered anatomy and biomechanics with limitation of motion at the same level and hypermobility above the LSTV level [19–21]. This hypermobility of adjacent segments may cause stress on muscular structures, which in turn may lead to increased muscle degeneration. As it has been previously shown that excessive muscular stress caused by decreased muscular activity or repetitive injuries may cause fat infiltration, correct training of stabilizing muscles of the spine may reduce this degenerative process [16, 22, 23]. Regarding the increased fatty infiltration shown in LSTV patients, this may be of particular importance in preventing early muscular degeneration.

Our results also confirm the findings of Bahadir and Ulger [24] showing that an asymmetrical degree of severity of an LSTV does not lead to significant muscular asymmetry. However, patients with LSTV showed significantly less degeneration of the caudal paraspinal muscles and more degeneration of the psoas muscle and the quadratus lumborum muscle. This suggests that patients with LSTV have a different muscular load than patients without LSTV.

As both a reduction in muscle volume and an increase in muscle degeneration may play a role in the pathogenesis of LBP in LSTV patients, preventive strategies against pain development need to be established. There is increasing evidence that in LBP patients, exercise alone or exercise in combination with education programs can reduce the risk of a future episode of LBP as well as future LBP intensity [25, 26]. Additionally, a recent study showed that early physiotherapy significantly improves functionality and reduces pain in patients with chronic LBP [15], highlighting the importance of physiotherapy in the initial treatment of LBP. As our results show changes in volume and degeneration of lumbar and trunk musculature of LSTV patients, which may be caused by or may cause the development of LBP, exercise and physiotherapy need to be considered important strategies in pain prevention. In addition to training autochthonous back muscles, which had a lower volume in patients with LSTV than in the control group, strengthening of the psoas and quadratus lumborum muscles as well as abdominal muscles should be investigated as preventive strategies in LSTV patients.

Some limitations have to be discussed. Due to insufficient data, we excluded six patients, which may have caused an unclear bias. However, as to our knowledge, this still is the largest analysis of CT scans of LSTV patients we are confident the presented data is robust. Due to the retrospective setting, we were not able to include clinical findings such as the occurrence of LBP in our analysis and thus were not able to differentiate between asymptomatic and symptomatic patients. Therefore, we were not able to establish a causal relationship between muscle changes and LBP development in LSTV patients. Additionally, morphological and degenerative changes especially in the facet or disc were not investigated but may play a role in muscle changes and degeneration.

Our results provide evidence that LSTV lead to a reduction of total muscle volume as well as a reduction of muscle volumes of the M. rectus abdominis, M. obliquus abdominis, and paraspinal muscles, all of which showed a significant negative correlation with the degree of fusion. Moreover, we found increased muscle degeneration of all analyzed lumbar and trunk muscles in patients with LSTV, which may be caused by the previously shown limitation of motion at the same level and hypermobility above the LSTV level. To evaluate the impact these changes have on the development of LBP in LSTV patients, further studies including clinical findings such as patient symptoms need to be performed.

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Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval and consent to participate All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was approved by the local ethics board (ethics proposal number EA1/300/19).

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References

1. Konin GP, Walz DM. Lumbosacral transitional vertebrae: classification, imaging findings, and clinical relevance. AJNR Am J Neuroradiol. 2010;31(10):1778–86.
2. Matson DM, Maccormick LM, Sembrano JN, Polly DW. Sacral dysmorphism and lumbosacral transitional vertebrae (LSTV) review. Int J Spine Surg. 2020;14(Suppl 1):14–9.
3. Castellvi AE, Goldstein LA, Chan DP. Lumbosacral transitional vertebrae and their relationship with lumbar extradural defects. Spine (Phila Pa 1976). 1984;9(5):493–5.
4. Tini PG, Wieser C, Zinn WM. The transitional vertebra of the lumbosacral spine: its radiological classification, incidence, prevalence, and clinical significance. Rheumatol Rehabil. 1977;16(3):180–5.
5. Elster AD. Bertolotti's syndrome revisited. Transitional vertebrae of the lumbar spine. Spine (Phila Pa 1976). 1989;14(12):1373–7.
6. Kalichman L, Carmeli E, Been E. The association between imaging parameters of the paraspinal muscles, spinal degeneration, and low back pain. Biomed Res Int. 2017;2017:2562957.
7. Belavý DL, Armbrecht G, Richardson CA, Felsenberg D, Hides JA. Muscle atrophy and changes in spinal morphology: is the lumbar spine vulnerable after prolonged bed-rest? Spine (Phila Pa 1976). 2011;36(2):137–45.
8. Beneck GJ, Kulig K. Multifidus atrophy is localized and bilateral in active persons with chronic unilateral low back pain. Arch Phys Med Rehabil. 2012;93(2):300–6.
9. Haddas R, Samocha Y, Yang J. Effects of volitional spine stabilization on trunk control during asymmetric lifting task in patients with recurrent low back pain. Global Spine J. 2020;10(8):1006–14.
10. Ward SR, Kim CW, Eng CM, Gottschalk LJ, Tomiya A, Garfin SR, et al. Architectural analysis and intraoperative measurements demonstrate the unique design of the multifidus muscle for lumbar spine stability. J Bone Joint Surg Am. 2009;91(1):176–85.
11. Bogduk N, Macintosh JE, Pearcy MJ. A universal model of the lumbar back muscles in the upright position. Spine (Phila Pa 1976). 1992;17(8):897–913.
12. Bok DH, Kim J, Kim TH. Comparison of MRI-defined back muscles volume between patients with ankylosing spondylitis and control patients with chronic back pain: age and spinopelvic alignment matched study. Eur Spine J. 2017;26(2):528–37.
13. Masaki M, Ikezoe T, Fukumoto Y, Minami S, Tsukagoshi R, Sakuma K, et al. Association of sagittal spinal alignment with thickness and echo intensity of lumbar back muscles in middle-aged and elderly women. Arch Gerontol Geriatr. 2015;61(2):197–201.

14. Jun HS, Kim JH, Ahn JH, Chang IB, Song JH, Kim TH, et al. The effect of lumbar spinal muscle on spinal sagittal alignment: evaluating muscle quantity and quality. Neurosurgery. 2016;79(6):847–55.
15. Martin S, Tallian K, Nguyen VT, van Dyke J, Sikand H. Does early physical therapy intervention reduce opioid burden and improve functionality in the management of chronic lower back pain? Ment Health Clin. 2020;10(4):215–21.
16. Lee SH, Park SW, Kim YB, Nam TK, Lee YS. The fatty degeneration of lumbar paraspinal muscles on computed tomography scan according to age and disc level. Spine J. 2017;17(1):81–7.
17. Battaglia PJ, Maeda Y, Welk A, Hough B, Kettner N. Reliability of the Goutallier classification in quantifying muscle fatty degeneration in the lumbar multifidus using magnetic resonance imaging. J Manip Physiol Ther. 2014;37(3):190–7.
18. Goutallier D, Postel JM, Bernageau J, Lavau L, Voisin MC. Fatty muscle degeneration in cuff ruptures. Pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res. 1994;304:78–83.
19. Zhang B, Wang L, Wang H, Guo Q, Lu X, Chen D. Lumbosacral transitional vertebra: possible role in the pathogenesis of adolescent lumbar disc herniation. World Neurosurg. 2017;107:983–9.
20. Aihara T, Takahashi K, Ogasawara A, Itadera E, Ono Y, Moriya H. Intervertebral disc degeneration associated with lumbosacral transitional vertebrae: a clinical and anatomical study. J Bone Joint Surg (Br). 2005;87(5):687–91.
21. Luoma K, Vehmas T, Raininko R, Luukkonen R, Riihimäki H. Lumbosacral transitional vertebra: relation to disc degeneration and low back pain. Spine (Phila Pa 1976). 2004;29(2):200–5.
22. O'Sullivan PB, Dankaerts W, Burnett AF, Farrell GT, Jefford E, Naylor CS, et al. Effect of different upright sitting postures on spinal-pelvic curvature and trunk muscle activation in a pain-free population. Spine (Phila Pa 1976). 2006;31(19):E707–12.
23. Pezolato A, de Vasconcelos EE, Defino HL, Nogueira-Barbosa MH. Fat infiltration in the lumbar multifidus and erector spinae muscles in subjects with sway-back posture. Eur Spine J. 2012;21(11):2158–64.
24. Bahadir Ulger FE, Illeez OG. The effect of lumbosacral transitional vertebrae (LSTV) on paraspinal muscle volume in patients with low back pain. Acad Radiol. 2020;27(7):944–50.
25. de Campos TF, Maher CG, Fuller JT, Steffens D, Attwell S, Hancock MJ. Prevention strategies to reduce future impact of low back pain: a systematic review and meta-analysis. Br J Sports Med. 2020. https://doi.org/10.1136/bjsports-2019-101436.
26. Steffens D, Maher CG, Pereira LS, Stevens ML, Oliveira VC, Chapple M, et al. Prevention of low back pain: a systematic review and meta-analysis. JAMA Intern Med. 2016;176(2):199–208.

2.5 Einfluss lumbo-sacraler Übergangsstörungen auf die spino-pelvine Verankerung

Becker L, Schömig F, Haffer H, Ziegeler K, Diekhoff T, Pumberger M

Safe Zones for Spinopelvic Screws in Patients With Lumbosacral Transitional Vertebra.

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Der Einfluss der lumbo-sacralen Übergangsstörung auf Therapiekonzepte geht jedoch über die in Arbeit 3 und Arbeit 4 gezeigten Auswirkungen auf die Bewegungsfunktion und Muskeladaptationen mit Implikationen für die konservative Therapie hinaus, es resultieren ebenso Besonderheiten für die operative Therapie. Durch eine Veränderung der knöchernen Anatomie des Beckens sowie der neuro-vaskulären Strukturen im Rahmen von lumbo-sacralen Übergangsstörungen resultieren Risiken bei der spino-pelvinen Verankerung bei fehlender Anpassung der Schraubentrajektorien [92, 93, 102].

Es wurde daher retrospektiv die Sicherheit verschiedener Schraubentrajektorien der S1-Pedikel-Schraube (S1PS), der S2-Ala-Schraube (S2AS), der S2-Ala-Ilium-Schraube (S2AIS) und der Iliumschraube (IS) bei 49 Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen untersucht.

Wir werteten insgesamt 10.192 Schraubentrajektorien aus. Es traten keine neuro-vaskulären Komplikationen bei den für die S1PS untersuchten Trajektorien auf. Lumbo-sacrale Übergangsstörungen erhöhten das Risiko einer Gefäßverletzung bei S2AS-Trajektorien (p=0,001), nicht aber bei S2AIS (p=0,526).

Die sacrale Verankerung von langen Wirbelsäulenkonstruktionen mit S1PS, S2AS, S2AIS und IS ist auch bei Vorhandensein von lumbo-sacralen Übergangsstörungen möglich. Bei S2AS zeigte die Trajektorie mit 30° lateraler und 10° kaudaler Angulation die geringsten Gefäßverletzungen und die geringste Rate an Verletzungen des Iliosacralgelenkes bei Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung. S2AIS-Trajektorien mit 40° lateraler und 0° sagittaler Angulation minimierten das Risiko schwerer Komplikationen für Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen.

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Safe Zones for Spinopelvic Screws in Patients With Lumbosacral Transitional Vertebra

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Abstract

Study Design: Retrospective matched-pair analysis.

Objectives: Lumbosacral transitional vertebrae (LSTV) have a reported prevalence of 4-36% in the population. The safe zones for screw placement for spinopelvic fusion in adult spinal deformity surgery for patients with LSTV have not been described in the literature. Our study aimed to assess the safety of S1-pedicle screw (S1PS), S2-alar screw (S2AS), S2-alar-iliac screw (S2AIS), and iliac screw (IS) placement in patients with LSTV.

Methods: Out of the 819 examined patients, 49 patients with LSTV were included in our retrospective analysis with a matched pair control group. We used the 3-dimensional planning tool mediCAD for screw placement of S1PS, S2AS, S2AIS, IS with different angles, length and diameters.

Results: We evaluated a total of 10 192 screw trajectories. No serious complications occurred due to the trajectories used for S1PS. LSTV increased the risk of vessel injury for S2AS trajectories (*P* ¼ .001) but not for S2AIS (*P* ¼ .526). Besides the presence of an LSTV, the screw trajectory had a major influence on the frequency of serious complications.

Conclusions: Sacral anchoring of long spinal constructions using S1PS, S2AS, S2AIS and IS is also possible in the presence of LSTV. For S2AS the trajectory with 30° lateral and caudal angulation of 10° showed the least vascular injuries and the least sacro-iliac-joint violations in patients with LSTV. S2AIS trajectories with 40° lateral and 0° sagittal angulation reduced the risk of serious complications in our patients collective with LSTV.

Keywords

LSTV, lumbarization, sacralization, S1-pedicle screw, S2-alar-screw, S2-alar-iliac-screw, iliac-screw, spino-pelvic fixation

Introduction

With a reported prevalence of 4-36% in the general population, lumbosacral transitional vertebrae (LSTV) are one of the most common congenital anomalies of the spine. LSTV is defined as either a sacralization of the lowest lumbar segment or a lumbarization of the superior sacral segment.[1,2] In 1984, a radiographic classification system was introduced by Castellvi et al, defining 4 different types of LSTVs as shown in Figure 1.[3]

Long spinal fusions are an increasingly common procedure in the surgical correction of adult spine deformity.[4] However, due to a high degree of mobility of the lumbosacral unit and intense stress on the sacrum, lumbosacral fusions show a high rate of pseudarthrosis and revision is indicated in about 25% of patients.[5] In order to prevent implant failure of fusions ending at S1, extension of the instrumentation to the pelvis has become increasingly common. However, spinopelvic fixation remains surgically challenging. Even though iliac screws provide biomechanically strong constructs, they may lead to wound dehiscence over screw heads or postoperative pain due to screw prominence, which is why S2-alar (S2AS) and S2-alar-iliac screws (S2AIS) were introduced.[6,7] In contrast to iliac screws

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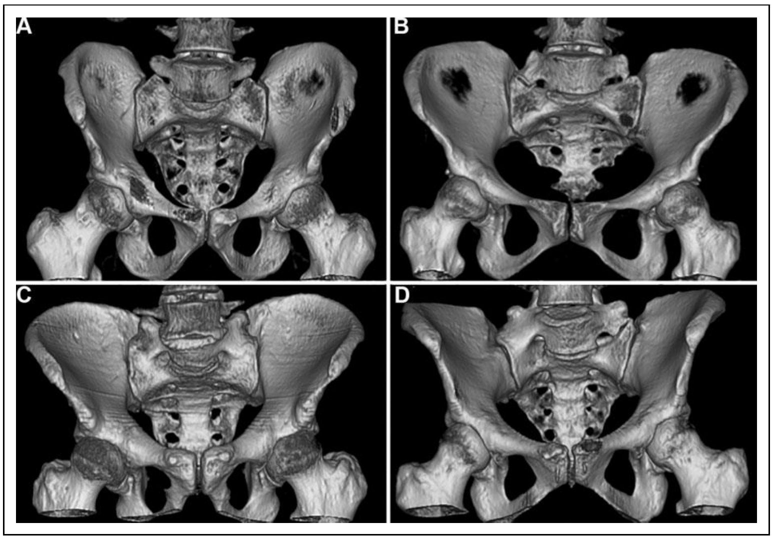

Figure 1. The Castelllvi classification allows the grouping in transitional vertebrae. Transitional vertebrae with an enlargement of the transverse process to at least 19.0 mm are classified as unilateral (Ia) or bilateral (Ib) (A). Pseudarticulation of the transversal process with the sacral bone is classified as IIa in unilateral occurrence and IIb (B) in bilateral occurrence. The fusion of the transversal process with the sacral bone is classified as IIIa in the case of unilateral occurrence and as IIIb (C) in the case of bilateral occurrence. Unilateral fusion and contralateral pseudarticulation of the transversal process with the sacral bone are classified as Castellvi IV (D).[3]

(IS), S2AIS require a deeper insertion point which is in line with that of S1-pedicle screws (S1PS) and thus offset use is not required.[8] A recent meta-analysis of 11 studies showed that S2AIS fixation has an improved fusion rate as well as fewer postoperative complications and reoperation rate compared with IS fixation.[9]

Placement of S2AS, S2AIS or IS remain potentially problematic with complications ranging from decreased fixation strength to injury of major vessels which is why safe insertion of these screws is crucial. However, to our knowledge, a larger analysis of safe spinopelvic screw insertion in patients with LSTVs has not been investigated yet. Our study's aim therefore was to assess the feasibility and safety regarding screw length, diameter and angles as well as complications of S1PS, S2AS, S2AIS and IS insertion in patients with LSTV compared to a matched control group.

