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ROZPRAWA DOKTORSKA

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**Rola siły mięśni obręczy biodrowej w klinicznej, funkcjonalnej i biomechanicznej ocenie
przewlekłej niestabilności stawu skokowo-goleniowego**

Promotor:

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„Ważna sprawa to nigdy nie przestać pytać”

— Albert Einstein

Wykaz skrótów

AII – Ankle Instability Instrument

CAI – Chronic Ankle Instability

CAIT-PL – the Polish version of the Cumberland Ankle Instability Tool

CON – Control group

COSMIN – Consensus-Based Standards for the Selection of Health Status Measurement Instruments

FAOS – Foot and Ankle Outcome Score

IAC – International Ankle Consortium

IdFAI – Identification of Functional Ankle Instability

ICC – Intraclass Correlation Coefficient

LAS – Lateral Ankle Sprain (skrót stosowany także w liczbie mnogiej)

MD – Mean Difference

MDC – Minimal Detectable Change

MFM – Multisegmented Foot Models (skrót stosowany także w liczbie pojedynczej)

MNiSW – Ministerstwo Nauki i Szkolnictwa Wyższego

PFPS – Patellofemoral Pain Syndrome

PROMs – Patient Reported Outcome Measures

SEBT – Star Excursion Balance Test

SEM – Standard Error of Measurement

YBT-LQ – Lower Quarter Y-Balance Test

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1. Artykuły wchodzące w skład cyklu publikacyjnego

Przedmiotem rozprawy doktorskiej jest cykl trzech powiązanych tematycznie publikacji naukowych. We wszystkich tych pracach jestem pierwszym autorem oraz autorem korespondencyjnym. W każdym z artykułów wchodzących w skład cyklu publikacyjnego pełniłem wiodącą rolę (patrz: oświadczenia współautorów str. 70–72). Poniżej przedstawiono powiązane tematycznie artykuły naukowe, opublikowane w recenzowanych czasopismach:

1. Olszewski, M.; Zając, B.; Golec, J. Cross Cultural Adaptation, Reliability and Validity of the Polish Version of the Cumberland Ankle Instability Tool. *Disabil Rehabil* **2024**, *46*, 2926–2932, doi:10.1080/09638288.2023.2232719.

Impact Factor: 2.0; Punktacja MNiSW: 70

2. Olszewski, M.; Golec, J.; Zając, B.; Kręzałek, P. Isometric and Isokinetic Hip Strength in Males with Chronic Ankle Instability and Its Relationship with Dynamic Balance and Self-Reported Instability. *Phys Ther Sport* **2025**, *72*, 9–17, doi:10.1016/j.ptsp.2024.12.007.

Impact Factor: 2.4; Punktacja MNiSW: 100

3. Olszewski, M.; Kręzałek, P.; Golec, J. Multisegmented Foot and Lower Limb Kinematics During Gait in Males with Chronic Ankle Instability: Exploring Links with Hip Abductor Strength. *J Clin Med* **2025**, *14*, 5977, doi:10.3390/jcm14175977.

Impact Factor: 2.9; Punktacja MNiSW: 140

Łączna punktacja cyklu publikacji: Impact Factor: 7.3; Punktacja MNiSW: 310.

Badania, na podstawie których powstała niniejsza rozprawa doktorska, zostały przeprowadzone za zgodą Komisji Bioetycznej przy Okręgowej Izbie Lekarskiej w Krakowie nr 11/KBL/OIL/2022 oraz sfinansowane przez Akademię Wychowania Fizycznego w Krakowie (obecnie Akademia Kultury Fizycznej w Krakowie), projekt nr 158/MN/IRK/2022.

Pozostałe publikacje autora rozprawy doktorskiej, nie wchodzące w skład cyklu publikacyjnego:

4. Olszewski, M.; Gamrot, S.; Golec, J.; Szczygieł, E. Reliability of Scapula Clinical Assessment and Effectiveness of Scapular-Focused Exercises in a Non-Athletic Population with Shoulder Pain – a Literature Review. *Rehabilitacja Medyczna* **2023**, 27, doi:10.5604/01.3001.0053.6027.

Punktacja MNiSW: 100

5. Zając, B.; Olszewski, M.; Mika, A.; Maciejczyk, M. Do Highly Trained Mountain Runners Differ from Recreational Active Non-Runners on Range of Motion and Strength in the Hip and Ankle as Well as Postural Control? *J Clin Med* **2023**, 12, 2715, doi:10.3390/jcm12072715.

Impact Factor: 2.9; Punktacja MNiSW: 140

6. Olszewski, M.; Zając, B.; Mika, A.; Golec, J. Ankle Dorsiflexion Range of Motion and Hip Abductor Strength Can Predict Lower Quarter Y-Balance Test Performance in Healthy Males. *J Bodyw Mov Ther* **2024**, 38, 567–573, doi:10.1016/j.jbmt.2024.03.053.

Impact Factor: 1.4; Punktacja MNiSW: 70

7. Zając, B.; Olszewski, M.; Mika, A. Influence of Protocol Variables on Outcomes of the Star Excursion Balance Test Group (SEBT, mSEBT, YBT-LQ) in Healthy Individuals: A Systematic Review. *Front Physiol* **2024**, 15, doi:10.3389/fphys.2024.1415887.

Impact Factor: 3.4; Punktacja MNiSW: 100

Łączna punktacja pozostałych publikacji wynosi: Impact Factor: 7.7; Punktacja MNiSW: 410. Całkowity dorobek autora rozprawy doktorskiej to: Impact Factor: 15.0 oraz 720 punktów MNiSW.

2. Wstęp i uzasadnienie podjęcia badań

Urazy skrętne stawu skokowo-goleniowego w mechanizmie inwersyjnym (Lateral Ankle Sprains – LAS) są jednymi z najczęściej spotykanych uszkodzeń mięśniowo-szkieletowych wśród aktywnych fizycznie młodych osób. Odpowiadają one za 25–30% wszystkich kontuzji związanych ze sportem [1]. Częstość ich występowania wynosi 2–7 ostrych LAS na 1000 osobolat [2]. W samych Stanach Zjednoczonych co roku ponad 2 miliony osób doznaje tego uszkodzenia urazowego [3], co stanowi obciążenie finansowe systemu opieki zdrowotnej szacunkowo na około 6,2 miliarda dolarów rocznie [4]. Niestety, jedynie 11% osób, które doznały LAS, podejmuje fizjoterapię po tym urazie [5]. Brak odpowiedniego leczenia pierwszorazowego LAS może zwiększać ryzyko występowania kolejnych skręceń i progresji do dysfunkcji nazywanej przewlekłą niestabilnością stawu skokowo-goleniowego (Chronic Ankle Instability – CAI). CAI rozwija się u około 46% osób (od 9% do 76%), które doświadczyły pierwszorazowego LAS [6].

Głównymi objawami CAI są nawracające skręcenia stawu skokowo-goleniowego, powtarzające się epizody „uciekania” stawu oraz subiektywne odczucia niestabilności [4]. W 2002 roku Hertel zaproponował klasyfikację CAI, dzieląc ją na niestabilność mechaniczną i funkcjonalną [7]. Podział ten tłumaczy dwa główne mechanizmy rozwoju CAI, choć nie odzwierciedla całego spektrum patologii prowadzących do tej dysfunkcji. Niestabilność funkcjonalna wynika z zaburzeń propriocepcji, kontroli nerwowo-mięśniowej, kontroli posturalnej lub siły mięśniowej. Z kolei niestabilność mechaniczna jest następstwem czynników zaburzających mechanikę kompleksu skokowego, takich jak patologiczna wiotkość więzadłowa, zaburzenia artrokinematyki, stan zapalny i konflikt błony maziowej czy zmiany zwyrodnieniowe. W efekcie CAI może być wynikiem niestabilności mechanicznej, funkcjonalnej lub współwystępowania obu tych mechanizmów. CAI oddziałuje na życie osób dotkniętych tą dysfunkcją na wielu różnych płaszczyznach, zwłaszcza fizycznej, psychicznej i społecznej. Osoby z CAI zgłaszają ograniczoną funkcję stawu skokowo-goleniowego, a uszkodzony aparat więzadłowy i niestabilność stawu przyczyniają się do występowania pourazowej choroby zwyrodnieniowej stawu skokowo-goleniowego [8]. Dodatkowo u części z nich może rozwijać się kinezyfobia, czyli lęk przed ruchem [9]. W konsekwencji ograniczenia te mogą wpływać na zmniejszony poziom aktywności fizycznej [10] oraz obniżać jakość życia [11].

Obecnie leczenie zachowawcze CAI opiera się najczęściej na treningu równowagi i propriocepcji, treningu nerwowo-mięśniowym, terapii manualnej oraz ćwiczeniach

wzmacniających mięśnie stabilizujące stopę i staw skokowo-goleniowy [12]. Wspomagająco stosuje się także ortezy stawu skokowo-goleniowego, taping sztywny, kinesiotaping, a także wkładki ortopedyczne [13]. Według dostępnych przeglądów systematycznych to właśnie trening nerwowo-mięśniowy [14] i trening równowagi [15] wydają się być najbardziej skutecznymi metodami leczenia zachowawczego CAI. Pomimo tego nie ma wyraźnych dowodów, że częstość występowania nawracających skręceń stawu skokowo-goleniowego maleje. Dodatkowo interwencje terapeutyczne skupiające się na lokalnym leczeniu stawu skokowo-goleniowego, takie jak izolowany trening siłowy mięśni stopy i stawu skokowo-goleniowego, mogą być nieskuteczne w zakresie poprawy dynamicznej równowagi i metod samoceny pacjentów [16]. Protokoły rehabilitacyjne obecne w badaniach nad CAI wciąż często pomijają proksymalne elementy łańcucha kinematycznego kończyny dolnej i miednicy, co może potencjalnie ograniczać ich skuteczność.

W literaturze można znaleźć doniesienia potwierdzające zasadność treningu mięśni obręczy biodrowej u osób z dysfunkcjami stawu kolanowego. W przypadku zespołu bólu rzepkowo-udowego (Patellofemoral Pain Syndrome – PFPS) zarówno ćwiczenia wzmacniające mięśnie stawu kolanowego, jak i ćwiczenia wzmacniające mięśnie obręczy biodrowej są skuteczne w redukcji objawów PFPS [17,18]. Jednakże liczne prace sugerują, że połączenie tych interwencji, czyli włączenie ćwiczeń obręczy biodrowej do ćwiczeń skupionych na stawie kolanowym, oferuje dodatkowe korzyści funkcjonalne w porównaniu z ćwiczeniami wyłącznie stawu kolanowego [19,20]. Z uwagi na dużą liczbę wysokiej jakości badań klinicznych rola obręczy biodrowej w rehabilitacji stawu kolanowego jest powszechnie określona i stała się standardem w rehabilitacji PFPS [21]. W przypadku CAI rola mięśni obręczy biodrowej nie została jeszcze w pełni poznana i ustalona. Istnieją natomiast wstępne doniesienia wskazujące, że ich rola może być istotna w zarządzaniu objawami CAI [22–24]. Dotychczasowe przeglądy systematyczne, oparte na ograniczonej liczbie badań, sugerowały obniżoną siłę izometryczną wybranych grup mięśniowych stawu biodrowego i kolanowego u pacjentów z CAI w porównaniu z osobami zdrowymi [25,26]. Dejong i wsp. [25] ograniczyli się do analizy izometrycznej siły prostowników, odwodźcicieli i rotatorów zewnętrznych, przy czym trzy z czterech włączonych badań pochodziły od tego samego zespołu badawczego, co zwiększa ryzyko stronniczości. Natomiast Khalaj i wsp. [26], ze względu na różnice w rodzajach skurczu i prędkościach kątowych, przeprowadzili dla mięśni obręczy biodrowej jedynie analizę opisową na podstawie trzech prac, rezygnując z metaanalizy. Dopiero w 2025 roku opublikowano pierwszą metaanalizę skupioną na sile mięśni obręczy biodrowej w populacji z CAI [27].

Co istotne, jedna z publikacji wchodzących w skład niniejszej rozprawy została w niej uwzględniona [28].

Kolejnym zagadnieniem podejmowanym w literaturze jest potencjalna wartość siły mięśni obręczy biodrowej jako czynnika predykcyjnego uszkodzeń urazowych kończyny dolnej. Prace Powersa i wsp. [29] oraz De Riddera i wsp. [30] sugerują, że niska siła izometryczna mięśni odwodźcicieli i prostowników stawu biodrowego może być predyktorem skręceń stawu skokowo-goleniowego u piłkarzy nożnych. Odmienne wnioski płyną z przeglądu Steinberga i wsp. [31], który skupiał się na określeniu związków między wydolnością mięśni obręczy biodrowej a uszkodzeniami w obrębie stopy, stawu skokowo-goleniowego i podudzia. Według autorów istnieją ograniczone dowody, że parametry związane z wydolnością mięśni obręczy biodrowej są związane z uszkodzeniami kompleksu stawu skokowo-goleniowego i stopy, sugerując, że obserwowane deficyty wydolności są raczej konsekwencjami urazu niż czynnikami przyczyniającymi się do jego wystąpienia. Wyniki te potwierdza prospektywne badanie Khalaj i wsp. [32], raportujące brak występowania zaburzeń siły mięśniowej okolicy stawu kolanowego i biodrowego w ciągu trzech miesięcy od pierwszorazowego urazu skrętnego stawu skokowo-goleniowego. Może to wskazywać, że deficyty siły proksymalnych grup mięśniowych kończyny dolnej ujawniają się dopiero w przebiegu przewlekłych dolegliwości stawu skokowo-goleniowego. Podkreśla to potrzebę kompleksowej oceny osób z CAI w celu wczesnego wychwycenia powstających deficytów. Ocena ta powinna obejmować aspekty kliniczne, funkcjonalne i biomechaniczne, które zostaną omówione w kolejnych częściach wstępu.