Material and Methods

Patients

The study protocol was approved by the local institutional ethics board (ethics proposal number EA1/300/19). We retrospectively included patients in which abdominal-pelvic computed tomographies (CTs) from at least level L1 to the greater trochanter of the femur had been performed in our department of radiology from 2016 to 2019 due to tumor staging or exclusion of visceral bleeding. Exclusion criteria were metastatic and primary malignancy of the musculoskeletal system and previous spinal or pelvic fusion surgery. A total of 819 patients were identified, of which 52 showed anatomical changes in the lumbosacral transition. Three were excluded because of inadequate image quality for software evaluation. The remaining 49 patients were matched with control patients from the cohort described above, using propensity score matching with a tolerance of 0.01, matching for age and gender. The data was collected and analyzed completely anonymized, patients informed consent was not required by the local ethics committee.

Radiographic Measurements

CT images were reconstructed with the Food and Drug Administration certified hybrid planning spine 3D reconstruction software (mediCAD Hectec GmbH, Germany). The screw trajectories were placed by one of the authors (B.L.), a spinal surgeon trained by a spinal attending surgeon (author; M.P.). Screw malplacement was assessed in a consensus reading approach in order to minimize the risk of systematic bias.

LSTVs were detected by 2 independent experienced radiologists. The vertebral body S1 was defined as the first vertebral body below an at least rudimentary vertebral disc. To normalize the screw trajectory angles and reduce bias opportunities, the oblique lying position of the patients on CT table was evaluated and

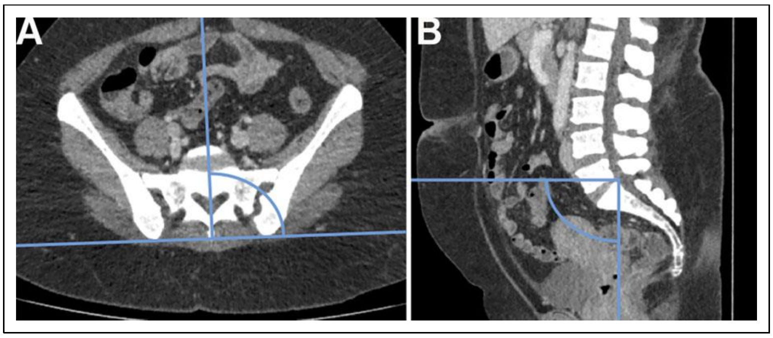

Figure 2. In (A) an axial CT image is shown, in which the line connecting the 2 spinae iliacae posteriores superiores and the orthogonal line defining 0° axial angulation are highlighted. In (B) a sagittal CT image is shown. A line parallel to the CT table and a line orthogonal to it defining 0° sagittal angulation are depicted. The intersection of the 2 lines was placed on each predefined screw entry point for screw placement.

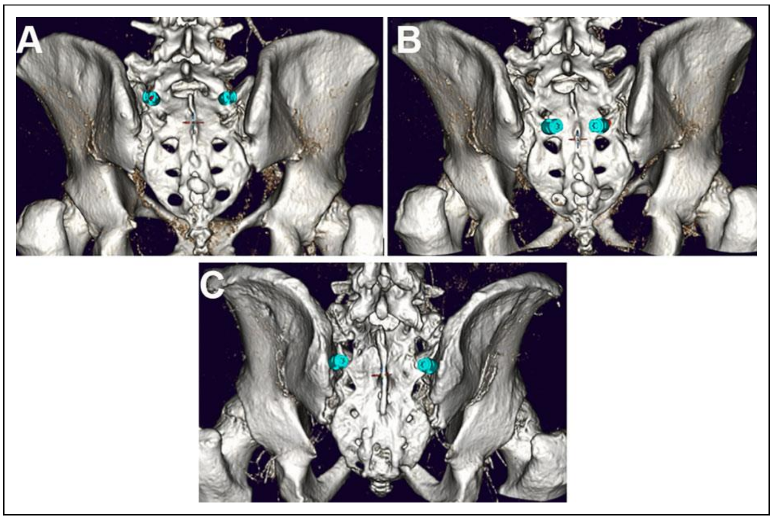

Figure 3. For the S1PS trajectory (A) the intersection between a transverse line at the level of the inferior tip of the inferior articular process of L5 and a longitudinal line along the ridge of the superior articular process of S1 was selected as the screw entry point.[5,10] For S2AS and S2AIS trajectories (B) the intersection between a vertical line through the S1 and S2 dorsal foramina and midway between these dorsal foraminae was selected as the screw entry point.[5,10] For the IS (C) trajectory the entry point was selected 1 cm medial to the iliac crest and inferior to the spina iliaca posterior superior.[11]

reflected in the placement of the screw trajectories. For this purpose, a line tangentially intersecting both spinae iliacae posteriores superiores was defined in the axial plane. An orthogonal line to this line was defined as 0° axial angulation. The sagittal screw angulation was determined in the sagittal plane. The line that was perpendicular to the displayed CT table in the sagittal plane was defined as 0° sagittal angulation as shown in Figure 2.

All screw trajectories were examined for penetrating the cortical bone apart from the entry point, which was classified as a cortical breach. Entry points were defined as mentioned in Figure 3.

For all screw trajectories the interference of the screw trajectory with iliac or gluteal vessels was assessed as presented in Figure 4. In case of even partial interference, this was evaluated as vascular injury.

We subgrouped each patient side according to the extent of the transition to 1 of the 4 groups: No transition, enlarged transverse processes, pseudarthrosis, osseous fusion. For

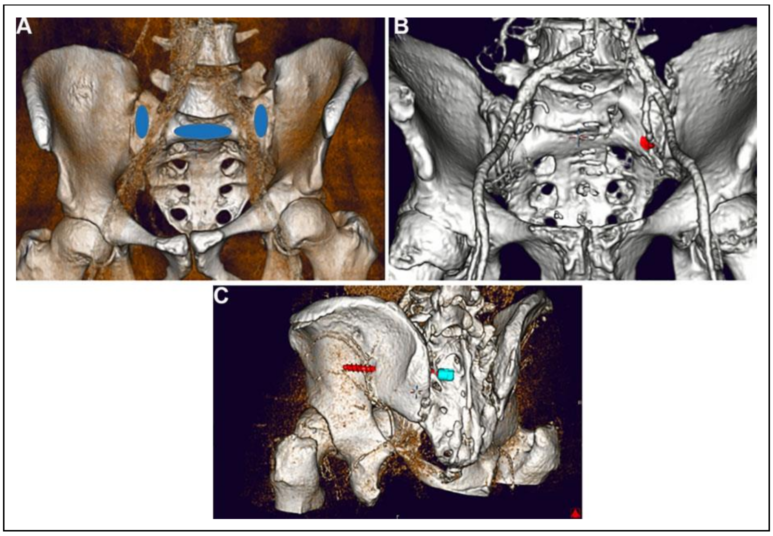

Figure 4. A, Anterior vessel interference in a patient with LSTV due to an S2AS with 30° lateral and 25° sagittal angulation, 8.5 mm diameter and 50 mm length. B, Posterior vessel injury due to an S2AIS with 60° lateral and 10° sagittal angulation, 9.5 mm diameter and 95 mm length.

Table 1. Examined Screw Diameters, Length and Screw Trajectory.[5,8,11,17,23,24,25]

	Diameter 1	Diameter 2	Length 1	Length 2	Sagittal Ang. 1	Sagittal Ang. 2	Axial Ang. 1	Axial Ang. 2
S1PS	6.5 mm	∅	45 mm	∅	10°	25°	20°	30°
S2AS	6.5 mm	8.5 mm	45 mm	50 mm	10°	25°	30°	45°
S2AIS	6.5 mm	9.5 mm	65 mm	95 mm	0°	10°	40°	60°
IS	6.5 mm	9.5 mm	65 mm	95 mm	30°	45°	20°	35°

Abbreviation: Ang., angulation.

S1PS trajectories accuracy of the pedicle screw position regarding the medial pedicle breach was evaluated using the Rampersaud classification.[12] For S2AS trajectories position in relation to the sacroiliac joint (SIJ) was additionally classified (0 = no SIJ infiltration, 1 = infiltration of the os sacrum cortex (belonging to the SIJ), 2 = in the SIJ gap, 3 = infiltration os ilium). In all patients, all the screw trajectories options listed in Table 1 were placed on both sides of the os sacrum/ilium. Examples of screw trajectories are presented in Figure 5.

Statistical Analysis

All statistical analyzes were performed using IBM SPSS Statistics 27 software (IBM, Armonk, USA). The chi-square test was used for nominal scaled variables and for metrical data Wilcoxon signed-rank test. The association between the degree of fusion (none, enlarged transverse process, pseudoarticulation, fusion) and breach frequencies was investigated using Spearman's correlation coefficients. We tested the data for statistically significant frequency distributions of screw breaches, vascular injuries and SIJ violations depending on the screw trajectory of the defined groups against each other. A P-value $< .05$ was considered statistically significant.

Results

Patients

Based on the study design there were no significant differences in age (mean 52.0 years, range 16-81/19-86 years (LSTV/control) $P = .893$) and gender (24/49 female and 25/49 male in LSTV and control group). Transitional vertebrae had a prevalence of 6.3% in our patient's population. Castellvi types in our population are given in Table 2.

S1-Pedicle Screw

None of the 784 S1PS trajectories showed neither a violation of the spinal canal nor vascular injury. Patients with LSTV were significantly more likely to have a ventral screw breach with selected screw trajectories ($P < .001$; LSTV 98/392, control 43/392). Castellvi type of LSTV significantly correlated with the frequency of a ventral breach of the screw tip ($P = .009$, r = 0.132).

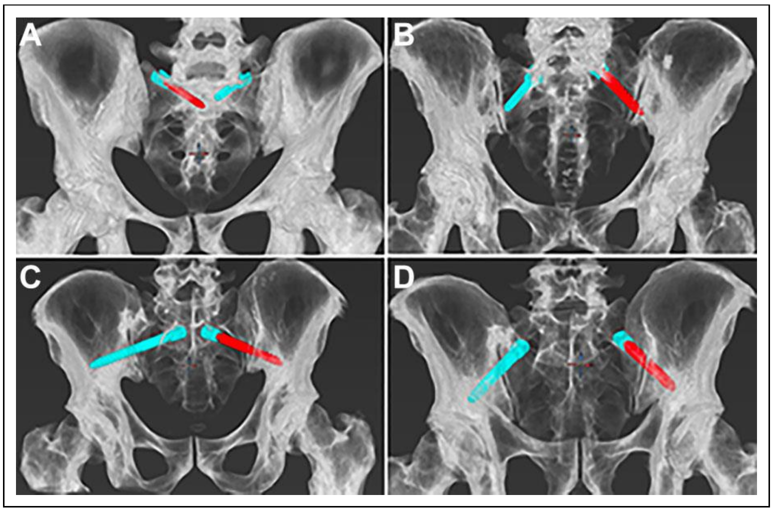

Figure 5. Examples of screw positioning of S1PS (A) with 30° medial and 25° sagittal angulation on the right sacral side and 20° medial and 10° sagittal angulation on the left sacral side, each 6.5 mm in diameter and 45 mm length. S2AS (B) right with 30° lateral and 10° sagittal angulation, left with SIJ violation with 45° lateral and 25° caudal angulation each with a screw diameter of 8.5 mm and a screw length of 50 mm. S2AIS (C) right with 40° lateral and 0° caudal angulation, left with dorsal screw breach at 60° lateral and 10° caudal angulation with a screw diameter of 9.5 mm and a screw length of 95 mm. IS (D) right with 20° lateral and 30° caudal angulation and left with 35° lateral and 45° caudal angulation.

Table 2. Degree of Expression of Transition in Our Patients Sample Regarding Castellvi-Classification.[3]

	Castellvi classification			
	I	II	III	IV
n =	16	23	6	4

Upper end plate infiltration did not differ significantly between the control group and LSTV ($P = .720$) nor was it influenced by the Castellvi type ($P = .484$). Screw trajectories with 20° medial angulation instead of 30° resulted in significantly more ventral breaches in both the control group ($P < .001$; 20° 27/196, 30° 16/196) and patients with LSTV ($P < .001$, 20° 62/196, 30° 36/196). Sagittal angulation had a significant effect on the overall frequency of a breach in both the control group ($P < .028$; 10° 82/196, 25° 41/196) and patients with LSTV ($P < .001$; 10° 101/196, 25° 73/196). Screw trajectories with 10° sagittal angulation perforated the endplate by 38.27% whereas trajectories with 25° sagittal angulation infiltrated the endplate only by 1.53% ($P = .149$; 10° sagittal angulation 150/392, 25° 6/392).

S2-Alar Screw

1252 of the 3136 tested S2AS trajectories caused a breach. The frequency of ventral screw breaches of the trajectories did not differ significantly between the control group and patients with LSTV ($P = .141$; LSTV: 40/1586, control: 28/1586). However, patients with LSTV were significantly more likely to have a violation of the SIJ by S2AS trajectories tested ($P < .001$; LSTV 784/1586, control 400/1586). The frequency of SIJ injury by S2AS trajectories showed a significant but weak correlation with the degree of expression of a transitional vertebra ($P < .001$, $r = 0.109$).

In the group with LSTV, the reported S2AS trajectories led to significantly more vessel injuries ($P = .001$; LSTV 11/1568 vessel injuries, control 0/1568). The frequency of vascular injuries caused by S2AS trajectories showed no connection with the Castellvi type of LSTV ($P = .465$). Vascular injuries in patients with LSTV resulted only from screw trajectories with a lateral angulation of 30° and sagittal angulation of 25° (11/392) while none of the other screw trajectories led to vessel injury (0/1176). The use of screw trajectories with a length of 50 mm resulted in significantly more vascular injuries compared to 45 mm screws in the LSTV group ($P = .034$; 50 mm 9/784, 45 mm 2/784).

S2-Alar-Iliac Screw

Patients with LSTV showed significant more screw breaches than the control group caused by tested S2AIS trajectories ($P < .001$; LSTV 625/1568 screw breaches, control 590/1568). Ventral breaches of the screw trajectory were

Table 3. Overview of the Frequency of Anterior and Posterior Breaches of the Iliac Screws Depending on the Castellvi Classification.

	Control	Enlarged trans. proc.	Pseud-articulation	Fusion	LSTV versus control group
Anterior breach	2.4% (38/1568)	4.3% (16/368)	3.5% (20/576)	1.1% (2/176)	$P > .05$
Posterior breach	4.1% (64/1568)	4.9% (18/368)	7.3% (42/576)	1.1% (2/176)	$P > .05$

significantly more frequent in the control group ($P < .001$; LSTV 103/1568, control 278/1568), while dorsal exits were significantly more frequent in the group of LSTV patients ($P < .001$; LSTV 522/1568, control 312/1568).