Do oceny stopnia nasilenia objawów CAI w warunkach klinicznych najczęściej stosuje się wywiad, badanie fizykalne oraz kwestionariusze samooceny pacjentów (Patient Reported Outcome Measures – PROMs). Kwestionariusze te stanowią subiektywną ocenę pacjentów dotyczącą ich stanu zdrowia. PROMs są niedrogie, a przy tym bardzo efektywne i rzetelne, dzięki czemu znajdują szerokie zastosowanie w praktyce klinicznej oraz badaniach naukowych [33]. Mogą one wspomagać klinicystów i badaczy w stawianiu diagnozy lub ocenie efektów interwencji, obok badania fizykalnego i metod obrazowania medycznego. Istnieje wiele kwestionariuszy dotyczących stopy i stawu skokowo-goleniowego, jednak większość z nich służy do oceny ogólnych ograniczeń odnoszących się do tych regionów. Aby ocenić nasilenie objawów w takich przypadkach jak CAI, konieczne wydaje się wdrożenie PROMs specyficznych dla danej jednostki chorobowej obejmujące pytania odnoszące się do jej kluczowych cech. Jedynie trzy narzędzia zostały zarekomendowane przez International Ankle

Consortium (IAC) [34] jako specyficzne do oceny objawów CAI, ponieważ uwzględniają pytania o subiektywnie odczuwaną niestabilność podczas określonych aktywności oraz o epizody „uciekania” stawu skokowo-goleniowego. Są to: Ankle Instability Instrument (AII), Identification of Functional Ankle Instability (IdFAI) oraz Cumberland Ankle Instability Tool (CAIT) [35]. Kwestionariusz CAIT jest jednym z najczęściej stosowanych narzędzi samooceny u pacjentów z CAI. Został opracowany w języku angielskim w celu oceny nasilenia funkcjonalnej niestabilności stawu skokowo-goleniowego oraz wspomagania decyzji terapeutycznych w procesie postępowania z CAI. Oryginalna wersja CAIT została poddana adaptacji kulturowej na wiele języków [36]. Do niedawna brakowało polskiego narzędzia specyficznego do oceny objawów CAI, co utrudniało diagnostykę, leczenie oraz planowanie badań zgodnych z kryteriami IAC [34]. Kryteria te stanowią obecnie międzynarodowy standard w badaniach nad CAI, a ich niestosowanie uznawane jest w środowisku naukowym za poważny błąd metodologiczny.

Złotym standardem oceny funkcjonalnej w badaniach nad LAS i CAI są testy równowagi dynamicznej [37]. Do tej grupy zalicza się m.in. Star Excursion Balance Test (SEBT), obejmujący osiem kierunków, oraz jego uproszczoną wersję, Lower Quarter Y-Balance Test (YBT-LQ). YBT-LQ koncentruje się wyłącznie na trzech kluczowych kierunkach i wykorzystuje standaryzowany zestaw testowy (Y-Balance Test Kit), co czyni go szybszym i bardziej praktycznym w wykonaniu, a tym samym jest powszechnie stosowany w praktyce klinicznej i badaniach naukowych. Metaanaliza Song i wsp. [38] wykazała istotne deficyty we wszystkich zasięgach w teście SEBT u osób z CAI w porównaniu z grupą kontrolną lub ich zdrową kończyną. Dotychczasowe prace analizowały również zależności między siłą mięśni obręczy biodrowej a równowagą dynamiczną w populacjach z CAI [39–41], wskazując na powiązania różnych grup mięśniowych z wynikami testów SEBT/YBT-LQ. Wyniki tych badań sugerują, że siła mięśni obręczy biodrowej może stanowić istotny czynnik warunkujący wykonanie zadań funkcjonalnych u osób z CAI. W literaturze nadal jednak brakuje jednoznacznych ustaleń dotyczących tego, które grupy mięśniowe oraz jakie rodzaje pracy mięśniowej odgrywają kluczową rolę w utrzymaniu równowagi dynamicznej u pacjentów z CAI. Precyzyjna identyfikacja tych mechanizmów jest kluczowa dla opracowania kompleksowych programów rehabilitacyjnych ukierunkowanych na potrzeby osób z CAI.

Ocena biomechaniczna CAI może obejmować szereg różnych metod pomiarowych. Najczęściej wykorzystuje się trójwymiarową analizę ruchu dostarczającą danych kinematycznych, analizę dynamiczną (kinetyczną) sił i momentów [42] oraz ocenę aktywności

mięśni przy użyciu elektromiografii podczas różnorodnych wzorców i zadań ruchowych [43]. Wymienione metody są obiektywne i precyzyjne dzięki wykorzystaniu wysokiej jakości aparatury badawczej. Pozwala to na wychwycenie zarówno znacznych, jak i nawet niewielkich dysfunkcji, które mogą być niezauważalne w klasycznym badaniu klinicznym lub funkcjonalnym. Dysfunkcje biomechaniczne, nawet te niewielkie, mogą mieć potencjalne znaczenie kliniczne podczas diagnostyki i rehabilitacji osób z CAI. Z tych względów w środowisku naukowym podejmuje się liczne badania biomechaniczne pozwalające w sposób obiektywny scharakteryzować CAI jako jednostkę kliniczną oraz wskazać zaburzenia z nią związane.

Chód to złożona, cykliczna czynność lokomocyjna umożliwiającą przemieszczanie środka masy ciała do przodu dzięki rytmicznej i skoordynowanej pracy kończyn i tułowia [44]. Mimo że chód jest czynnością zautomatyzowaną i powtarzalną [45], w populacji z CAI może stanowić źródło odczuć niestabilności i epizodów „uciekania” stawu skokowo-goleniowego [46] oraz nawracających urazów skrętnych [47]. Oznacza to, że badania analizujące chód w populacji z CAI mogą wciąż dostarczać wartościowych informacji, szczególnie w przypadku wykorzystania najnowocześniejszych modeli biomechanicznych. Do tej pory w zdecydowanej większości badań nad CAI stosowano głównie jednosegmentowe modele stopy, które traktują ją jako sztywną bryłę. Takie podejście jest niezgodne ze złożoną anatomią i biomechaniką stopy, która składa się z wielu stawów umożliwiających ruchy między poszczególnymi segmentami [48]. Pominięcie międzysegmentowych ruchów stopy w analizie chodu u osób z CAI może maskować subtelne dysfunkcje w jej kontroli, co potencjalnie może prowadzić do zaburzeń równowagi, zmienionego rozkładu obciążeń oraz zwiększonego ryzyka kolejnych uszkodzeń. Dodatkowo takie uproszczenie może ograniczać precyzję strategii rehabilitacyjnych poprzez nieuwzględnianie specyficznych zaburzeń, które mogą wymagać ukierunkowanych interwencji. W celu zapewnienia pełnej biomechanicznej analizy ruchów stopy stosuje się wielosegmentowe modele stopy (MFM – multisegmented foot models) [49]. MFM najczęściej dzielą stopę i staw skokowo-goleniowy na segmenty takie jak: podudzie, tyłostopie, śródstopie, przodostopie (przyśrodkowe i boczne) oraz paluch. Liczba prac badawczych wykorzystujących MFM w analizie chodu w populacji z CAI jest nadal niewielka [50–52], a ich wyniki są niejednoznaczne. Dotychczasowe badania z wykorzystaniem MFM u osób z CAI wskazują na zwiększoną inwersję tyłostopia [50,51] oraz zmniejszone zgięcie grzbietowe stawu skokowo-goleniowego w fazie podporu [51]. De Ridder i wsp. [52] nie stwierdzili istotnych różnic w zakresie inwersji tyłostopia podczas chodu, co stoi

w sprzeczności z innymi doniesieniami. Autorzy jako jedyni zaobserwowali natomiast zwiększoną inwersję przyśrodkowego segmentu przodostopia w końcowej części fazy podporu, co może sugerować kompensacyjne mechanizmy w przedniej części stopy. Niejednoznaczne wyniki dotychczasowych badań z wykorzystaniem MFM wskazują, że biomechaniczne ujęcie chodu w populacji z CAI wciąż wymaga pogłębionej analizy.

Badania nad siłą mięśni obręczy biodrowej i jej rolę w ocenie klinicznej, funkcjonalnej oraz biomechanicznej CAI podjęto w celu poszerzenia aktualnego stanu wiedzy i uzupełnienia istniejących luk w literaturze. W dotychczasowych opracowaniach brakowało polskojęzycznego narzędzia specyficznego do oceny stopnia nasilenia CAI. Nie prowadzono również badań oceniających jednocześnie momenty sił mięśni obręczy biodrowej w warunkach izometrycznych i izokinetycznych w populacji z CAI. Dotychczas nie wiadomo, które grupy mięśniowe oraz jakie rodzaje pracy mięśniowej są kluczowe dla osób z CAI w odniesieniu do równowagi dynamicznej i subiektywnie odczuwanej niestabilności stawu skokowo-goleniowego. Kolejnym problemem jest brak badań kompleksowo analizujących chód w tej populacji. Dotychczas nie łączono MFM z oceną kinematyki stawów proksymalnych, takich jak staw kolanowy i biodrowy. W wielu analizach pomijano również pełny cykl chodu, a zwłaszcza fazę przenoszenia. Nie odnotowano także badań oceniających związek pomiędzy siłą mięśni obręczy biodrowej a kinematyką stawu skokowo-goleniowego. W niniejszych badaniach zastosowano najnowsze narzędzia pomiarowe i modele biomechaniczne, które dotychczas rzadko były standardem w analizie CAI, takie jak dynamometria izokinetyczna czy trójwymiarowa analiza chodu z wykorzystaniem MFM. Uzyskanie takich danych pozwoli na dokładniejszą identyfikację deficytów związanych z CAI, a w konsekwencji na wielowymiarowe określenie roli siły mięśni obręczy biodrowej w CAI oraz stworzenie nowych strategii diagnostycznych i terapeutycznych dedykowanych tej grupie pacjentów.

3. Cel pracy

Głównym celem pracy było zbadanie roli siły mięśni obręczy biodrowej w przewlekłej niestabilności stawu skokowo-goleniowego, z uwzględnieniem aspektów oceny klinicznej, funkcjonalnej i biomechanicznej.

3.1. Pytania badawcze

Na potrzeby rozprawy doktorskiej sformułowano problemy szczegółowe w formie pytań badawczych:

1. Czy polska wersja narzędzia Cumberland Ankle Instability Tool (CAIT-PL) charakteryzuje się odpowiednią rzetelnością i trafnością, aby mogła być stosowana w badaniach nad przewlekłą niestabilnością stawu skokowo-goleniowego?
2. Czy wartości momentów sił mięśni obręczy biodrowej, mierzone w warunkach izometrycznych i izokinetycznych, różnią się między osobami z przewlekłą niestabilnością stawu skokowo-goleniowego a grupą kontrolną?
3. Czy istnieje związek między momentami sił mięśni obręczy biodrowej a oceną funkcjonalną równowagi dynamicznej i kliniczną oceną subiektywnie zgłaszanej niestabilności stawu skokowo-goleniowego?
4. Czy u osób z przewlekłą niestabilnością stawu skokowo-goleniowego występują zaburzenia biomechaniczne w zakresie kinematyki stopy oraz stawu skokowo-goleniowego, kolanowego i biodrowego podczas cyklu chodu?
5. Czy izometryczny moment siły mięśni odwodźcicieli stawu biodrowego jest związany z oceną biomechaniczną kinematyki stawu skokowo-goleniowego u osób z przewlekłą niestabilnością tego stawu?

4. Metodologia i opis poszczególnych publikacji

4.1. Publikacja 1

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Celem tej pracy było stworzenie i adaptacja kulturowa pierwszego polskojęzycznego narzędzia specyficznego do oceny stopnia nasilenia funkcjonalnej niestabilności stawu skokowo-goleniowego wraz z oceną jego właściwości psychometrycznych. Sformułowano następującą hipotezę badawczą:

1. Polska wersja kwestionariusza Cumberland Ankle Instability Tool (CAIT-PL) jest rzetelnym i trafnym narzędziem do oceny stopnia nasilenia funkcjonalnej niestabilności stawu skokowo-goleniowego.

Badanie składało się z dwóch etapów:

1. stworzenie kwestionariusza CAIT-PL wraz z jego adaptacją dopasowaną do realiów polskiej kultury;
2. ewaluacja właściwości psychometrycznych kwestionariusza CAIT-PL.

Do pierwszego etapu wykorzystano metodę tłumaczenia w przód i wstecz zgodnie z wytycznymi Beaton i wsp. [53], która składała się z sześciu następujących kroków: krok I (tłumaczenie wstępne), krok II (synteza tłumaczeń), krok III (tłumaczenie wsteczne), krok IV (komisja ekspertów), krok V (test wersji wstępnej), krok VI (opracowanie ostatecznej wersji CAIT-PL do oceny psychometrycznej). Podczas drugiego etapu badania zaproszono do udziału 118 osób – zarówno z historią skręceń stawu skokowo-goleniowego, jak i osoby zdrowe, bez urazów w tym obszarze. Uczestnicy mieli za zadanie podać dane metrykalne oraz szczegóły dotyczące urazów stawu skokowo-goleniowego, a także wypełnić kwestionariusz CAIT-PL oraz Foot and Ankle Outcome Score (FAOS) dwukrotnie, w odstępie tygodnia. Ostatecznie 105 osób poprawnie wypełniło kwestionariusze podczas dwóch okazji i dane z tej populacji wykorzystano do ewaluacji psychometrycznej CAIT-PL. Ocenę właściwości psychometrycznych przeprowadzono zgodnie z wytycznymi Consensus-Based Standards for the Selection of Health Status Measurement Instruments (COSMIN) [54]. Ewaluacja obejmowała ocenę spójności wewnętrznej, rzetelności test–retest, błąd pomiaru, minimalną wykrywalną zmianę oraz trafność konstruktu i trafność zbieżną kwestionariusza CAIT-PL.

Analizę statystyczną wykonano z wykorzystaniem oprogramowania PQStat v.1.8.4 (PQStat Software Company, Polska). Różnice pomiędzy grupami oceniano za pomocą testu chi-kwadrat (dla zmiennych kategorycznych) lub testu t dla prób niezależnych (dla zmiennych liczbowych). Rozkład danych weryfikowano testem Shapiro–Wilka, a jednorodność wariancji sprawdzano testem Levene’a. Do oceny zależności pomiędzy zmiennymi zastosowano współczynnik korelacji Pearsona lub Spearmana, w zależności od spełnienia założeń normalności rozkładu. Za poziom istotności statystycznej przyjęto $p < 0,05$.

Polska wersja CAIT cechuje się odpowiednią spójnością wewnętrzną, porównywalną z oryginalną angielskojęzyczną wersją (współczynnik Cronbacha $\alpha = 0,83$). Rzetelność test–retest była odpowiednia i wyniosła $ICC_{2,1} = 0,89$. Trafność konstruktu potwierdzono dzięki weryfikacji 86% hipotez, a trafność zbieżna była odpowiednia dzięki istotnym korelacjom z FAOS, które wahały się od słabych do silnych ($r = 0,39–0,67$). Błąd pomiaru CAIT-PL był niski (Standard Error of Measurement – SEM) i wynosił 0,76 punktu, a minimalna wykrywalna zmiana (Minimal Detectable Change – MDC) 2,10 punktu.