The frequency of vascular injuries caused by S2AIS trajectories did not differ significantly between LSTV patients and the control group ($P = .526$; LSTV 6/1568, control 4/1568). However, degree of expression of LSTV correlated significant but poor with vascular injuries ($P < .001$, $r = 0.101$). Vessel injuries with the S2AIS trajectories occurred only with a lateral angulation of 60° and sagittal angulation of 10°. Screw trajectories with a length of 65 mm led to a significant reduction in vascular injuries compared with 95 mm screws ($P < .001$; 65 mm length 2/1568, 95 mm 8/1568). Whereas the screw trajectories diameter ($P = 1.00$) had no significant influence on the frequency of vascular injuries.

Iliac Screw

234 of the 3136 IS trajectories showed a breach. The anterior ($P = .502$) and posterior breach frequency ($P = .066$) did not differ significantly between the control group and patients with LSTV as presented in Table 3.

The screw trajectory with a lateral angulation of 20° did not differ significantly in the frequency of breaches compared to the 35° insertion ($P = .095$; 20° lateral angulation 77/1568, 35° 157/1568). Whereas trajectories with a sagittal angulation of 30° resulted in a significantly higher frequency of overall breaches compared to 45° downward angulation ($P < .001$; 30° downward angulation 149/1568, 45° 85/1568). A longer trajectory resulted in significantly more frequent breaches ($P < .001$; 65 mm screw length 25/1569, 95 mm 209/1568). Two screw misalignments occurred into the sciatic notch with a screw trajectory with a lateral angulation of 20° and a sagittal angulation of 45° downward for patients with LSTV. The frequency of vascular lesions for the trajectories of IS of LSTV patients and the control group did not differ significantly ($P = .057$; LSTV 8/1568, control group 2/1568). Vascular injuries with the IS trajectories occurred only with a lateral angulation of 35° (35° axial angulation 10/1568, 20° axial angulation 0/1568). Sagittal angulation of screw trajectories of 45° compared to 30° significantly increased the risk of vascular injury ($P < .001$; 30° 4/1568, 45° 6/1568) as well as the use of longer screws trajectories ($P < .001$; 65 mm 4/1568, 95 mm 6/1568). The screw diameter ($P = 1.00$) had no significant influence on the frequency of vascular injuries.

Discussion

As a clinical impact this study shows, that sacral anchoring of long spinal constructions using S1PS, S2AS and S2AIS is also possible and a safe option in the presence of LSTV.

S1-Pedicle Screw

S1PS with a bicortical anchorage have a lower risk of loosening.[5,13] Especially the anchorage by the S1 cover plate further increases the pull-out strength.[13,14] Considering these results, an S1PS with 10° sagittal angulation may lead to biomechanically superior fixation. While no spinal canal injury was detected independently of medial angulation. Convergence of the screws at 20° is recommended due to more frequent bicortical fixation. Consistent with the results in the literature, which report very low rates of vascular damage, no vascular injury was found regardless of the screw trajectory for control group and LSTV patients.[15]

S2-Alar Screw

Bicortical anchoring of S2AS leads to a lower risk of loosening[5,16] but increases the risk of injury to presacral neurovascular structures.[17] LSTV have a significant influence on the morphology of the os sacrum and the pelvis.[18] Our results confirm a higher risk of vascular injuries for patients with LSTV ($P = .001$), especially for longer screws ($P = .034$) and a trajectory with a steeper caudal angulation of 25° ($P = .001$). Accordingly, insertion with 10° angulation and utilization of shorter screws could reduce the risk of vascular injury for patients with LSTV. Maximum tested lateral angulation angle for S2AS lead to an increased rate of SIJ injuries in patients with LSTV ($P < .001$), so a lateral angulation of 30° and 10° caudal angulation should be considered for placement.

S2-Alar-Iliac Screw

S2-alar-iliac screws seems to have clinically lower complication rates compared to iliac screws.[9,19,20] According to the findings of Yamada et al, that a low-riding L5 vertebra is supposed to reduce the safety margin for the implantation of a S2-alar-iliac screw[11] we saw a significant ($P < .001$) accumulation of dorsal breaches in LSTV. The bicortical anchorage in the os ilium does not lead to biomechanical superiority of the screws.[21] A screw trajectory of 40° lateral angulation significantly reduced the breach frequency and lowered the risk for serious complications with injury to the superior gluteal artery ($P = .014$).

For the treatment of transitional vertebrae, the need for a higher cranial entry point was reported.[22] Screw trajectories with a sagittal angulation of 0° showed no vascular injury, whereas trajectories with a 10° sagittal angulation showed 0.8% vascular injury ($P = .014$). According to these results, it should be considered to choose the trajectory of S2AIS angulated 40° laterally and 0°.

Longer trajectories had a significantly higher frequency of breaches ($P < .001$). O'Brien et al showed that S2AIS with a length of 65 mm could be biomechanically equivalent to screws with a length of 80 mm.[21] Recognizing this fact, the need for a longer S2AIS for each specific fusion should be evaluated.

S2AIS, in contrast to the S2AS, did not affect the presacral vessels but, with the trajectories selected, mainly posed a risk of injury to the superior gluteal artery. LSTV did not lead to an increased risk of vascular injury in S2AIS. Therefore S2AIS can be considered as an safe alternative for spinopelvic anchoring in patients with LSTV.

Iliac Screw

The complications of IS did not differ significantly between the control group and patients with LSTV ($P = .057$). In screw trajectories with 20° lateral angulation, no vascular injury occurred. Sagittal angulation of 45° significantly reduced the breach frequency and therefore should be preferred compared to 30° but did not affect the frequency of vascular lesions.

Limitations

Despite the significant and clinically relevant findings of our study, there are remaining limitations and the results have to be interpreted accordingly. Since each parameter of the screw geometry and angulation has a 3-dimensional influence on possible complications. The clinical implication of this manuscript should not be the ideal screw position, rather illustrate common complications. We evaluated 49 patients with LSTV this might compromise the generalization of the results. Not all of the Castellvi subgroups included the same number of patients, this introduces a bias opportunity. We examined a patient population that did not receive the imaging due to back pain and therefore might differ in the degree of degeneration from a typical patient population for spine surgery. The investigator could see the vessels during screw placement, but the angles for the screw trajectories were applied as described in the methods and the screw trajectories were placed based on this and the defined entry point so that a bias opportunity was reduced as much as possible.

Conclusion

This is, to the knowledge of the authors, the first clinical study to evaluate the safe zones for spinopelvic anchoring of screws in patients with LSTV compared to a matched control group. Due to more frequent screw misalignments in patients with LSTV, sectional imaging may need to be performed more frequently and detailed screw placement planning should be performed. The studied screw trajectories provided a safe insertion of S1PS in LSTV regarding vascular and spinal canal injury. LSTV increased the risk of vessel injury by using S2AS. The S2AS with 30° angulation laterally and a caudal angulation of 10° showed the least vascular injuries and the least SIJ violations in patients with LSTV. No increased risk of vascular injury was found for the S2AIS in patients with LSTV in our patients collective with LSTV. No increased risk of vascular or nerve injury was observed for IS in our patient population with LSTV. Based on our results, in patients with LSTV requiring augmentation of the spino-sacral fixation, the use of S2AIS as well as IS should be considered due to the lower risk of vascular injury evaluated in our collective when compared with S2AS. If fixation with S2AS is necessary in patients with LSTV despite the possible increased risk of vascular injury, a prior detailed radiographic assessment using cross-sectional imaging and preoperative planning of screw trajectories should be performed to account for the altered bone and soft tissue anatomy. Intraoperative navigation could further aid to improve patient safety for S2AS in LSTV patients.

Declaration of Conflicting Interests

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References

1. Konin GP, Walz DM. Lumbosacral transitional vertebrae: classification, imaging findings, and clinical relevance. *AJNR Am J Neuroradiol*. 2010;31(10):1778-1786.
2. Matson DM, Maccormick LM, Sembrano JN, Polly DW. Sacral dysmorphism and lumbosacral transitional vertebrae (LSTV) review. *Int J Spine Surg*. 2020;14(Suppl 1):14-19.
3. Castellvi AE, Goldstein LA, Chan DP. Lumbosacral transitional vertebrae and their relationship with lumbar extradural defects. *Spine (Phila Pa 1976)*. 1984;9(5):493-495.
4. Rajaee SS, Bae HW, Kanim LE, Delamarter RB. Spinal fusion in the United States: analysis of trends from 1998 to 2008. *Spine (Phila Pa 1976)*. 2012;37(1):67-76.
5. Koller H, Zenner J, Hempfing A, Ferraris L, Meier O. Reinforcement of lumbosacral instrumentation using S1-pedicle screws combined with S2-alar screws. *Oper Orthop Traumatol*. 2013; 25(3):294-314.
6. Jain A, Hassanzadeh H, Strike SA, Menga EN, Sponseller PD, Kebaish KM. Pelvic fixation in adult and pediatric spine surgery: historical perspective, indications, and techniques: AAOS exhibit selection. *J Bone Joint Surg Am*. 2015;97(18):1521-1528.
7. Sponseller P. The S2 portal to the ilium. *Semin Spine Surg*. 2007; 2(2):83-87.

8. Chang TL, Sponseller PD, Kebaish KM, Fishman EK. Low profile pelvic fixation: anatomic parameters for sacral alar-iliac fixation versus traditional iliac fixation. *Spine (Phila Pa 1976)*. 2009; 34(5):436-440.
9. Keorochana G, Arirachakaran A, Setrkraising K, Kongtharvonskul J. Comparison of complications and revisions after sacral 2 alar iliac screw and iliac screw fixation for sacropelvic fixation in pediatric and adult populations: systematic review and meta-analysis. *World Neurosurg*. 2019;132:408-420. e1.
10. Kwan MK, Jeffry A, Chan CY, Saw LB. A radiological evaluation of the morphometry and safety of S1, S2 and S2-ilium screws in the Asian population using three dimensional computed tomography scan: an analysis of 180 pelvis. *Surg Radiol Anat*. 2012;34(3): 217-227.
11. Yamada K, Abe Y, Satoh S. Safe insertion of S-2 alar iliac screws: radiological comparison between 2 insertion points using computed tomography and 3D analysis software. *J Neurosurg Spine*. 2018;28(5):536-542.
12. Rampersaud YR, Pik JH, Salonen D, Farooq S. Clinical accuracy of fluoroscopic computer-assisted pedicle screw fixation: a CT analysis. *Spine (Phila Pa 1976)*. 2005;30(7):E183-190.
13. Orita S, Ohtori S, Eguchi Y, et al. Radiographic evaluation of monocortical versus tricortical purchase approaches in lumbosacral fixation with sacral pedicle screws: a prospective study of ninety consecutive patients. *Spine (Phila Pa 1976)*. 2010;35(22): E1230-1237.
14. Luk KD, Chen L, Lu WW. A stronger bicortical sacral pedicle screw fixation through the s1 endplate: an in vitro cyclic loading and pull-out force evaluation. *Spine (Phila Pa 1976)*. 2005;30(5): 525-529.
15. Parker SL, McGirt MJ, Farber SH, et al. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery*. 2011;68(1):170-178.
16. Zindrick MR, Wiltse LL, Widell EH, et al. A biomechanical study of intrapeduncular screw fixation in the lumbosacral spine. *Clin Orthop Relat Res*. 1986(203):99-112.
17. Mirkovic S, Abitbol JJ, Steinman J, et al. Anatomic consideration for sacral screw placement. *Spine (Phila Pa 1976)*. 1991;16(6 Suppl):S289-294.
18. Mahato NK. Relationship of sacral articular surfaces and gender with occurrence of lumbosacral transitional vertebrae. *Spine J*. 2011;11(10):961-965.
19. De la Garza Ramos R, Nakhla J, Sciubba DM, Yassari R. Iliac screw versus S2 alar-iliac screw fixation in adults: a meta-analysis. *J Neurosurg Spine*. 2018;30(2):253-258.
20. Hasan MY, Liu G, Wong HK, Tan JH. Postoperative complications of S2AI versus iliac screw in spinopelvic fixation: a meta-analysis and recent trends review. *Spine J*. 2020;20(6):964-972.
21. O'Brien JR, Yu W, Kaufman BE, et al. Biomechanical evaluation of S2 alar-iliac screws: effect of length and quad-cortical purchase as compared with iliac fixation. *Spine (Phila Pa 1976)*. 2013; 38(20):E1250-1255.
22. Lin JD, Tan LA, Wei C, et al. The posterior superior iliac spine and sacral laminar slope: key anatomical landmarks for freehand S2-alar-iliac screw placement. *J Neurosurg Spine*. 2018;29(4):429-434.
23. Arman C, Naderi S, Kiray A, et al. The human sacrum and safe approaches for screw placement. *J Clin Neurosci*. 2009;16(8): 1046-1049.
24. Ebraheim NA, Xu R, Biyani A, Nadaud MC. Morphologic considerations of the first sacral pedicle for iliosacral screw placement. *Spine (Phila Pa 1976)*. 1997;22(8):841-846.
25. Okutan O, Kaptanoglu E, Solaroglu I, Beskonakli E, Tekdemir I. Determination of the length of anteromedial screw trajectory by measuring interforaminal distance in the first sacral vertebra. *Spine (Phila Pa 1976)*. 2004;29(15):1608-1611.

3. Diskussion

Die vorliegende Arbeit beurteilt klinische (Arbeit 1) und nicht-invasive objektivierbare Messverfahren (Arbeit 2) zur Erfassung der Wirbelsäule als Bewegungsorgan sowie des Einflusses von lumbo-sacralen Übergangsstörungen auf die Rückenfunktion (Arbeit 3) und Anatomie des Bewegungsapparates (Arbeit 4) mit konsekutiven Therapieimplikationen (Arbeit 5). Dabei konnte gezeigt werden, dass klinische Untersuchungstests anhand des Beispiels des Finger-Boden-Abstands eine nur eingeschränkte Validität für die Beurteilung der spino-pelvinen Bewegung aufweisen [103]. Demgegenüber lassen sich durch nicht-invasive Messinstrumente wie Epionics SPINE, die Rasterstereographie oder der Idiag M360 objektivierbare, untersucherunabhängige und valide Werte für die Rückenform und -funktion erheben. Jedoch zeigen die Messwerte der Einzelinstrumente signifikante Differenzen im intermodalen Vergleich, sodass für longitudinale Funktionsbeurteilungen lediglich ein Einzelmessinstrument verwendet werden sollte [104]. Die Beurteilung der Rückenfunktion stellt durch die gegenseitige Beeinflussung von Form und Funktion einen relevanten Parameter für die Planung konservativer und operativer Therapieverfahren dar und ist maßgeblich in der pathophysiologischen Einschätzung von Wirbelsäulenerkrankungen. So zeigt sich auch für lumbo-sacrale Übergangsstörungen ein Einfluss auf die Bewegung mit einer verringerten Mobilität des Übergangssegments sowie einer relativ vermehrten Bewegung im kranialen Anschlusssegment, das von einer erhöhten Rate an Degenerationen betroffen ist [51, 66, 101]. Diese Funktionsveränderungen spiegeln sich in muskulären Adaptationen mit einem reduzierten Volumen der Rumpfmuskulatur sowie einem höheren Degenerationsgrad der Muskulatur wider [105]. Einhergehend mit den Einflüssen auf den Bewegungsapparat, ossären Unterschieden sowie der neurovaskulären Anatomie ergeben sich Besonderheiten für die Notwendigkeit der operativen Zugangswege sowie der Schraubenplatzierung im Rahmen der spino-pelvinen Verankerung. Hierbei zeigt sich, dass die Verwendung von S2-Ala-Ilium Schrauben auch bei Vorhandensein einer lumbo-sacralen Übergangsstörung ein sicheres Verfahren darstellen kann [106]. Jedoch haben lumbo-sacrale Übergangsstörungen nicht nur einen lokalen Einfluss auf den Bewegungsapparat, vielmehr resultieren ebenso Adaptionen der Partner in beteiligten Bewegungsketten. Dabei zeigt sich ein Einfluss auf die Beckenkonfiguration [93] sowie auf die acetabuläre Orientierung [65, 107].