Finalnie narzędzie CAIT-PL odzwierciedla intencje oryginalnego kwestionariusza CAIT, zostało prawidłowo zaadaptowane do polskiej kultury i posiada odpowiednie właściwości psychometryczne. Z tego względu polska wersja kwestionariusza Cumberland Ankle Instability Tool (CAIT-PL) może być szeroko stosowana w celach klinicznych oraz badawczych.

W niniejszym cyklu publikacyjnym stworzenie narzędzia CAIT-PL (publikacja nr 1) stanowiło niezbędny krok przy realizacji publikacji nr 2 i 3. Zgodnie z wytycznymi IAC [34] specyficzne narzędzie do oceny stopnia nasilenia CAI jest wymagane podczas rekrutacji populacji z CAI do badań naukowych.

Cross cultural adaptation, reliability and validity of the Polish version of the Cumberland Ankle Instability Tool

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ABSTRACT

Purpose: The aim of this study was to develop a Polish version of the Cumberland Ankle Instability Tool (CAIT-PL) questionnaire and perform CAIT-PL cultural adaptation with assessment of its psychometric properties.

Methods: The original CAIT was translated into the Polish language using standard guidelines. The CAIT-PL was completed on 2 occasions by 105 participants both with and without a history of ankle sprains. Psychometric evaluation of CAIT-PL included an assessment of internal consistency, test-retest reliability, standard error of measurement, convergent and construct validity.

Results: The CAIT-PL was successfully translated and adapted into Polish culture with satisfactory internal consistency (Cronbach's $\alpha=0.83$) and adequate test-retest reliability resulting in $ICC_{2,1} = 0.89$ (95% CI: 0.84–0.92). Measurement error was low (SEM = 0.76 and MDC = 2.10). Convergent validity of the CAIT-PL ranged from weak to strong using Spearman's correlation coefficient between CAIT-PL and FAOS subscales ($r=0.39$ – 0.67 ; $p<0.05$). Construct validity was confirmed.

Conclusion: The Polish version of the Cumberland Ankle Instability Tool is a valid and reliable questionnaire for assessment of functional ankle instability among the Polish population.

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KEYWORDS

CAIT; ankle instability; polish version; cultural adaptation; validity and reliability

> IMPLICATIONS FOR REHABILITATION

- The Cumberland Ankle Instability Tool is broadly used to assess functional ankle instability and its severity.
- The Polish version of Cumberland Ankle Instability Tool (CAIT-PL) showed adequate psychometric properties.
- The CAIT-PL is ready to be used in clinical practice and for research applications in Polish-speaking population.

Introduction

Ankle sprains are one of the most common injuries among young and physically active people. In epidemiological studies, it has been suggested that ankle sprains account for as much as 25–30% of all sports injuries [1, 2]. Although the symptoms associated with ankle sprain usually resolve within a short period of time, it is estimated that approximately 30% or more people who experience a first-time ankle sprain will develop other symptoms. These are pain, loss of function, subjective feeling of instability and subsequent recurrent injuries leading to long-term dysfunction called Chronic Ankle Instability (CAI). The International Ankle Consortium provided a short definition of CAI focused on repetitive episodes of “giving way” and self-reported dysfunction [3–6]. CAI can be separated into mechanical and functional ankle instability. Mechanical ankle instability refers to ankle ligamentous laxity, which can be assessed mainly during physical examination using anterior drawer and talar tilt tests. In addition to structural joint dysfunction, people with mechanical ankle instability may exhibit functional symptoms. On the other hand, Functional Ankle Instability (FAI) is not due to ankle joint laxity but appears to be related to neuromuscular deficits [7, 8]. To evaluate symptoms of

FAI in clinical settings, balance tests, muscle strength tests and Patient Reported Outcome Measures (PROMs) are applied.

PROMs are the patients' subjective perception of their health condition. PROMs are inexpensive, highly efficient and reliable, which makes them widely used in research and clinical practice [9]. PROMs can help clinicians and researchers set a diagnosis or measure intervention effects along with physical examination and medical imaging. There are many foot and ankle questionnaires, but their majority are used to assess general limitations according to foot and ankle regions. To assess the severity of symptoms in conditions such as ankle instability, disease-specific PROMs are needed because they include questions about key features in the particular disease. Only three instruments have been recommended by the International Ankle Consortium [6] as specific for symptoms of CAI by including questions about self-perceived instability during certain activities and ankle “giving way” incidents. These are the three following questionnaires: Ankle Instability Instrument (AII) [10], Identification of Functional Ankle Instability (IdFAI) [11] and the Cumberland Ankle Instability Tool (CAIT) [12].

The CAIT questionnaire is one of the most widely used PROMs for CAI patients. It was developed in the English language to evaluate severity of functional ankle instability and aids treatment

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decisions during the management of CAI. The original CAIT has been culturally adapted into multiple languages: Dutch [13], French [14], Greek [15], Chinese [16], Japanese [17], Taiwan-Chinese [18], Persian [19], Brazilian-Portuguese [20], Korean [21], Urdu [22] and even 2 Spanish versions [23, 24]. All listed versions of the CAIT have demonstrated good psychometric properties and are broadly applied in clinical practice and research among different cultures.

To the best of authors' knowledge, there is no Polish version of the questionnaire specific to symptoms of CAI. This fact significantly hinders the diagnosis and treatment of chronic ankle instability in the Polish population. Therefore, the aim of this study was to develop a Polish version of the CAIT questionnaire, perform CAIT-PL cultural adaptation with assessment of its reliability and validity.

Methods

Ethical approval

All procedures were performed in accordance with the 1964 Helsinki declaration and its later amendments. The approval of the Bioethics Committee at the Regional Medical Association in Krakow (No. 11/KBL/OIL/2022) was obtained for this study.

Participants

Participants of this study were students both without a history of ankle trauma (control group) as well as individuals who had reported at least 1 significant ankle sprain (instability group). The division of groups was adapted from Greek [15] and Persian [19] CAIT validation studies. The inclusion criteria were as follows: i) at least 18 years of age and ii) speaking Polish as one's first language. The participants were excluded if they had experienced any ankle injuries less than 3 months prior to study or if they had undergone lower limb surgery in the past. All the participants were informed about the research protocol in detail and provided their written informed consent to participate in the study. Sample size determination was based on guidelines from Terwee et al. [25] and it requires a minimum of 100 participants to measure questionnaire's internal consistency, for construct validity subgroups of 50 participants are needed.

Study procedure

This study consisted of two main parts: (1) The CAIT translation and adaptation into the Polish culture, (2) psychometric evaluation of the Polish version of the CAIT. These parts are described in detail in the following sections. Each participant was supposed to individually fill out a paper version of the CAIT-PL questionnaire twice, with a 1-week interval between interventions. After that time, none of the participants reported changes regarding their health status. Both administrations were performed in the same environment at the University. In addition to the CAIT-PL questionnaire, participants also filled out the Foot and Ankle Outcome Score (FAOS) and provided demographic (age, sex) and anthropometric data (body mass, body height) as well as a history of ankle sprain incidents. We invited 118 individuals for participation in this study. Results were excluded from the analysis when a participant failed to complete the questionnaire twice (8%) or left missing answers (3%). Finally, 105 participants (89%) filled out both questionnaires correctly and their results were considered for psychometric evaluation of CAIT-PL.