3.1 Interaktion von Rückenform und -funktion

Die Wirbelsäule des Menschen ist ein Paradebeispiel des Einflusses der Funktion auf die Wirbelsäulenform. Während Neugeborene das Licht der Welt mit einer nahezu geraden Wirbelsäule erblicken, entwickelt sich die Lordose der HWS im Rahmen des Anhebens des Kopfes. Mit einer zunehmenden Vertikalisierung des Lebensstils bildet sich zunehmend unsere doppelt S-förmige Wirbelsäule aus [20]. Durch stetige Bewegung und Belastung sowie Alterung resultiert eine im Alter zunehmende Degeneration der Wirbelsäule. Diese geht häufig mit einer lumbalen Abflachung und thorakalen Hyperkyphosierung sowie einer Reduktion der zervikalen Lordose einher und wird zur Aufrechterhaltung der sagittalen Balancierung durch eine pelvine Retroversion kompensiert [108]. Gleichsam ist jedoch eine relevante Formveränderungen wie beispielsweise durch Verknöcherungen bei der Spondylitis ankylosans mit einem maßgeblichen Verlust der dynamischen Funktion des Achsskeletts assoziiert [109].

Trotz des Wissens über den engen Zusammenhang zwischen Form und Funktion sowie der Adaptationsprinzipien des Bewegungsapparates gegenüber einwirkenden Belastungen stellt für die operative Wirbelsäulentherapie ein maßgebliches Kriterium vor allem die Wiederherstellung der Wirbelsäulenform dar. Hierfür wurden im Speziellen für Deformitätenkorrekturen klare Zielvorgaben für das Sagittal- sowie Frontalprofil beispielsweise durch den ‚Global Alignment and Proportion (GAP) Score' definiert [110]. Jedoch zeigt die Literatur, dass trotz korrekter Wiederherstellung der Form in einem Drittel der Fälle eine radiologisch ersichtliche Implantat-assoziierte Komplikation durch Stabbrüche, Lockerungen oder kraniale Anschlussfrakturen mit einer proximalen junktionalen Kyphosierung im Rahmen von langstreckigen Spondylodesen im Rahmen der adulten Deformitätenkorrekturen resultiert [111]. Ebenso stellt die relevante Rate an Anschlussdegenerationen bei Spondylodesen für die Wirbelsäulenchirurgie nach wie vor eine Herausforderung dar. Dabei treten entsprechende Komplikationen trotz Wiederherstellung der anvisierten Wirbelsäulenform auf [112]. Neben biologischen Faktoren und natürlichen Degenerationsprozessen wird die Funktionsveränderung mit einer kompensatorisch vermehrten Belastung der angrenzenden Strukturen als ursächlich für die dargelegten Komplikationen diskutiert [113]. Jedoch findet weder die präoperative- ebenso wenig wie die postoperative spino-pelvine dynamische Funktion in entsprechenden

Korrekturformeln des Achsskelettes einen Einfluss, obwohl diese möglicherweise als relevanter Parameter für die resultierende Beanspruchung zu betrachten ist.

Demgegenüber zeigt eine rezente Arbeit, dass durch die Analyse der Alltagshaltung und Bewegung wesentliche Erkenntnisse auf den Krankheitsprogress von neuromuskulären Erkrankungen mit Wirbelsäulenbeteiligung prognostiziert werden können [114]. Entsprechend sollte perspektivisch nicht nur die morphologische Erfassung einer Pathologie, sondern vielmehr eine Einordnung des Einflusses auf die wechselseitige Interaktion von Form und Funktion des Achsskelettes sowie der involvierten Bewegungsketten erfolgen.

Derart detaillierte Aussagen können aus klinischen Untersuchungstest wie dem Finger-Boden-Abstand aufgrund der punktuellen Erhebung nicht gewonnen werden. Zudem weisen diese aufgrund des Einbezugs von Bewegungsketten sowie anthropometrischer Differenzen nur eine eingeschränkte Aussage über die lumbale Mobilität auf. Insbesondere sollten interindividuelle Vergleiche der endgradigen Werte zur Beurteilung der Rückenfunktion vermieden werden. In der personenindividuellen Betrachtung ermöglicht der Parameter jedoch – die konstante Hüftfunktion über den longitudinalen Beurteilungszeitraum vorausgesetzt – aufgrund der gleichbleibenden maßgeblichen anthropometrischen Daten eine Aussage über Veränderungen in der Rückenbeweglichkeit und ist damit in der orientierenden Verlaufsbeurteilung ein einfach zu erhebender Parameter [103].

Neben der klinischen Untersuchung treten zunehmend Messinstrumente zur nicht-invasiven Beurteilung der Rückenform auf den Markt um bei seriellen Untersuchungen resultierende Röntgenbilder mit kumulativer Strahlenbelastung von Patientinnen und Patienten, die sich einer längerfristigen Therapie aufgrund von Wirbelsäulenbeschwerden unterziehen zu vermeiden und objektivierbare untersucherunabhängige Aussagen über die Rückenform und -beweglichkeit zu erhalten. Exemplarisch seien hierfür neben den bereits erläuterten und zu Teilen für den klinischen Gebrauch validierten und zugelassenen Messgeräten Idiag M360 [115], Epionics SPINE [116] sowie der Rastersterography [117] die vorwiegend im Forschungskontext benutzten Instrumente Vicon [118], Zebris [119], 3D SpineMoveGuard [120], X-Sens sensors [121] oder Arbeitsplatz bezogene Erfassungsinstrumente wie der Lumbar Motion Monitor [122] oder das CUELA System [123] genannt. Jedoch beruhen unterschiedliche Messinstrumente auf verschiedenen

Definitionen der lumbalen Lordose, erfassen die Rückenform nicht konsistent im Bereich der Processi spinosi sondern teils ebenso paravertebral und beruhen auf optischen, mechano-sensitiven oder Lagesensoren. Entsprechend zeigen sich trotz jeweilig nachgewiesener Reliabilität und Validität von Messinstrumenten gegenüber dem Goldstandard, der röntgenologischen Bildgebung nur eine ungenügende Vergleichbarkeit in den absoluten Werten für die lumbale Form und Mobilität untereinander, sodass verlässliche Aussagen für longitudinale Untersuchungen nur bei Verwendung des gleichen Messinstruments zu treffen sind [104]. Ein relevanter Vorteil der nicht-invasiven Messinstrumente wie Epionics SPINE ist dabei, dass ohne Exposition von ionisierender Strahlung dynamische Prozesse als solche und nicht nur mittels Einzelaufnahmen im Vergleich zur Röntgendiagnostik beurteilbar gemacht werden und damit Alltagsbelastungen außerhalb artifizieller Untersuchungen aufzeigen können [116].

3.2 Einflussfaktoren auf die Dynamik und Statik des Achsskelettes

Faktoren, für die ein Einfluss auf die Rückenform und -funktion diskutiert wird, entstammen unterschiedlichster Dimensionen. Neben Faktoren wie degenerativen Veränderungen der Wirbelsäule [124] nehmen anatomische Variationen wie lumbosacrale Übergangsstörungen [101], Spondylolisthesen [125] oder die idiopathische Skoliose Einfluss [126]. Jedoch werden neben den greifbaren und objektivierbaren Formveränderungen auch Alterationen mit multimodaler Ursache unter Einbezug psycho-sozialer Faktoren wie der chronische Rückenschmerz in der Beeinflussung der Rückenform und -funktion kontrovers diskutiert.

Während für die Rückenform einerseits ein Zusammenhang zwischen einer reduzierten lumbalen Lordose sowie Rückenschmerzen berichtet wird [24, 127, 128], zeigen andere Übersichtsarbeiten keinen signifikanten Zusammenhang des Sagittalprofils der lumbalen Lordose gegenüber Rückenschmerzen auf [129, 130]. Ebenso besteht über die Interaktion der lumbalen Beweglichkeit gegenüber Rückenschmerzen kein Konsens, was möglicherweise aus der großen Heterogenität der Studien resultiert, die Patientinnen und Patienten mit spezifischen und unspezifischen Rückenschmerzen, unterschiedlichem Chronifizierungsgrad, Messmethoden der lumbalen Bewegung, Begleiterkrankungen und Altersstrukturen einschließen [129, 131-134]. Dies wird eindrucksvoll durch die berichteten Differenzen für Normwerte der lumbalen Flexionsfähigkeit in der Übersichtsarbeit von Laird et al. mit Unterschieden in den gesunden Kontrollkohorten der eingeschlossenen Arbeiten von bis zu 70° unterstrichen [129]. Gegenüber der sehr heterogenen Datenlage multidimensionaler Symptomkomplexe lässt sich die anatomische Variation leichter fassen und in ihrem Einfluss auf die Wirbelsäule beschreiben.

3.3 Die lumbo-sacrale Übergangsstörung als Einflussfaktor auf Form und Funktion

Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen sind ein Kollektiv, das sich häufig bereits in jüngerem Alter mit chronischen Rückenschmerzen ärztlich vorstellt [135] und signifikant häufiger Degenerationen der kranial angrenzenden Segmente wie Bandscheibendegenerationen, Facettengelenksarthrosen oder Spinalkanalstenosen aufweisen [51, 66]. Das gehäufte Auftreten tieflumbaler Schmerzen im jungen adulten Alter mit einer etwaigen zusätzlichen radikulären Schmerzkomponente wird unter dem Bertolotti‘s Syndrom subsumiert [58, 135]. Dies wird deutlich durch die höheren Prävalenzraten von lumbo-sacralen Übergangsstörungen in Kohortenstudien, bei welchen Patientinnen und Patienten mit Rückenschmerzen betrachtet werden, gegenüber Kollektiven welche eine Bildgebung aufgrund nicht-orthopädischer Ursachen erhalten haben und die lumbo-sacrale Übergangsstörung einen asymptomatischen akzidentiellen Befund darstellen [136]. Die zu erhebende Prävalenz der lumbo-sacralen Übergangsstörung variiert dementsprechend je nach ausgewähltem Patientenkollektiv und zeigt zudem aufgrund genetischer Veranlagung regionale Unterschiede in der Prävalenz [49, 66, 93, 136, 137]. Dabei wird in großen Kohortenstudien eine Prävalenz von 9,9 bis 29 % berichtet [48-51, 66]. Als für den mit lumbo-sacralen Übergangsstörungen assoziierten Rückenschmerz [114] ursächlich wird einerseits eine vermehrte Degeneration des kranial angrenzenden Segments zur lumbo-sacralen Übergangsstörung erachtet. Dabei wird In der Literatur übereinstimmend eine vermehrte Bandscheibendegeneration [51, 52, 66, 138-140] sowie eine höhere Prävalenz von Facettengelenksdegenerationen und Neuroforamenstenosen im kranial angrenzenden Segment berichtet [66, 141]. Dies resultiert möglicherweise durch eine veränderte Belastung des kranial an die lumbo-sacrale Übergangsstörung angrenzenden Segments. Durch *in-vitro* sowie *in-silico* Arbeiten konnte bereits gezeigt werden, dass lumbo-sacrale Übergangsstörungen mit einer Reduktion der Beweglichkeit des Übergangssegmentes einhergehen. Hierbei identifiziert eine *in-vitro* Arbeiten für asymmetrische Übergangsstörungen einen Einfluss auf die Segmentbelastung des Anschlusssegments mit vermehrter unilateraler Belastung sowie Torsionsbewegungen als mögliche Ursache [142, 143]. In Arbeit 3 konnte *in-vivo* gezeigt werden, dass durch die lumbo-sacrale Übergangsstörung eine Minderbeweglichkeit im Übergangssegment resultiert sowie eine kompensatorische relative Mehrbeweglichkeit im Bereich des kranial angrenzenden Segments [101]. Ebenso wie in unserer Arbeit zeigen Verhaegen et al. jedoch keine signifikanten Unterschiede in der lumbalen Lordose im aufrechten Stand sowie in der lumbalen Gesamtbewegung [101, 144].

Diese funktionellen Adaptionen gehen ebenso mit einer Veränderung der knöchernen sowie Weichgewebsanatomie einher. Durch Aihara et al. wurde für die lumbo-sacrale Übergangsstörung ein ausgedünntes Ligamentum iliolumbale in einer Kadaverstudie gegenüber einem Kollektiv ohne Übergangsanomalie detektiert [140]. In Arbeit 4 konnte gezeigt werden, dass lumbo-sacrale Übergangsstörungen zudem mit einer reduzierten Muskelquerschnittsfläche sowie einem reduzierten Volumen und einem höheren Grad an Muskeldegeneration sowohl der paraspinalen Muskulatur als auch der ventralen Rumpfmuskulatur vergesellschaftet sind. Mit einem zunehmenden Ausprägungsgrad der lumbo-sacralen Übergangsstörung resultiert ein reduziertes Muskelvolumen sowie ein höherer Verfettungsgrad der Muskulatur [105]. Dabei geht der Einfluss von lumbo-sacralen Übergangsstörungen auf die Wirbelsäulenfunktion über die in *in-vitro* und *in-silico* Studien gezeigten Effekte auf das Übergangssegment hinaus [142, 143]. Die lumbo-sacrale Übergangsstörung beeinflusst die lumbale Bewegungsfunktion und ist mit relevanten anatomischen Veränderungen des Bewegungsapparates sowie des umgebenden Weichgewebes assoziiert [93, 101, 102, 145]. Hierbei sind bezüglich des Bewegungsapparates Adaptationen der Muskulatur [105], der knöchernen Anatomie des Os sacrum [146] und des Beckens [93, 145], der Hüftgelenke [65] sowie eine hohe Koprävalenz mit der Hüftdysplasie [107, 147] zu detektieren. Daneben sind relevante Veränderungen in Zugangswegen zur Wirbelsäule durch Verlagerungen der großen Gefäße sowie neuraler Strukturen mit lumbo-sacralen Übergangsstörungen vergesellschaftet [102, 145]. Dies gemeinsam erfordert eine Adaptation der Versorgungsstrategien an die besonderen funktionellen und anatomischen Verhältnisse bei Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen.

3.4 Einfluss von lumbo-sacralen Übergangsstörungen auf Versorgungsstrategien des spino-pelvinen Übergangs

Die Therapie von Patientinnen und Patienten mit tieflumbalen Rückenschmerzen sowie etwaiger Radikulärsymptomatik bei lumbo-sacraler Übergangsstörung ist aufgrund der unterschiedlichen möglichen zugrundeliegenden Pathomechanismen mitunter komplex. Einerseits können Schmerzen aus einer irregulären Kraftübertragung, durch die mit dem Ala ossis sacri artikulierenden verbreiterten Querfortsätze resultieren und hierbei zu Überlastungssituationen und Knochenmarksödemen an den hierfür nicht ausgelegten Pseudarthrosen oder ossären Verschmelzungen führen. Ebenso werden Degenerationen im kranialen Anschlusssegment mit einer höheren Prävalenz ebenso wie die extraforaminelle Kompressionen von Nervenwurzeln durch den dysplastisch verbreiterten Processus transversus berichtet [138, 148].