Translation and cultural adaptation procedure

For the translation permission was given from the original questionnaire's developer (Dr Hiller). Cross-cultural adaptation of the Polish version of CAIT was performed according to Beaton's guidelines using forward-backward translation [26]. This process included the six following steps.

Step I (Initial translation) - Original English version of the CAIT was translated into Polish by 2 independent bilingual translators, with Polish as their mother tongue (one with medical background and the other without medical or clinical background). Each translator produced his own Polish version of the questionnaire.

Step II (Synthesis of the translations) - Both translators met to synthesise their versions into 1 common translation, resolving any discrepancies.

Step III (Back translation) - The synthesised version from the previous step was sent to a backward translator (English native speaker), who was totally blind to the original CAIT version. The English native speaker translated the questionnaire back into the English language. This step allows to highlight unclear wording in the translations.

Step IV (Expert committee) - All the translators, language specialists, methodologist and physiotherapist participated in the meeting of experts. Every version of the previous translations, original CAIT questionnaire and written reports were analysed by the committee. A consensus was reached at the meeting, which resulted in the creation of a pre-final Polish version of the CAIT questionnaire.

Step V (Test of the pre-final version) - The pre-final CAIT-PL was administered to 10 people with varied educational levels to confirm the comprehensibility and syntax of all questions.

Step VI (Development of the final CAIT-PL version for psychometric evaluation) - No significant changes were made to the post-pilot version of the questionnaire, which allowed for the creation of the final CAIT-PL version. The CAIT-PL questionnaire is available in [Appendix A](#).

Instruments

The Cumberland Ankle Instability Tool

The CAIT questionnaire contains 9 items and is aimed to measure severity of ankle instability with a total score ranging from 0 - indicating extreme functional ankle instability to 30 points - indicating a stable ankle. CAIT items comprise 3 to 6 answers, while the subjects can choose only 1 best describing their ankle. The total CAIT score (CAIT_{T3}) is expressed as the sum of points from 9 questions. CAIT allows to separately evaluate the right and left ankle during one sitting. Developers of the CAIT calculated cut-off value as 27.5 points, which means that ankles with scores below that value are considered as unstable [12]. However, the CAIT cut-off values differ among other studies and populations from 11.5 points in a Dutch study [13] to ≤25 points in a recalibrated English version [27].

Foot and Ankle Outcome Score

The FAOS questionnaire contains 42 questions divided into 5 subscales: Pain (9 items), Symptoms/Stiffness (7 items), Activities of Daily Life (17 items), Sport and Recreation (5 items) and Ankle-Related Quality of Life (4 items). FAOS is used to assess functional limitations caused by foot or ankle dysfunctions [28]. To answer each of the questions, 5 boxes were used ("no," "mild," "moderate," "severe," "extreme"). Each item is scored from 0 to 4

points. Results of each FAOS subscale are the sum of the item's points divided by the maximum possible number of points expressed in percentages. FAOS_{TS} was calculated as the mean of all subscales.

Statistical analysis

Statistical analysis was performed using PQStat v. 1.8.4 software (PQStat Software Company, Poland). Differences between groups were evaluated using χ^2 test (categorical variables) or independent samples *t*-test (numerical variables). Data distribution was checked using the Shapiro–Wilk test. Homogeneity of variance within the groups was tested via Levene's test. The probability of Type I error below 0.05 was adopted as the level of significance.

Psychometric evaluation

Following the Consensus-Based Standards for the Selection of Health Status Measurement Instruments (COSMIN) checklist, the internal consistency, test-retest reliability, measurement error, minimal detectable change, construct and convergent validity of the CAIT-PL were assessed [29].

Internal consistency was determined using Cronbach's α . A satisfactory internal consistency rating is provided when Cronbach's α is between 0.70 and 0.95. In addition, internal consistency was assessed based on Spearman's correlation coefficient between each question and total score. Correlations were considered negligible when ≤ 0.20 , weak between 0.21 and 0.40, 0.41 to 0.60 as moderate, 0.61 to 0.80 strong, and very strong when ≥ 0.81 [30].

Test-retest reliability of the CAIT-PL_{TS} was evaluated with the two-way model single measure intraclass correlation coefficient (ICC_{2,1}) and 95% confidence intervals. ICC_{2,1} was considered acceptable when ≥ 0.70 [25].

Standard error of measurement (SEM) and minimal detectable change (MDC) of CAIT-PL_{TS} was calculated using the following formulas:

$$SEM = \text{standard deviation of difference between test and retest} \times \sqrt{1 - ICC}.$$

$$MDC = SEM \times 1.96 \times \sqrt{2}.$$

According to COSMIN Delphi study in 2010, "criterion validity" was defined as adequate reflection of "gold standard" [31]. Due to the fact that there is no "gold standard" for PROM's instruments, convergent validity was assessed in terms of consistency of the CAIT-PL_{TS} in relation to each of the 5 FAOS subscales and FAOS_{TS}. FAOS was chosen because it was already validated as a measure of functional status in individuals with chronic ankle instability [32] and previously used to validate other CAIT cross-cultural adaptations [13, 22]. Moreover, FAOS was endorsed by International Ankle Consortium as general self-reported foot and ankle function questionnaire in patients with chronic ankle instability [6].

To evaluate construct validity hypotheses testing was performed. If at least 75% of the previously formulated hypotheses were confirmed, the rating for construct validity is positive [25]. Before data collection we hypothesized moderate or strong correlations between CAIT-PL_{TS} and each of 5 FAOS subscales as well as FAOS_{TS}. Another of the hypotheses was that CAIT-PL has an appropriate discriminative power ($p < 0.05$) which allows to distinguish between, "known groups" (instability and control).

Results

Translation process

The systematic process according to the guidelines proposed by Beaton et al. [26] was successfully completed. This was not simple word-to-word translation. It required cultural adaptation of the CAIT to Polish maintaining each item's semantic, conceptual and true meaning. We have asked the developer of the CAIT Dr Claire Hiller about the 2 following phases: Item 6 - "hop from side to side" and Item 8 - "roll over on my ankle (or twist)" to confirm the original intentional meaning of these questions. "Hop" means that it is performed on one leg. That was revealing, because in the Polish language, this word does not differentiate whether it is a one- or two-legged activity. "Rolling over on ankle" is a term not widely used in our culture, and the given synonym "twist" means "sprain" in Polish. However we could not use the "ankle sprain" phrase because it is a definition of acute injury resulting in pain, swelling and other functional limitations. Finally, we decided to choose the Polish equivalent of the phrase "giving way" due to confirmation from Dr Hiller that this is of the same meaning as "rolling over." No other major difficulties were reported during translation, the remaining details of the CAIT-PL were set during the committee of experts. After a pilot study with 10 participants, no significant changes were made because the questionnaire was easy to understand for all respondents.

Study population

Descriptive statistics of study population are presented in Table 1. From 105 subjects who completed correctly 2 questionnaires, 52 participants (49%) had at least one ankle sprain and 35 of them (33%) had more than one sprain in the same ankle.