Aus den unterschiedlichen Pathologien ergeben sich insbesondere für die operative Therapie unterschiedliche Versorgungsansätze [149]. Das Repertoire der konservativen Therapie umfasst für die erläuterten zugrunde liegenden Ursachen eine Belastungsanpassung, die pharmakologische Analgesie, die physikalische Therapie sowie die interventionelle Infiltration. Für die konservative Therapie durch Physiotherapie und manuelle Therapie wird dabei in Fallberichten von Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung von einer Beschwerdebesserung berichtet, wobei Arbeiten mit höherem Evidenzlevel fehlen, um klare Behandlungsempfehlungen abzuleiten [150-152]. Die interventionelle Therapie umfasst die Infiltrationstherapie der Pseudarthrose zu diagnostischen sowie therapeutischen Zwecken. Dabei kann die adäquate Schmerzbesserung durch die Infiltration im Bereich der Pseudarthrose als hinweisend auf eine Schmerzentstehung durch die Pseudartikulation des Processus transversus mit dem Ala ossis sacri gewertet werden und damit zur Abgrenzung gegenüber anderweitigen Ursachen wie Degenerationen im kranialen Anschlusssegment dienen [150, 153-155]. Aufgrund der erfolgreichen Einzelfallberichte sowie Studien mit kleinen Fallzahlen und longitudinaler

Observation von Injektionstherapien lumbo-sacraler Übergangsstörung resultiert in der Übersichtsarbeit von McGrath et al. eine Empfehlung zur Durchführung, auch wenn die Befundbesserung zu Teilen lediglich als transient berichtet wird [156]. Daneben wird die Radiofrequenzablation bei erfolgreicher Schmerzreduktion als probate Therapie in zwei Einzelfallberichten diskutiert [157, 158].

Als operative Therapieansätze bei tieflumbalen Schmerzen werden maßgeblich die Dekompression durch Resektion des dysplastischen Processus transversus sowie die Fusionsoperation diskutiert. Dabei stehen für die Beurteilung des Therapieerfolges der operativen Versorgung lediglich kleine Fallserien, Fallberichte sowie eine Arbeit von Ju et al. mit 61 Patientinnen und Patienten zu Verfügung, die Chang et al. in einer Übersichtsarbeit mit insgesamt 138 Fällen zusammenfassen [159]. Hierbei zeigen in der mindestens sechsmonatigen Nachuntersuchung 118 Patientinnen und Patienten nach Resektion des Processus transversus eine exzellente oder gute Schmerzbesserung sowie 20 Patientinnen und Patienten ein unbefriedigendes Ergebnis [154, 155, 159, 160]. In einer aktuellen Arbeit von Jenkins et al. teilen die Autorinnen und Autoren lumbo-sacrale Übergangsstörungen vergleichbar mit der Klassifikation von Castellvi in vier Kategorien ein. Hierbei berichten sie für Typ I an 13 Patientinnen und Patienten, welche eine Lücke zwischen Querfortsatz und Os sacrum von weniger als 10 mm jedoch mehr als 2 mm aufweisen, in 85 % eine Schmerzreduktion durch die Resektion. Bei Patientinnen und Patienten mit einer Distanz von weniger als 2 mm zwischen Querfortsatz und Os sacrum jedoch ohne ossäre Verschmelzung zeigt sich die Fusion der alleinigen Dekompression in Bezug auf die postoperative Schmerzbesserung überlegen (Dekompression 6/18 deutliche Schmerzbesserung, Fusion 13/18 deutliche Schmerzbesserung). Zudem zeigten die Patientinnen und Patienten mit alleiniger Dekompression in dieser Gruppe eine Revisionsrate von 67 % innerhalb von zwei Jahren. Patientinnen oder Patienten mit bilateraler ossärer Fusion (Typ IIIb) wurden in der Arbeit nicht mit einbezogen. Patientinnen oder Patienten mit unilateraler Fusion (Typ IIIa und IV) zeigten durch die unilaterale Fusionsoperation eine Symptombesserung [161]. Jedoch berichten Jenkins et al. sowie Santavirta et al. in den operativ versorgten Patientinnen und Patienten von einem gehäuften Auftreten von Degenerationen im kranialen Anschlusssegment an die lumbo-sacrale Übergangsstörung [155, 161].

Entsprechend sollte neben der diagnostischen Infiltrationstherapie die Schnittbildgebung mittels MRT oder CT zur Detektion von lumbo-sacralen

Übergangsstörungen erfolgen sowie das kraniale Anschlusssegment kritisch auf Bandscheiben- oder Facettengelenksdegenerationen vor einer Versorgung evaluiert werden, um Revisionsraten zu minimieren. Dabei weist eine Schnittbildgebung sowohl mit MRT als auch CT in Bezug auf die korrekte Klassifizierung der Übergangsstörung gegenüber der a.-p. Röntgendiagnostik ebenso wie gegenüber der Ferguson-Aufnahme eine höhere Genauigkeit auf [162, 163]. Für die korrekte Nummerierung der Wirbel werden neben dem Goldstandard, der kranio-kaudalen Nummerierung in der Wirbelsäulenganzaufnahme verschiedene Landmarken-gestützte Ansätze diskutiert [59, 164]. Dies ist insbesondere in der Planung der Durchführung von Eingriffen sowie in der reliablen ärztlichen Dokumentation von hoher Bedeutung. Dabei wird exemplarisch der Ansatz des iliolumbalen Ligamentes an der Wirbelsäule [165], die tieflumbale Konfiguration gegenüber der Neigung des Os sacrum [166, 167] oder extraspinale Strukturen wie die Höhe der Aortenbifurkation, der Konfluens der Vena cava inferior oder die Nierenarterien herangezogen [168].

Lumbo-sacrale Übergangsstörungen werden neben dem Einfluss auf die knöcherne Anatomie ebenso von Anpassungen der Weichgewebsanatomie begleitet. Dabei werden neben muskulären Adaptionen ebenso Veränderungen der neuro-vaskulären Anatomie beschrieben [91, 92, 102]. In einer rezenten Arbeit wurde der Einfluss lumbo-sacraler Übergangsstörungen sowie die Anzahl der freien Lendenwirbel auf die retroperitonealen chirurgischen Zugangswege mittels anteriorer- (ALIF), obliquer- (OLIF) sowie lateraler (LLIF) lumbaler intersomatischer Fusion auf Höhe L4/5 evaluiert. Dieses Segment ist bei Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung in besonderem Maße von Degenerationen betroffen. Dabei zeigt sich, dass bei lumbo-sacralen Übergangsstörungen und fünf oder vier freien Lendenwirbeln der LLIF-Zugang zum Segment L4/5 aufgrund einer relativ zum Bandscheibenfach höherstehenden Crista iliaca sowie einer anterioren Translokation des M. psoas erschwert sein kann. Für ALIF und OLIF reduziert eine geringere notwendige Retraktion der Iliakalvenen möglicherweise das Risiko einer Gefäßverletzung. Bei Patientinnen und Patienten mit sechs Lendenwirbeln erleichtert eine geringere relative Höhe des Beckenkamms den lateralen Zugang der LLIF. Für die ALIF ist eine stärkere Gefäßretraktion aufgrund der tiefer gelegenen Bifurkation erforderlich und daher potenziell ein höheres Risiko für Gefäßverletzungen gegeben [91]. Aus den Ergebnissen dieser Arbeit resultierend muss für die Wahl des operativen Zugangswegs mit dem geringsten Risiko für Patientinnen und Patienten eine akkurate

Segmentbenennung sowie Bestimmung der Anzahl der Lendenwirbel erfolgen und in der präoperativen Planung die genannten Weichgewebsadaptationen als Besonderheiten im Zugangsweg bedacht werden.

Bei langstreckigen Spondylodesen sowie bei sacralen Frakturen wird häufig eine spino-pelvine Verankerung aufgrund der hohen Versagensraten bei isoliert mittels S1-Pedikelschrauben sacral verankerter Spondylodesen gewählt. Dabei resultieren die hohen Versagensraten maßgeblich aus der reduzierten Knochendichte des Os sacrums sowie dem langen Hebelarm von multisegmentalen Spondylodesen [88]. Insbesondere für Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung zeigte Mahato, dass eine geringere Knochendichte mit einer Ausdünnung der Spongiosatrabekel vorliegt, sodass ein höheres Risiko für ein Implantatversagen in entsprechenden Wirbeln besteht [169]. Die Morphologie und Angulation des S1-Pedikels im ersten Sacralsegment unterscheidet sich bei Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung in Abhängigkeit des Vorliegens einer Sacralisation oder Lumbalisation [170]. Als Konsequenz der anatomischen Besonderheiten bei lumbo-sacralen Übergangsstörungen, lässt sich möglicherweise durch die fluoroskopisch oder navigationsgestützte Pedikelschraubenimplantation das Risiko einer Schraubenfehllage gegenüber der frei Hand Einbringung reduzieren.

Neben der isolierten Betrachtung der knöchernen Anatomie stellt die veränderte Gefäßanatomie [92] sowie die veränderte Beckengeometrie [93] einhergehend mit lumbo-sacralen Übergangsstörungen ebenso ein Risiko bei der spino-pelvinen Verankerung mittels S2-Ala- sowie S2-Ala-Ilium Schrauben dar. Dementsprechend wurde in Arbeit 5 die Auswirkung verschiedener Schraubenangulationen auf das Risiko für eine neuro-vaskuläre Schädigung untersucht. Hierbei zeigt sich, dass die spino-pelvine Verankerung von langen Wirbelsäulenkonstruktionen mittels S2-Ala- sowie S2-Ala-Ilium Schrauben auch bei lumbo-sacralen Übergangsstörungen eine sichere Option darstellen kann [106]. In Zusammenschau mit der reduzierten sacralen Knochendichte bei lumbo-sacralen Übergangsstörungen [169] sollte daraus resultierend die Verankerung langstreckiger Spondylodesen mittels S2-Ala-Ilium Schrauben erwogen werden. Durch die begleitenden neuro-vaskulären Veränderungen im Retroperitoneum ist dabei die ventro-dorsale Fusion mit zusätzlicher ventraler Abstützung mittels retroperitonealen Zugangswegs gegenüber der dorsalen Versorgung mit Augmentation durch S2-Ala-Ilium Schrauben mit einer verlängerten Operationszeit und einem höheren Komplikationsrisiko assoziiert.

3.5 Die lumbo-sacrale Übergangsstörung: Pathologie oder anatomische Variation?

Die Bezeichnung der lumbo-sacralen Übergangsvariation als lumbo-sacrale Übergangsstörung stellt im deutschen Sprachgebrauch die übliche Bezeichnung dar. Dieser Terminus inkludiert bereits eine Wertung über die in der Kapitelüberschrift aufgeworfenen Frage. Dem gegenüber wird diese auf Englisch wertneutral als ‚lumbo-sacral transitional vertebra' bezeichnet.

Die Definition der Weltgesundheitsorganisation von Gesundheit zugrunde legend („Gesundheit ist ein Zustand des vollständigen körperlichen, geistigen und sozialen Wohlergehens und nicht nur das Fehlen von Krankheit oder Gebrechen.")[171], stellt lediglich die symptomatische lumbo-sacrale Übergangsstörung somit eine Pathologie dar. Einerseits können die mit der lumbo-sacralen Übergangsstörung assoziierten Beschwerden direkt aus dem Vorliegen der Übergangsstörung durch eine Überlastungsreaktionen der Pseudarthrose des verbreiterten Processus transversus mit dem Ala ossis sacri oder Nervenwurzelkompressionen resultieren. Andererseits können degenerative Veränderungen des kranialen Anschlusssegmentes, die aus einer chronischen Alteration der Biomechanik mit kompensatorischer Überlastungsreaktion des kranialen Anschlusssegments resultieren. Menschen mit lumbo-sacraler Übergangsstörung weisen überproportional häufig Rückenschmerzen im Vergleich zu einer Kontrollkohorte auf, jedoch leidet nichtsdestotrotz der überwiegende Anteil der Betroffenen nicht unter Symptomen [51, 66]. Jedoch scheinen Patientinnen und Patienten mit uni- oder bilateraler Pseudarthrose zwischen Processus transversus und Ala ossis sacri, entsprechend Castellvi Grad II oder IV, eine höhere Prävalenz an Rückenschmerzen gegenüber den übrigen Übergangsanomalien aufzuweisen [48]. Aufgrund des fakultativen Charakters und der hohen Rate asymptomatischer Personen mit lumbo-sacraler Übergangsstörung ist für die Einzelperson allein aufgrund des Vorliegens einer anatomischen Variation jedoch nicht die obligatorische Definition als Pathologie zu treffen.

Ein anderer Ansatz für die Beurteilung der Frage können die evolutionären Auswirkungen im Rahmen unseres vertikalisierten Lebensstils darstellen. Wie bereits in der Einleitung aufgezeigt, wird eine genetische Ursache aufgrund familiärer Häufungen für lumbo-sacrale Übergangsstörungen angenommen. Dabei zeigen insbesondere Polymorphismen der homeobox Gene 10 und 11 in Tierversuchen einen elementaren Einfluss auf die sacrale sowie lumbale Entwicklung [55-57]. Nichtsdestotrotz stellt die lumbo-sacrale Übergangstörung keinen bislang belegten evolutionären Nachteil im Sinne einer Reduktion des Fortpflanzungserfolges dar und es ist bislang kein Einfluss auf den Geburtskanal untersucht und beschrieben.

In eigener Arbeit konnte gezeigt werden, dass lumbo-sacrale Übergangsstörungen mit einer signifikant erhöhten pelvinen Inzidenz (PI) sowie reduziertem sacralen Endplattenwinkel (Sacral table angle) einhergehen [93]. Ebenso zeigt sich eine höherstehende Crista iliaca bei Patientinnen und Patienten mit lumbo-sacraler Übergangsstörung [145]. Aus diesen Erkenntnissen wurde ein Einfluss der Veränderungen der knöchernen Anatomie des Beckens auf das Hüftgelenk postuliert und in eigener Arbeit untersucht. Hierbei zeigte sich, dass ein zunehmender Ausprägungsgrad der lumbo-sacralen Übergangsstörung mit einer geringeren Beckenkippung in Rückenlage einhergeht. Ebenso nehmen die funktionelle Anteversion der Hüftpfanne und die anatomische Anteversion der Hüftpfanne mit steigendem Castellvi-Grad zu [65]. Zudem wird eine hohe Ko-Prävalenzrate lumbo-sacraler Übergangsstörungen mit Hüftpathologien wie der Hüftdysplasie berichtet [147, 172, 173].

Anhand der zugrundeliegenden Erkenntnisse kann konkludiert werden, dass die lumbo-sacrale Übergangsstörung, im Falle der Symptomfreiheit eine anatomische Variation mit weitreichenden Auswirkungen darstellt – nicht nur auf das Achsskelett, sondern ebenso auf die angrenzenden Gelenke, mit denen der lumbo-sacrale Übergang in Bewegungsketten zusammenwirkt. Im Falle einer Symptomatik durch Nervenkompression, atypische Lastübertragung mit Knochenödemen oder frühzeitige Degenerationen der Anschlusssegmente kann die lumbo-sacrale Übergangsstörung jedoch durchaus als Pathologie betrachtet werden, für welche die dargelegten Besonderheiten in Versorgungsstrategien bestehen. Insbesondere unter Betrachtung der längerfristigen menschlichen Entwicklung mit stetiger Zunahme unserer Körpergröße mit konsekutiv erhöhter Rumpflast und einer damit erhöhten mechanischen Beanspruchung des lumbo-sacralen Übergangs sowie einer gesteigerten Lebenserwartung, fällt der Relevanz der lumbo-sacralen Übergangsstörung als symptomatische Pathologie möglicherweise eine größere Rolle zu. Gleichgelagerte Effekte sind möglicherweise durch das aktuell in vielen Staaten steigende Körpergewicht im Zuge von Übergewicht und einer Abnahme der Rumpfmuskulatur durch reduzierte Bewegung und vermehrtes Sitzen erwartbar.

3.6 Zusammenfassung und Ausblick

Die Beweglichkeit sowie die Stützfunktion des Rumpfes stellen die zentrale Funktion des Achsskeletts dar. Aus dem aufrechten Gang und damit für die Rolle des Menschen in seiner Umwelt ergeben sich besondere Anforderungen. Einerseits ermöglicht die Dynamik der Wirbelsäule sowie des lumbo-sacralen Übergangs im Zusammenspiel mit dem Becken unseren zweibeinigen Gang sowie Haltungsveränderungen im Kontext von Bewegungsketten. Andererseits obliegt dem Achsskelett die Aufrechterhaltung der effizienten vertikalen Haltung durch eine Reduktion der notwendigen aktiven Muskelarbeit durch die Form sowie gemeinsam mit dem Becken die Stützfunktion der Rumpflast.

Formvariationen und Degeneration nehmen einen entscheidenden Einfluss auf die umgebende Anatomie und Funktion. Die Form und Funktion unseres Achsskeletts steht in einer engen wechselseitigen Abhängigkeit, weshalb neben der Erfassung der Form durch statische Bildgebung wie dem MRT oder Röntgen die Erfassung der dynamischen Prozesse unseres Achsskeletts eine maßgebliche Rolle in der pathophysiologischen Beurteilung von Wirbelsäulendegenerationen zukommt.

Die etablierte Testung des Hilfsparameters Finger-Boden-Abstands eignet sich aufgrund der hohen Abhängigkeit von anthropometrischen Faktoren für den interindividuellen Vergleich der lumbalen Beweglichkeit nur eingeschränkt. Dieser ist abhängig von der gesamten involvierten Bewegungskette sowie anthropometrischen Faktoren, kann jedoch in der seriellen Untersuchung als orientierender Prädiktor für Funktionsveränderungen herangezogen werden.[103]

Für die genauere Quantifizierung der Wirbelsäulenform und -beweglichkeit eignen sich vielmehr nicht-invasive Messinstrumente, welche die Rückenform beurteilen und damit einen Rückschluss auf das zugrundeliegende Stützskelett zulassen. Durch diese lassen sich objektivierbare Werte ermitteln und vergleichen. Wie jedoch in Arbeit 2 gezeigt, ist die Vergleichbarkeit intermodal nur eingeschränkt [104]. Demensprechend sollte trotz hoher Reliabilität und Validität der Einzelverfahren die serielle Beurteilung der Wirbelsäulenform und -bewegung mittels eines Einzelsystems erfolgen und der Vergleich der absoluten Messwerte zwischen Systemen unterbleiben, um Fehleinschätzungen zu vermeiden.

Auch bei den mit bis zu 29 % Prävalenz sehr häufigen Formvarianten des lumbo-sacralen Übergangs ist die Erfassung der in Arbeit 3 gezeigten assoziierten Funktionsveränderung im Alltag bislang kein klinischer Standard und fließt nur bedingt in Therapieentscheidungen mit ein. Jedoch spielt für die Genese des Bertolotti Syndroms sowie einer erhöhten Prävalenz an Wirbelsäulendegeneration im Zusammenhang mit lumbo-sacralen Übergangsstörungen die Funktionsveränderung eine elementare Rolle [140, 142].

Einhergehend mit dem Einfluss auf die Funktion resultiert eine Adaptation des Weichgewebes. Dabei wird einerseits von Veränderungen der Weichgewebe des Bewegungsapparats berichtet, wie die Schwächung des Ligamentum iliolumbale [140], sowie in Arbeit 4 dargelegt, eine Reduktion des Muskelquerschnittes sowie ein höherer Muskelverfettungsgrad [105]. Daneben wird ein Einfluss auf die Gefäßanatomie beschrieben, die einen relevanten Einflussfaktor für die Zugangswege zum Übergangssegment sowie zu den kranial angrenzenden Segmenten darstellen kann [91, 102]. Ebenso wie für die anterioren und lateralen retroperitonealen Zugangswege spielt für die Versorgungssicherheit von langstreckigen Spondylodesen mit spino-pelviner Verankerung mittels S2-Ala- sowie S2-Ala-Ilium Schrauben die Lageveränderung der neuro-vaskulären Strukturen eine entscheidende Rolle in der Sicherheit einzelner Schraubentrajektorien [106]. Trotz zunehmend breiter Anwendung von navigationsgestützter Schraubenplatzierung zur Vermeidung von Fehllagen stellt die genaue Kenntnis der neurovaskulären Strukturen eine grundlegende Voraussetzung dar. Aufgrund der Veränderungen im Rahmen von lumbo-sacralen Übergangsstörungen sollte in der präoperativen Vorbereitung die Durchführbarkeit sonst etablierter Zugangswege kritisch überprüft und intraoperativ eine erhöhte Achtsamkeit gegenüber Lageanomalien der neuro-vaskulären Strukturen sowie Muskeltranspositionen und Strukturveränderungen aufgebracht werden, um den dargelegten anatomischen Adaptationen von Patientinnen und Patienten mit lumbo-sacralen Übergangsstörungen Rechnung zu tragen.

Jedoch gehen mit lumbo-sacralen Übergangsstörungen nicht nur Veränderungen der direkt angrenzenden ossären und Weichgewebsstrukturen einher, vielmehr zeigt sich ein Einfluss ubiquitär in der Bewegungskette des Achsskeletts mit dem Becken und der Hüfte [65, 107].

Entsprechend ist neben der Anpassung operativer Verfahren und Zugangswege aufgrund des dargelegten Erkenntnisgewinns über anatomische Begebenheiten die Erfassung der Dynamik als Kernfunktion unseres Bewegungsapparates im Sinne von Bewegungsketten zum Verständnis der Auswirkungen von anatomischen Alterationen erforderlich. Hierfür sind neben der aktuell üblichen punktuellen Diagnostik von Körperhaltung mittels statischer Aufnahmen, dynamische und objektivierbare Untersuchungen in Alltagsaktivitäten notwendig [174].

Der dynamische Einfluss der lumbo-sacralen Übergangsstörung auf die Bewegungskette Wirbelsäulen-Becken-Hüfte ist bislang in einem Kollektiv von nur 17 Patientinnen und Patienten lediglich beginnend untersucht und der konkrete Einfluss der lumbo-sacralen Übergangsstörung auf die Hüfte sowie die untere Extremität noch unklar [144].

Dieser kann mittels dreidimensionaler Laufbandanalysen erfasst werden. Belastungstests unter Detektion durch Bewegungssensoren wie das ‚Vicon Motion Capture System' erlauben die Beurteilung von Bewegungsabläufen sowie des Muskeltonus mittels Elektromyographie und können als Prädiktoren für die Wirbelsäulenbelastung im Alltag dienen. Die Zusammenschau aus spezifischer Anatomie, erfasst mittels Magnetresonanztomographie, Haltungsbeurteilung im Alltag sowie der persönlichen Bewegungsabläufe unter Belastung ermöglicht die Einschätzung eines individuellen Beanspruchungsprofils.

Aktuelle Studien assoziieren lumbo-sacrale Übergangsstörungen Castellvi Grad II und IV gegenüber anderen Ausprägungsgraden zu einem höheren Prozentsatz mit Rückenschmerzen [48]. Jedoch besteht keine Möglichkeit einer verlässlichen Prädiktion von Beschwerden für das Individuum, die sich aus einer Evidenz jenseits des Vorliegens der lumbo-sacralen Übergangsstörung ergibt. Entsprechend wäre durch die Erstellung von individuellen Beanspruchungsprofilen unter Einbezug von anatomischen Variationen in Analogie zu bestehenden Möglichkeiten der Algorithmus-basierten Vorhersage des Progresses einer Muskeldystrophie aus der Detektion von Haltung und Dynamik in Alltagssituationen, eine personalisierte Risikostratifizierung für die symptomatische lumbo-sacrale Übergangsstörung denkbar [114].

Entsprechend der Differenzierung symptomatischer lumbo-sacraler Übergangsstörung in direkt der Übergangsanomalie zuordenbaren Beschwerden durch eine Überlastungsreaktion der Pseudarthrose sowie extraforamineller

Nervenwurzelkompressionen gegenüber Degenerationsprozessen des kranial angrenzenden Segmentes müssen die gewählten Therapiestrategien unterschieden werden. Während die direkt attribuierbaren Beschwerden durch die Denervierung oder Resektion des Processus transversus chirurgisch ursächlich adressierbar sind, stehen bislang für die Degenerationsprozesse des Anschlusssegments nur eingeschränkt chirurgisch-rekonstruktive Therapieverfahren unter Erhalt der biologischen ‚Articular triad' zur Verfügung. Daraus ergibt sich eine relevante Rolle für die Prävention des frühzeitigen Auftretens von Degenerationen. Den Erkenntnissen Julius Wolffs folgend könnte nach Risikostratifizierung in Patientinnen und Patienten mit erhöhtem Risiko für frühzeitige Degenerationen des kranialen Anschlusssegments durch gezielte Funktionsadaptation mittels individueller muskulärer Beübung und Biofeedback durch im Alltag anwendbare Haltungs- und Bewegungssensoren die Degeneration im Sinne einer Formveränderung beeinflusst werden.

Entsprechend der dargelegten Erwägungen stellt die lumbo-sacrale Übergangsstörung eine lediglich fakultativ pathologische Formvariation dar, die ebenso häufig in anderen Säugetieren ohne vertikalisierten Lebensstil auftreten [175]. Dies unterstreicht die Schwierigkeit der Einordnung der anatomischen Variation des lumbo-sacralen Übergangs in eine lineare Ordnung nach Komplexität und Vollkommenheit der Anpassung im Sinne der *Scala naturae*. Vielmehr zeigen die Häufigkeit von Degenerationen und Pathologien des lumbo-sacralen Übergangs sowie seine hohe interindividuelle anatomische Varianz, dass die Vertikalisierung des Lebensstils keine rein lineare Entwicklung mit stets optimierter Anpassung an unseren Lebensstil, sondern vielmehr eine Anpassung basierend auf sporadischen Veränderungen darstellt. Dies verdeutlicht eindrücklich, dass sich der menschliche Adaptationsprozess an unseren Lebensstil und die funktionelle Beanspruchung nach wie vor in vollem Gange befindet. Insbesondere unter vermehrter spinaler Belastung durch höhere Körpergröße, steigendes Gewicht und längeres Lebensalter ist der lumbo-sacrale Übergang in besonderem Maße belastet und die Relevanz der lumbo-sacralen Variationen als Pathomorphologie möglicherweise zunehmend. Daraus resultierend kommt der Weiterentwicklung präventiver und kurativer Behandlungsstrategien der symptomatischen lumbo-sacralen Übergangsanomalie eine Schlüsselrolle zu.

4. Literaturverzeichnis

1. Lamarck, J.B.P.A.d.M.d., *Philosophie zoologique, ou, Exposition des considerations relative a l'histoire naturelle des animaux [microform] / par J.B.P.A. Lamarck*. Landmarks of science. 1809, Paris: Chez Dentu [et] L'Auteur.
2. Darwin, C., *On the Origin of Species by Means of Natural Selection, Or, The Preservation of Favoured Races in the Struggle for Life*. 1859: J. Murray.
3. Vaughan, C.L., *Theories of bipedal walking: an odyssey.* J Biomech, 2003. **36**(4): p. 513-23.
4. Leakey, M.D. and R.L. Hay, *Pliocene footprints in the Laetolil Beds at Laetoli, northern Tanzania.* Nature, 1979. **278**(5702): p. 317-323.
5. Ward, C.V., W.H. Kimbel, and D.C. Johanson, *Complete fourth metatarsal and arches in the foot of Australopithecus afarensis.* Science, 2011. **331**(6018): p. 750-3.
6. Saunders, J.B., V.T. Inman, and H.D. Eberhart, *The major determinants in normal and pathological gait.* J Bone Joint Surg Am, 1953. **35-A**(3): p. 543-58.
7. Betti, L., *Human Variation in Pelvic Shape and the Effects of Climate and Past Population History.* Anat Rec (Hoboken), 2017. **300**(4): p. 687-697.
8. Rosenberg, K.R., *The evolution of modern human childbirth.* American Journal of Physical Anthropology, 1992. **35**(S15): p. 89-124.
9. Thurston, A.J. and J.D. Harris, *Normal kinematics of the lumbar spine and pelvis.* Spine (Phila Pa 1976), 1983. **8**(2): p. 199-205.
10. Dubousset, J., *The Pelvic Vertebra, the Cephalic Vertebra and the Concept of the Chain of Balance*, in *Spinal Anatomy : Modern Concepts*, J.M. Vital and D.T. Cawley, Editors. 2020, Springer International Publishing: Cham. p. 171-187.
11. Legaye, J. and G. Duval-Beaupere, *Gravitational forces and sagittal shape of the spine. Clinical estimation of their relations.* Int Orthop, 2008. **32**(6): p. 809-16.
12. D'Ambrosi, R., et al., *The role of the iliofemoral ligament as a stabilizer of the hip joint.* EFORT Open Rev, 2021. **6**(7): p. 545-555.
13. Lovejoy, C.O., *Evolution of human walking.* Sci Am, 1988. **259**(5): p. 118-25.
14. Legaye, J., et al., *Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves.* Eur Spine J, 1998. **7**(2): p. 99-103.
15. Boulay, C., et al., *Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis.* Eur Spine J, 2006. **15**(4): p. 415-22.
16. Roussouly, P. and J.L. Pinheiro-Franco, *Biomechanical analysis of the spino-pelvic organization and adaptation in pathology.* Eur Spine J, 2011. **20 Suppl 5**(Suppl 5): p. 609-18.
17. Tardieu, C., et al., *How is sagittal balance acquired during bipedal gait acquisition? Comparison of neonatal and adult pelves in three dimensions. Evolutionary implications.* J Hum Evol, 2013. **65**(2): p. 209-22.
18. Putz, R.L. and M. Muller-Gerbl, *The vertebral column--a phylogenetic failure? A theory explaining the function and vulnerability of the human spine.* Clin Anat, 1996. **9**(3): p. 205-12.
19. McCollum, M.A., et al., *The vertebral formula of the last common ancestor of African apes and humans.* J Exp Zool B Mol Dev Evol, 2010. **314**(2): p. 123-34.
20. Shefi, S., et al., *Development of the lumbar lordotic curvature in children from age 2 to 20 years.* Spine (Phila Pa 1976), 2013. **38**(10): p. E602-8.
21. Duval-Beaupere, G. and G. Robain, *Visualization on full spine radiographs of the anatomical connections of the centres of the segmental body mass supported by each vertebra and measured in vivo.* Int Orthop, 1987. **11**(3): p. 261-9.
22. Selby, M.S., et al., *Modern Medical Consequences of the Ancient Evolution of a Long, Flexible Lumbar Spine.* Journal of Osteopathic Medicine, 2019. **119**(9): p. 622-630.
23. Machnicki, A.L. and P.L. Reno, *Great apes and humans evolved from a long-backed ancestor.* J Hum Evol, 2020. **144**: p. 102791.
24. Chun, S.W., et al., *The relationships between low back pain and lumbar lordosis: a systematic review and meta-analysis.* Spine J, 2017. **17**(8): p. 1180-1191.