Discriminative power

Participants with a history of ankle sprain (instability group) presented with significantly lower CAIT-PL_{TS} compared to control group ($p < 0.05$). It means that CAIT-PL can differentiate between functionally stable and unstable ankles. Results are presented in Table 1.

Internal consistency

The CAIT-PL showed satisfactory internal consistency for the entire questionnaire (Cronbach's $\alpha = 0.83$). Spearman's correlation

Table 1. Descriptive statistic (mean (SD)) of study population.

	Total sample <i>n</i> = 105	Instability group <i>n</i> = 52	Control group <i>n</i> = 53	<i>p</i>
Gender, <i>n</i> (%)				0.50
Female	62 (59.0)	29 (55.8)	33 (62.3)	
Male	32 (41.0)	23 (44.2)	20 (37.7)	
Age [years]	20.3 (1.4)	20.3 (1.4)	20.2 (1.5)	0.59
Body mass [kg]	67.0 (12.0)	66.6 (11.5)	67.4 (12.5)	0.53
Body height [cm]	171.6 (8.9)	172.1 (9.7)	171.1 (8.0)	0.17
BMI [kg/m ²]	22.6 (2.6)	22.4 (2.4)	22.9 (2.9)	0.16
CAIT Total score [pt.]	25.5 (4.8)	24.6 (5.5)	27.5 (3.0)	<0.05*
Ankle sprain, <i>n</i> (%)			N/A	N/A
0	53 (50.5)	0 (0.0)		
1	17 (16.2)	17 (32.7)		
>1	35 (33.3)	35 (67.3)		

n – number of observation, *p* – probability of type I error, *statistically significant difference, N/A – not applicable.

Table 2. Internal consistency of CAIT-PL.

	Cronbach's α	Total score – item correlation ^r	p
Item 1 (I have pain in my ankle)	0.81	0.74	<0.05*
Item 2 (My ankle feels unstable)	0.79	0.73	<0.05*
Item 3 (When I make sharp turns, my ankle feels unstable)	0.80	0.70	<0.05*
Item 4 (When going down the stairs, my ankle feels unstable)	0.82	0.51	<0.05*
Item 5 (My ankle feels unstable when standing on one leg)	0.82	0.68	<0.05*
Item 6 (My ankle feels unstable when)	0.82	0.62	<0.05*
Item 7 (My ankle feels unstable when)	0.80	0.74	<0.05*
Item 8 (Typically, when I start to roll over (or “twist”) on my ankle, I can stop it)	0.84	0.51	<0.05*
Item 9 (After a typical incident of my ankle rolling over, my ankle returns to normal)	0.83	0.43	<0.05*
Total score	N/A	N/A	N/A

α – Cronbach's α if item was deleted, r – Spearman correlation coefficient, p – probability of type I error, *statistically significant difference, N/A – not applicable.

Table 3. Convergent validity of CAIT-PL.

	r	p
FAOS Pain	0.56	<0.05*
FAOS Symptoms/Stiffness	0.39	<0.05*
FAOS Difficulty in daily activities	0.52	<0.05*
FAOS Sport and Recreation	0.63	<0.05*
FAOS Quality of Life	0.57	<0.05*
FAOS Total	0.67	<0.05*

r – Spearman correlation coefficient, p – probability of type I error, *statistically significant correlation.

coefficients between the CAIT-PL items and CAIT-PL_{T5} ranged from moderate to very strong ($r=0.43$ – 0.74). Results are presented in Table 2.

Test-retest reliability

Test-retest reliability of the CAIT-PL_{T5} was acceptable resulting in $ICC_{2,1} = 0.89$ (95% CI: 0.84–0.92).

Measurement error

The measurement error of the CAIT-PL_{T5} was low (SEM = 0.76 and MDC = 2.10).

Convergent validity

Convergent validity was expressed as a weak to strong correlations between the CAIT-PL_{T5} and FAOS subscales and total score ($r=0.39$ – 0.67). Results are presented in Table 3.

Construct validity

Good construct validity was indicated by confirming 6 of 7 (86%) hypotheses.

Discussion

The CAIT-PL questionnaire was successfully translated and adapted to the Polish culture, showing appropriate reliability and validity.

For these reasons, the Polish version of the CAIT appears to reflect the intentions of the English original version. In fact, this is the first specific tool for assessment of functional ankle instability in the Polish-speaking population.

Internal consistency of CAIT-PL was expressed as Cronbach's $\alpha=0.83$, this is the same result as in the original English version, for which Cronbach's $\alpha=0.83$ [12]. Our results are also comparable to other CAIT adaptations in which Cronbach's α ranged from 0.76 to 0.97 [13–24]. A satisfactory level of internal consistency rating is provided when Cronbach's α is between 0.70 and 0.95 [25]. If alpha is too high, this may suggest that some items are redundant as they are testing the same question but in a different guise [33]. In our study, internal consistency slightly increased when question 8 was deleted, which also appeared in the Chinese [16] and Spanish [24] versions. This may result from the hypothesis context of this question (“Typically, when I start to roll over (or “twist”) on my ankle, I can stop it”), which makes it difficult to give an unambiguous answer in contrast to items from 1 to 7. In Japanese [17], Korean [21] and Persian [19] adaptations, deleting question 9 resulted in improvement of internal consistency. Items 8 and 9 are related to “rolling over on ankle” or “giving way” episodes, which we assume are the most important features of ankle instability. However, the person completing the questionnaire may not be able to distinguish between an ankle sprain and a giving way episode. Another measurement of the questionnaire's internal consistency could be correlations between each question and the total score. In our study, Spearman's correlation coefficient ranged from 0.43 to 0.74, which is adequate and comparable with other CAIT adaptations [14, 15, 17, 18, 21, 23].

Test-retest reliability of CAIT-PL_{T5} was almost perfect resulting in $ICC_{2,1} = 0.89$. The $ICC_{2,1}$ levels in previous studies were similar or higher than our results ($ICC_{2,1} = 0.91$ – 0.98) [12–16, 18–22, 24]. Only the Japanese version of the CAIT [17] was shown to have slightly lower test-retest reliability ($ICC = 0.82$). This may have arisen from interval time between the initial test and retest, which was about 3 weeks in contrast to 1 week from other studies.

SEM and MDC of the CAIT-PL_{T5} were 0.76 and 2.10, respectively. This means that changes in point values below these levels cannot be considered as real changes in health status, but as certain inaccuracies and natural measurement errors of this questionnaire. When comparing our results to other studies, values of SEM and MDC were only lower in the Urdu CAIT version [22] (SEM = 0.33; MDC = 1.59). While the other language versions reported higher measurement errors (SEM = 0.82–2.40) and (MDC = 2.28–6.5) [13, 14, 16, 19, 21].