25. Zheng, Z., et al., *A Systematic Review and Meta-Analysis on Comparative Kinematics in the Lumbopelvic Region in the Patients Suffering from Spinal Pain.* J Healthc Eng, 2022. **2022**: p. 7369242.
26. Zander, T., M. Bashkuev, and H. Schmidt, *Are there characteristic motion patterns in the lumbar spine during flexion?* J Biomech, 2018. **70**: p. 77-81.
27. Rohlmann, A., et al., *Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period.* Eur Spine J, 2014. **23**(11): p. 2375-84.
28. Troke, M., et al., *A normative database of lumbar spine ranges of motion.* Man Ther, 2005. **10**(3): p. 198-206.
29. Harvey, S.B., F.W. Smith, and D.W. Hukins, *Measurement of lumbar spine flexion-extension using a low-field open-magnet magnetic resonance scanner.* Invest Radiol, 1998. **33**(8): p. 439-43.
30. Trudelle-Jackson, E., et al., *Lumbar spine flexion and extension extremes of motion in women of different age and racial groups: the WIN Study.* Spine (Phila Pa 1976), 2010. **35**(16): p. 1539-44.
31. Mannion, A. and M. Troke, *A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility.* Clin Biomech (Bristol, Avon), 1999. **14**(9): p. 612-9.
32. Ng, J.K., et al., *Range of motion and lordosis of the lumbar spine: reliability of measurement and normative values.* Spine (Phila Pa 1976), 2001. **26**(1): p. 53-60.
33. Dreischarf, M., et al., *Age-related loss of lumbar spinal lordosis and mobility--a study of 323 asymptomatic volunteers.* PLoS One, 2014. **9**(12): p. e116186.
34. Pearcy, M., I. Portek, and J. Shepherd, *Three-dimensional x-ray analysis of normal movement in the lumbar spine.* Spine (Phila Pa 1976), 1984. **9**(3): p. 294-7.
35. Twomey, L.T. and J.R. Taylor, *Age changes in the lumbar articular triad.* Aust J Physiother, 1985. **31**(3): p. 106-12.
36. Masani, K., D.G. Sayenko, and A.H. Vette, *What triggers the continuous muscle activity during upright standing?* Gait Posture, 2013. **37**(1): p. 72-7.
37. Nachemson, A.L., *Disc pressure measurements.* Spine (Phila Pa 1976), 1981. **6**(1): p. 93-7.
38. Khoo, B.C., et al., *A comparison of lumbosacral loads during static and dynamic activities.* Australas Phys Eng Sci Med, 1994. **17**(2): p. 55-63.
39. Bazrgari, B., A. Shirazi-Adl, and N. Arjmand, *Analysis of squat and stoop dynamic liftings: muscle forces and internal spinal loads.* Eur Spine J, 2007. **16**(5): p. 687-99.
40. Damm, P., et al., *In vivo hip and lumbar spine implant loads during activities in forward bent postures.* J Biomech, 2020. **102**: p. 109517.
41. Evans, W., W. Jobe, and C. Seibert, *A cross-sectional prevalence study of lumbar disc degeneration in a working population.* Spine (Phila Pa 1976), 1989. **14**(1): p. 60-4.
42. Stokes, I.A. and J.C. Iatridis, *Mechanical conditions that accelerate intervertebral disc degeneration: overload versus immobilization.* Spine (Phila Pa 1976), 2004. **29**(23): p. 2724-32.
43. Roberts, S., et al., *Analysis of trends in lumbar disc degeneration using kinematic MRI.* Clinical Imaging, 2021. **79**: p. 136-141.
44. Tan, Y., et al., *Kinetic magnetic resonance imaging analysis of lumbar segmental mobility in patients without significant spondylosis.* Eur Spine J, 2012. **21**(12): p. 2673-9.
45. Fredrickson, B.E., et al., *The natural history of spondylolysis and spondylolisthesis.* J Bone Joint Surg Am, 1984. **66**(5): p. 699-707.
46. Sakai, T., et al., *Incidence of lumbar spondylolysis in the general population in Japan based on multidetector computed tomography scans from two thousand subjects.* Spine (Phila Pa 1976), 2009. **34**(21): p. 2346-50.
47. Bhalla, A. and C.M. Bono, *Isthmic Lumbar Spondylolisthesis.* Neurosurg Clin N Am, 2019. **30**(3): p. 283-290.
48. Nardo, L., et al., *Lumbosacral transitional vertebrae: association with low back pain.* Radiology, 2012. **265**(2): p. 497-503.
49. Tang, M., et al., *Lumbosacral transitional vertebra in a population-based study of 5860 individuals: prevalence and relationship to low back pain.* Eur J Radiol, 2014. **83**(9): p. 1679-82.

50. French, H.D., et al., *Lumbosacral transitional vertebrae and its prevalence in the Australian population.* Global Spine J, 2014. **4**(4): p. 229-32.
51. Hanhivaara, J., et al., *Lumbosacral transitional vertebrae are associated with lumbar degeneration: retrospective evaluation of 3855 consecutive abdominal CT scans.* Eur Radiol, 2020. **30**(6): p. 3409-3416.
52. Bhagchandani, C., et al., *A Whole Spine MRI Based Study of the Prevalence, Associated Disc Degeneration and Anatomical Correlations of Lumbosacral Transitional Vertebra.* Global Spine J, 2023: p. 21925682231161559.
53. Mahato, N.K., *Disc spaces, vertebral dimensions, and angle values at the lumbar region: a radioanatomical perspective in spines with L5–S1 transitions: Clinical article.* Journal of Neurosurgery: Spine SPI, 2011. **15**(4): p. 371-379.
54. Mahato, N.K., *Complexity of neutral zones, lumbar stability and subsystem adaptations: probable alterations in lumbosacral transitional vertebrae (LSTV) subtypes.* Med Hypotheses, 2013. **80**(1): p. 61-4.
55. Tini, P.G., C. Wieser, and W.M. Zinn, *The transitional vertebra of the lumbosacral spine: its radiological classification, incidence, prevalence, and clinical significance.* Rheumatol Rehabil, 1977. **16**(3): p. 180-5.
56. Carapuço, M., et al., *Hox genes specify vertebral types in the presomitic mesoderm.* Genes Dev, 2005. **19**(18): p. 2116-21.
57. Wellik, D.M. and M.R. Capecchi, *Hox10 and Hox11 genes are required to globally pattern the mammalian skeleton.* Science, 2003. **301**(5631): p. 363-7.
58. Bertolotti, M., *Contributo alla conoscenze dei vizi di differenzazione regionale del racide con speciale riguardo alla assimilazione sacrale della V. lombare.* Radiol. Med (Torino), 1917. **4**: p. 113-144.
59. Paik, N.C., C.S. Lim, and H.S. Jang, *Numeric and morphological verification of lumbosacral segments in 8280 consecutive patients.* Spine (Phila Pa 1976), 2013. **38**(10): p. E573-8.
60. Dai, L., *Lumbosacral transitional vertebrae and low back pain.* Bull Hosp Jt Dis, 1999. **58**(4): p. 191-3.
61. Apazidis, A., et al., *The prevalence of transitional vertebrae in the lumbar spine.* Spine J, 2011. **11**(9): p. 858-62.
62. Peterson, C.K., et al., *A cross-sectional study comparing pain and disability levels in patients with low back pain with and without transitional lumbosacral vertebrae.* J Manipulative Physiol Ther, 2005. **28**(8): p. 570-4.
63. Castellvi, A.E., L.A. Goldstein, and D.P. Chan, *Lumbosacral transitional vertebrae and their relationship with lumbar extradural defects.* Spine (Phila Pa 1976), 1984. **9**(5): p. 493-5.
64. Mahato, N.K., *Redefining lumbosacral transitional vertebrae (LSTV) classification: integrating the full spectrum of morphological alterations in a biomechanical continuum.* Med Hypotheses, 2013. **81**(1): p. 76-81.
65. Becker, L., et al., *Lumbosacral Transitional Vertebrae Influence on Acetabular Orientation and Pelvic Tilt.* J Clin Med, 2022. **11**(17).
66. Hanhivaara, J., et al., *The Association of Lumbosacral Transitional Vertebrae with Low Back Pain and Lumbar Degenerative Findings in MRI: A Large Cohort Study.* Spine (Phila Pa 1976), 2022. **47**(2): p. 153-162.
67. Wu, A., et al., *Global low back pain prevalence and years lived with disability from 1990 to 2017: estimates from the Global Burden of Disease Study 2017.* Ann Transl Med, 2020. **8**(6): p. 299.
68. *Robert Koch-Institut (Hrsg) (2015) Gesundheit in Deutschland. Gesundheitsberichterstattung des Bundes. Gemeinsam getragen von RKI und Destatis. RKI, Berlin.*
69. Vos, T., et al., *Years lived with disability (YLDs) for 1160 sequelae of 289 diseases and injuries 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010.* Lancet, 2012. **380**(9859): p. 2163-96.
70. Andersson, G.B., *Epidemiologic aspects on low-back pain in industry.* Spine (Phila Pa 1976), 1981. **6**(1): p. 53-60.

71. Meucci, R.D., A.G. Fassa, and N.M. Faria, *Prevalence of chronic low back pain: systematic review.* Rev Saude Publica, 2015. **49**.
72. Wenig, C.M., et al., *Costs of back pain in Germany.* Eur J Pain, 2009. **13**(3): p. 280-6.
73. Yoshihara, H. and D. Yoneoka, *National trends in the surgical treatment for lumbar degenerative disc disease: United States, 2000 to 2009.* Spine J, 2015. **15**(2): p. 265-71.
74. Maher, C., M. Underwood, and R. Buchbinder, *Non-specific low back pain.* Lancet, 2017. **389**(10070): p. 736-747.
75. Koes, B.W., M.W. van Tulder, and S. Thomas, *Diagnosis and treatment of low back pain.* BMJ, 2006. **332**(7555): p. 1430-4.
76. Nicholas, M.K., et al., *Early identification and management of psychological risk factors ("yellow flags") in patients with low back pain: a reappraisal.* Phys Ther, 2011. **91**(5): p. 737-53.
77. Chapman, J.R., et al., *Evaluating common outcomes for measuring treatment success for chronic low back pain.* Spine (Phila Pa 1976), 2011. **36**(21 Suppl): p. S54-68.
78. Hartvigsen, J., et al., *What low back pain is and why we need to pay attention.* Lancet, 2018. **391**(10137): p. 2356-2367.
79. Foster, N.E., et al., *Prevention and treatment of low back pain: evidence, challenges, and promising directions.* Lancet, 2018. **391**(10137): p. 2368-2383.
80. Niederer, D., et al., *Which Functional Outcomes Can be Measured in Low Back Pain Trials and Therapies?: A Prospective 2-Year Factor-, Cluster-, and Reliability-Multicenter Analysis on 42 Variables in 1049 Individuals.* Spine (Phila Pa 1976), 2021. **46**(21): p. 1495-1508.
81. *Bundesärztekammer (BÄK), Kassenärztliche Bundesvereinigung (KBV), Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften (AWMF). Nationale VersorgungsLeitlinie Nicht-spezifischer Kreuzschmerz – Langfassung, 2. Auflage. Version 1. 2017 [cited: 2022/09/14]. DOI: 10.6101/AZQ/000353.* www.kreuzschmerz.versorgungsleitlinien.de.
82. Oliveira, C.B., et al., *Clinical practice guidelines for the management of non-specific low back pain in primary care: an updated overview.* Eur Spine J, 2018. **27**(11): p. 2791-2803.
83. Kreiner, D.S., et al., *Guideline summary review: an evidence-based clinical guideline for the diagnosis and treatment of low back pain.* Spine J, 2020. **20**(7): p. 998-1024.
84. Wolff, J., *Das Gesetz der Transformation der Knochen.* Dtsch Med Wochenschr, 1893. **19**(47): p. 1222-1224.
85. Brodersen, K., *Hippocrates: Sämtliche Werke*. 2022, Darmstadt: Wissenschaftliche Buchgesellschaft.
86. Cooley, J.R., et al., *Spinal degeneration is associated with lumbar multifidus morphology in secondary care patients with low back or leg pain.* Sci Rep, 2022. **12**(1): p. 14676.
87. Koller, H., et al., *Reinforcement of lumbosacral instrumentation using S1-pedicle screws combined with S2-alar screws.* Oper Orthop Traumatol, 2013. **25**(3): p. 294-314.
88. Lee, C.S., et al., *Critical length of fusion requiring additional fixation to prevent nonunion of the lumbosacral junction.* Spine (Phila Pa 1976), 2010. **35**(6): p. E206-11.
89. Chang, T.L., et al., *Low profile pelvic fixation: anatomic parameters for sacral alar-iliac fixation versus traditional iliac fixation.* Spine (Phila Pa 1976), 2009. **34**(5): p. 436-40.
90. O'Brien, J.R., et al., *Biomechanical evaluation of S2 alar-iliac screws: effect of length and quad-cortical purchase as compared with iliac fixation.* Spine (Phila Pa 1976), 2013. **38**(20): p. E1250-5.
91. Becker, L., et al., *Approach-related anatomical differences in patients with lumbo-sacral transitional vertebrae undergoing lumbar fusion surgery at level L4/5.* Arch Orthop Trauma Surg, 2022.
92. Weiner, B.K., M. Walker, and R.D. Fraser, *Vascular anatomy anterior to lumbosacral transitional vertebrae and implications for anterior lumbar interbody fusion.* Spine J, 2001. **1**(6): p. 442-4.
93. Haffer, H., et al., *Changes of Fixed Anatomical Spinopelvic Parameter in Patients with Lumbosacral Transitional Vertebrae: A Matched Pair Analysis.* Diagnostics (Basel), 2021. **11**(1).

94. Uhlemann, C., T.U. Schreiber, and A. Sarafowa, *Reliabilität klinischer Wirbelsäulenbewegungsmaße bei Probanden.* Physikalische Medizin, Rehabilitationsmedizin, Kurortmedizin, 2001. **11**(05): p. 165-170.
95. Perret, C., et al., *Validity, reliability, and responsiveness of the fingertip-to-floor test.* Arch Phys Med Rehabil, 2001. **82**(11): p. 1566-70.
96. Schulte, T.L., et al., *Raster stereography versus radiography in the long-term follow-up of idiopathic scoliosis.* J Spinal Disord Tech, 2008. **21**(1): p. 23-8.
97. Biot, B., E. Clement, and M. Lejeune, *[Range of motion of the scoliotic spine in adults].* Ann Readapt Med Phys, 2004. **47**(2): p. 64-71.
98. Galvis, S., et al., *The effect of scoliotic deformity on spine kinematics in adolescents.* Scoliosis Spinal Disord, 2016. **11**: p. 42.
99. Lee, S.H., et al., *The change of whole lumbar segmental motion according to the mobility of degenerated disc in the lower lumbar spine: a kinetic MRI study.* Eur Spine J, 2015. **24**(9): p. 1893-900.
100. Rohlmann, A., et al., *Analysis of the influence of disc degeneration on the mechanical behaviour of a lumbar motion segment using the finite element method.* J Biomech, 2006. **39**(13): p. 2484-90.
101. Becker, L., et al., *Lumbosacral transitional vertebrae alter the distribution of lumbar mobility-Preliminary results of a radiographic evaluation.* PLoS One, 2022. **17**(9): p. e0274581.
102. Josiah, D.T., et al., *Anatomical differences in patients with lumbosacral transitional vertebrae and implications for minimally invasive spine surgery.* J Neurosurg Spine, 2017. **26**(2): p. 137-143.
103. Becker, L., et al., *Finger-Floor Distance Is Not a Valid Parameter for the Assessment of Lumbar Mobility.* Diagnostics (Basel), 2023. **13**(4).
104. Dreischarf, B., et al., *Comparison of three validated systems to analyse spinal shape and motion.* Sci Rep, 2022. **12**(1): p. 10222.
105. Becker, L., et al., *Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients.* Skeletal Radiol, 2021. **50**(8): p. 1697-1704.
106. Becker, L., et al., *Safe Zones for Spinopelvic Screws in Patients With Lumbosacral Transitional Vertebra.* Global Spine J, 2023. **13**(4): p. 1089-1096.
107. Becker, L., et al., *The influence of lumbo-sacral transitional vertebrae in developmental dysplasia of the hip: a matched pair analysis.* Sci Rep, 2023. **13**(1): p. 10027.
108. Sardar, Z.M., et al., *Age- and Gender-based Global Sagittal Spinal Alignment in Asymptomatic Adult Volunteers: Results of the Multiethnic Alignment Normative Study (MEANS).* Spine (Phila Pa 1976), 2022. **47**(19): p. 1372-1381.
109. Kiefer, D., et al., *Successful Evaluation of Spinal Mobility Measurements With the Epionics SPINE Device in Patients With Axial Spondyloarthritis Compared to Controls.* J Rheumatol, 2022. **49**(1): p. 44-52.
110. Yilgor, C., et al., *Global Alignment and Proportion (GAP) Score: Development and Validation of a New Method of Analyzing Spinopelvic Alignment to Predict Mechanical Complications After Adult Spinal Deformity Surgery.* J Bone Joint Surg Am, 2017. **99**(19): p. 1661-1672.
111. Soroceanu, A., et al., *Radiographical and Implant-Related Complications in Adult Spinal Deformity Surgery: Incidence, Patient Risk Factors, and Impact on Health-Related Quality of Life.* Spine (Phila Pa 1976), 2015. **40**(18): p. 1414-21.
112. Helgeson, M.D., A.J. Bevevino, and A.S. Hilibrand, *Update on the evidence for adjacent segment degeneration and disease.* Spine J, 2013. **13**(3): p. 342-51.
113. Wang, T. and W. Ding, *Risk factors for adjacent segment degeneration after posterior lumbar fusion surgery in treatment for degenerative lumbar disorders: a meta-analysis.* Journal of Orthopaedic Surgery and Research, 2020. **15**(1): p. 582.
114. Ricotti, V., et al., *Wearable full-body motion tracking of activities of daily living predicts disease trajectory in Duchenne muscular dystrophy.* Nature Medicine, 2023. **29**(1): p. 95-103.
115. Guermazi, M., et al., *[Validity and reliability of Spinal Mouse to assess lumbar flexion].* Ann Readapt Med Phys, 2006. **49**(4): p. 172-7.

116. Consmüller, T., et al., *Comparative evaluation of a novel measurement tool to assess lumbar spine posture and range of motion.* Eur Spine J, 2012. **21**(11): p. 2170-80.
117. Degenhardt, B.F., Z. Starks, and S. Bhatia, *Reliability of the DIERS Formetric 4D Spine Shape Parameters in Adults without Postural Deformities.* Biomed Res Int, 2020. **2020**: p. 1796247.
118. Tsushima, H., M.E. Morris, and J. McGinley, *Test-retest reliability and inter-tester reliability of kinematic data from a three-dimensional gait analysis system.* J Jpn Phys Ther Assoc, 2003. **6**(1): p. 9-17.
119. Cagnie, B., et al., *Reliability and normative database of the Zebris cervical range-of-motion system in healthy controls with preliminary validation in a group of patients with neck pain.* J Manipulative Physiol Ther, 2007. **30**(6): p. 450-5.
120. Wunderlich, M., et al., *A new approach to assess movements and isometric postures of spine and trunk at the workplace.* Eur Spine J, 2011. **20**(8): p. 1393-402.
121. Hamacher, D., et al., *Evaluation of a visual feedback system in gait retraining: a pilot study.* Gait Posture, 2012. **36**(2): p. 182-6.
122. Gill, K.P. and M.J. Callaghan, *Intratester and intertester reproducibility of the lumbar motion monitor as a measure of range, velocity and acceleration of the thoracolumbar spine.* Clinical Biomechanics, 1996. **11**(7): p. 418-421.
123. Schiefer, C., et al., *Optimization of inertial sensor-based motion capturing for magnetically distorted field applications.* J Biomech Eng, 2014. **136**(12): p. 121008.
124. Farshad, M., et al., *How is spinal range of motion affected by disc- and facet degeneration and spinopelvic anatomy?* N Am Spine Soc J, 2021. **7**: p. 100076.
125. McGregor, A.H., H.R. Cattermole, and S.P. Hughes, *Global spinal motion in subjects with lumbar spondylolysis and spondylolisthesis: does the grade or type of slip affect global spinal motion?* Spine (Phila Pa 1976), 2001. **26**(3): p. 282-6.
126. Poussa, M. and G. Mellin, *Spinal mobility and posture in adolescent idiopathic scoliosis at three stages of curve magnitude.* Spine (Phila Pa 1976), 1992. **17**(7): p. 757-60.
127. Hansen, B.B., et al., *Effect of Lumbar Disc Degeneration and Low-Back Pain on the Lumbar Lordosis in Supine and Standing: A Cross-Sectional MRI Study.* Spine (Phila Pa 1976), 2015. **40**(21): p. 1690-6.
128. Sadler, S.G., et al., *Restriction in lateral bending range of motion, lumbar lordosis, and hamstring flexibility predicts the development of low back pain: a systematic review of prospective cohort studies.* BMC Musculoskelet Disord, 2017. **18**(1): p. 179.
129. Laird, R.A., et al., *Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis.* BMC Musculoskelet Disord, 2014. **15**: p. 229.
130. Christensen, S.T. and J. Hartvigsen, *Spinal curves and health: a systematic critical review of the epidemiological literature dealing with associations between sagittal spinal curves and health.* J Manipulative Physiol Ther, 2008. **31**(9): p. 690-714.
131. Kulig, K., et al., *Segmental lumbar mobility in individuals with low back pain: in vivo assessment during manual and self-imposed motion using dynamic MRI.* BMC Musculoskelet Disord, 2007. **8**: p. 8.
132. Zuberbier, O.A., et al., *Analysis of the convergent and discriminant validity of published lumbar flexion, extension, and lateral flexion scores.* Spine (Phila Pa 1976), 2001. **26**(20): p. E472-8.
133. Lehman, G.J., *Biomechanical assessments of lumbar spinal function. How low back pain sufferers differ from normals. Implications for outcome measures research. Part I: kinematic assessments of lumbar function.* J Manipulative Physiol Ther, 2004. **27**(1): p. 57-62.
134. Ferguson, S.A. and W.S. Marras, *Revised protocol for the kinematic assessment of impairment.* Spine J, 2004. **4**(2): p. 163-9.
135. Quinlan, J.F., D. Duke, and S. Eustace, *Bertolotti's syndrome. A cause of back pain in young people.* J Bone Joint Surg Br, 2006. **88**(9): p. 1183-6.
136. Sekharappa, V., et al., *Lumbosacral transition vertebra: prevalence and its significance.* Asian Spine J, 2014. **8**(1): p. 51-8.

137. Dzupa, V., et al., *Developmental malformations in the area of the lumbosacral transitional vertebrae and sacrum: differences in gender and left/right distribution.* Surg Radiol Anat, 2014. **36**(7): p. 689-93.
138. Luoma, K., et al., *Lumbosacral transitional vertebra: relation to disc degeneration and low back pain.* Spine (Phila Pa 1976), 2004. **29**(2): p. 200-5.
139. Lee, C.S., et al., *The clinical importance of lumbosacral transitional vertebra in patients with adolescent idiopathic scoliosis.* Spine (Phila Pa 1976), 2015. **40**(17): p. E964-70.
140. Aihara, T., et al., *Intervertebral disc degeneration associated with lumbosacral transitional vertebrae: a clinical and anatomical study.* J Bone Joint Surg Br, 2005. **87**(5): p. 687-91.
141. Vergauwen, S., et al., *Distribution and incidence of degenerative spine changes in patients with a lumbo-sacral transitional vertebra.* Eur Spine J, 1997. **6**(3): p. 168-72.
142. Golubovsky, J.L., et al., *Development of a novel in vitro cadaveric model for analysis of biomechanics and surgical treatment of Bertolotti syndrome.* Spine J, 2020. **20**(4): p. 638-656.
143. Ahuja, S., et al., *Biomechanical Study of L5/S1 Bertollotti Syndrome- a Finite Element Model Study.* The Spine Journal, 2017. **17**: p. S25-S26.
144. Verhaegen, J.C.F., et al., *Prevalence of Lumbosacral Transitional Vertebral Anomalies Among Healthy Volunteers and Patients with Hip Pathology: Association with Spinopelvic Characteristics.* JBJS Open Access, 2023. **8**(1): p. e22.00095.
145. Becker, L., et al., *Approach-related anatomical differences in patients with lumbo-sacral transitional vertebrae undergoing lumbar fusion surgery at level L4/5.* Arch Orthop Trauma Surg, 2023. **143**(4): p. 1753-1759.
146. Mahato, N.K., *Morphometric analysis and identification of characteristic features in sacra bearing accessory articulations with L5 vertebrae.* Spine J, 2010. **10**(7): p. 616-21.
147. Sun, J., et al., *The association of lumbosacral transitional vertebral anomalies with acetabular dysplasia in adult patients with hip-spine syndrome : a cross-sectional evaluation of a prospective hip registry cohort.* Bone Joint J, 2021. **103-B**(8): p. 1351-1357.
148. Otani, K., S. Konno, and S. Kikuchi, *Lumbosacral transitional vertebrae and nerve-root symptoms.* The Journal of bone and joint surgery. British volume, 2001. **83**(8): p. 1137-1140.
149. Jain, A., et al., *Bertolotti syndrome: a diagnostic and management dilemma for pain physicians.* Korean J Pain, 2013. **26**(4): p. 368-73.
150. Zhang, R. and J. Cheng, *Interventional Management of Chronic Low Back Pain Associated with Bertolotti's Syndrome: Report of Case Series.* Ann Clin Case Rep. 2017; 2, 2017. **1348**.
151. Mitra, R. and M. Carlisle, *Bertolotti's syndrome: a case report.* Pain Pract, 2009. **9**(2): p. 152-4.
152. Brenner, A.K., *Use of lumbosacral region manipulation and therapeutic exercises for a patient with a lumbosacral transitional vertebra and low back pain.* J Orthop Sports Phys Ther, 2005. **35**(6): p. 368-76.
153. Holm, E.K., C. Bunger, and C.B. Foldager, *Symptomatic lumbosacral transitional vertebra: a review of the current literature and clinical outcomes following steroid injection or surgical intervention.* SICOT J, 2017. **3**: p. 71.
154. Jonsson, B., B. Stromqvist, and N. Egund, *Anomalous lumbosacral articulations and low-back pain. Evaluation and treatment.* Spine (Phila Pa 1976), 1989. **14**(8): p. 831-4.
155. Santavirta, S., et al., *Surgical treatment of Bertolotti's syndrome. Follow-up of 16 patients.* Arch Orthop Trauma Surg, 1993. **112**(2): p. 82-7.
156. McGrath, K., et al., *Clinical assessment and management of Bertolotti Syndrome: a review of the literature.* Spine J, 2021. **21**(8): p. 1286-1296.
157. Burnham, R., *Radiofrequency sensory ablation as a treatment for symptomatic unilateral lumbosacral junction pseudarticulation (Bertolotti's syndrome): a case report.* Pain Med, 2010. **11**(6): p. 853-5.
158. Endo, K., et al., *A case of severe low back pain associated with Richard disease (lumbosacral transitional vertebra).* min-Minimally Invasive Neurosurgery, 2004. **47**(04): p. 253-255.
159. Chang, C.-J., et al., *Surgical interventions for Bertolotti's syndrome: case report and review of unsatisfactory cases in the literature.* BMC Surgery, 2022. **22**(1): p. 36.

160. il Ju, C., et al., *Decompressive L5 transverse processectomy for Bertolotti's syndrome: a preliminary study.* Pain Physician, 2017. **20**(6): p. E923.
161. Jenkins, A.L., et al., *Redefining the Treatment of Lumbosacral Transitional Vertebrae for Bertolotti Syndrome: Long-Term Outcomes Utilizing the Jenkins Classification to Determine Treatment.* World Neurosurgery, 2023.
162. Farshad-Amacker, N.A., et al., *Interreader and intermodality reliability of standard anteroposterior radiograph and magnetic resonance imaging in detection and classification of lumbosacral transitional vertebra.* Spine J, 2014. **14**(8): p. 1470-5.
163. Hou, L., et al., *Lumbar plain radiograph is not reliable to identify lumbosacral transitional vertebra types according to Castellvi classification principle.* BMC Musculoskelet Disord, 2020. **21**(1): p. 333.
164. Lian, J., N. Levine, and W. Cho, *A review of lumbosacral transitional vertebrae and associated vertebral numeration.* Eur Spine J, 2018. **27**(5): p. 995-1004.
165. Hughes, R.J. and A. Saifuddin, *Numbering of lumbosacral transitional vertebrae on MRI: role of the iliolumbar ligaments.* AJR Am J Roentgenol, 2006. **187**(1): p. W59-65.
166. Farshad, M., et al., *A reliable measurement for identifying a lumbosacral transitional vertebra with a solid bony bridge on a single-slice midsagittal MRI or plain lateral radiograph.* The bone & joint journal, 2013. **95**(11): p. 1533-1537.
167. Chalian, M., et al., *Prediction of transitional lumbosacral anatomy on magnetic resonance imaging of the lumbar spine.* World journal of radiology, 2012. **4**(3): p. 97.
168. Lee, C.H., et al., *Identification and prediction of transitional vertebrae on imaging studies: anatomical significance of paraspinal structures.* Clin Anat, 2007. **20**(8): p. 905-14.
169. Mahato, N.K., *Trabecular bone structure in lumbosacral transitional vertebrae: distribution and densities across sagittal vertebral body segments.* Spine J, 2013. **13**(8): p. 932-7.
170. Mahato, N.K., *Pedicular anatomy of the first sacral segment in transitional variations of the lumbo-sacral junction.* Spine (Phila Pa 1976), 2011. **36**(18): p. E1187-92.
171. Organization, W.H., *NOTE= NOTE.* Weekly Epidemiological Record= Relevé épidémiologique hebdomadaire, 1947. **22**(46): p. 373-373.
172. Montgomery, S.R., Jr., et al., *Patients With Low-Grade Lumbosacral Transitional Vertebrae Demonstrate No Difference in Achievement of Clinical Thresholds After Hip Arthroscopy for Femoroacetabular Impingement Syndrome.* Arthroscopy, 2023.
173. Heaps, B.M., et al., *Lumbosacral Transitional Vertebrae Predict Inferior Patient-Reported Outcomes After Hip Arthroscopy.* Am J Sports Med, 2020. **48**(13): p. 3272-3279.
174. Dreischarf, M., et al., *Differences between clinical "snap-shot" and "real-life" assessments of lumbar spine alignment and motion - What is the "real" lumbar lordosis of a human being?* J Biomech, 2016. **49**(5): p. 638-644.
175. Gong, H., et al., *Prevalence of lumbosacral transitional vertebrae in dogs in Berlin.* Polish journal of veterinary sciences, 2020. **23**: p. 261-265.

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6. Eidesstattliche Versicherung

Erklärung § 4 Abs. 3 (k) der HabOMed der Charité

Hiermit erkläre ich, dass

- weder früher noch gleichzeitig ein Habilitationsverfahren durchgeführt oder angemeldet wurde,
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- mir die geltende Habilitationsordnung bekannt ist. Ich erkläre ferner, dass mir die Satzung der Charité – Universitätsmedizin Berlin zur Sicherung Guter Wissenschaftlicher Praxis bekannt ist und ich mich zur Einhaltung dieser Satzung verpflichte.

Berlin, 27.02.2024

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