Validity of previous CAIT adaptations was assessed as correlation coefficients with various instruments such as the Foot and Ankle Ability Measure (FAAM), Foot and Ankle Outcome Score (FAOS), Visual Analogue Scale (VAS), Short Form 36-Item Health Survey (SF-36), Lower Extremity Functional Scale (LEFS) or Karlsson Score [12, 13, 15–17]. Our results can be compared only to those obtained in the Dutch and Urdu studies due to the use of FAOS. Validity of the Dutch CAIT [13] was shown as correlations ($r=0.36$ – 0.48) in relation to FAOS subscales. The Urdu adaptation [22] resulted in ($r=0.02$ to -0.78) between CAIT and FAOS items. The Urdu CAIT showed negative correlations between CAIT and FAOS in contrast to our study and Dutch one. We suppose this may be due to the opposite way of expressing the FAOS scale (i.e., in %). However, only the FAOS “Activities of Daily Life” subscale in the Urdu version demonstrated a very low correlation with the CAIT ($r=0.02$), while other items were much stronger negatively correlated with CAIT ($r=-0.53$ to -0.78). In the present study, correlations ranged between ($r=0.39$ – 0.67), which are slightly higher than in the Dutch version and similar to Urdu adaptation. Only

"Symptoms/Stiffness" FAOS subscale has weak correlation ($r=0.39$; $p<0.05$) with CAIT-PL, which could mean that the participants' main problems are not structural symptoms such as joint stiffness, clicking or swelling. Remaining FAOS subscales were moderate or strongly correlated with CAIT-PL_{TS} ($r=0.52$ – 0.67 ; $p<0.05$) and we can interpret this as functional problems (pain, daily activities, sport, quality of life) which is consistent with the assumptions of functional ankle instability. A priori we expected moderate or strong correlations between CAIT-PL_{TS} and 5 FAOS items as well as FAOS_{TS}. Moreover, we expected that CAIT-PL_{TS} has appropriate discriminative power to differentiate instability and control groups. It turned out that 6 of 7 (86%) hypotheses were confirmed indicating good construct validity. Although FAOS is not disease-specific for patients with functional ankle instability, it mainly focuses on the functional status of the patient's ankle and foot (region-specific), such as CAIT. This means that both questionnaires examine similar, but not identical concepts (what may be confirmed as weak to strong correlations), while the CAIT contains elements regarding "giving-way" episodes and the subjective feeling of instability during multiple activities, which is crucial in evaluating functional ankle instability. For this reason, we believe that the development of the Polish version of the CAIT, which shows adequate psychometric properties assessed in accordance with international guidelines such as the COSMIN checklist [29], it's necessary for the proper diagnosis and treatment of functional ankle instability in the Polish population.

A strong aspect of our study was the rigorous translation process, which allowed for the creation of an instrument tailored to the Polish culture. A limitation of our study is the narrow age range of the participants, focusing on young adults with a similar level of education. The population was homogeneous in the above-mentioned respects, which allows for reproducible results, but they may not reflect the entire Polish population. In future research, we suggest evaluating the CAIT-PL among patients with CAI representing different age and physical activity levels together with assessment of responsiveness and optimal cut-off score.

Conclusions

The Polish-language version of the Cumberland Ankle Instability Tool (CAIT-PL) is a valid and reliable questionnaire for assessing functional ankle instability among the Polish population. The CAIT-PL is ready to be used in clinical practice and for research applications.

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Disclosure statement

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Appendix A. The Polish version of the Cumberland Ankle Instability Tool (CAIT-PL).

Proszę o wybranie JEDNEGO stwierdzenia, które NAJLEPIEJ opisuje twoje stawy skokowe w KAŻDYM z wymienionych pytań.

	LEWY	PRAWY	Punktacja
1. Odczuwam ból w stawie skokowym:			
Nigdy	☐	☐	5
Podczas uprawiania sportu	☐	☐	4
Podczas biegania po nierównym podłożu	☐	☐	3
Podczas biegania po równym podłożu	☐	☐	2
Podczas chodzenia po nierównym podłożu	☐	☐	1
Podczas chodzenia po równym podłożu	☐	☐	0
2. Czuję, że staw skokowy jest NIESTABILNY:			
Nigdy	☐	☐	4
Czasami podczas uprawiania sportu (nie za każdym razem)	☐	☐	3
Często podczas uprawiania sportu (za każdym razem)	☐	☐	2
Czasami podczas wykonywania codziennych aktywności	☐	☐	1
Często podczas wykonywania codziennych aktywności	☐	☐	0
3. Wykonując NAGŁE zmiany kierunku czuję, że staw skokowy jest NIESTABILNY:			
Nigdy	☐	☐	3
Czasami podczas biegania	☐	☐	2
Często podczas biegania	☐	☐	1
Podczas chodzenia	☐	☐	0
4. Schodząc po schodach czuję, że staw skokowy jest NIESTABILNY			
Nigdy	☐	☐	3
Jeśli schodzę szybko	☐	☐	2
Od czasu do czasu	☐	☐	1
Zawsze	☐	☐	0
5. Stojąc na JEDNEJ nodze czuję, że staw skokowy jest NIESTABILNY:			
Nigdy	☐	☐	2
Stojąc na palcach	☐	☐	1
Stojąc na całej stopie	☐	☐	0
6. Czuję, że staw skokowy jest NIESTABILNY:			
Nigdy	☐	☐	3
Kiedy podskakuję jednonóż na boki	☐	☐	2
Kiedy podskakuję jednonóż w miejscu	☐	☐	1
Kiedy skaczę obunóż	☐	☐	0
7. Czuję, że staw skokowy jest NIESTABILNY:			
Nigdy	☐	☐	4
Kiedy biegam po nierównym podłożu	☐	☐	3
Kiedy truchtam po nierównym podłożu	☐	☐	2
Kiedy chodzę po nierównym podłożu	☐	☐	1
Kiedy chodzę po płaskim podłożu	☐	☐	0
8. ZAZWYCZAJ, kiedy staw skokowy zaczyna mi „uciekać” lub „podwijać się”, jestem w stanie to przerwać:			
Natychmiast	☐	☐	3
Często	☐	☐	2
Czasami	☐	☐	1
Nigdy	☐	☐	0
Nigdy mi nie „uciekał” staw skokowy	☐	☐	3
9. Po TYPOWYM „ucieknięciu”, staw skokowy wraca do stanu sprzed incydentu:			
Prawie natychmiast	☐	☐	3
Szybciej niż w ciągu jednego dnia	☐	☐	2
W ciągu 1-2 dni	☐	☐	1
Po 2 dniach lub więcej	☐	☐	0
Nigdy mi nie „uciekał” staw skokowy	☐	☐	3

UWAGA: Skala punktacji znajduje się po prawej stronie. System punktowania nie jest widoczny w wersji przeznaczonej dla osoby badanej.

4.2. Publikacja 2

Olszewski, M.; Golec, J.; Zajac, B.; Krężalek, P. *Isometric and Isokinetic Hip Strength in Males with Chronic Ankle Instability and Its Relationship with Dynamic Balance and Self-Reported Instability. Phys Ther Sport* **2025**, 72, 9–17, doi:10.1016/j.ptsp.2024.12.007.

Głównym celem niniejszej pracy było ustalenie, czy moment siły mięśni obręczy biodrowej mierzony w warunkach izometrycznych i izokinetycznych jest obniżony u mężczyzn z CAI w porównaniu z grupą kontrolną. Celem dodatkowym było porównanie równowagi dynamicznej między grupami oraz analiza potencjalnych powiązań pomiędzy momentem siły mięśni obręczy biodrowej, równowagą dynamiczną a subiektywnie zgłaszaną niestabilnością. Sformułowano następujące hipotezy badawcze:

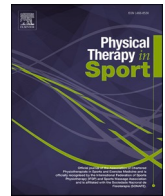
1. U mężczyzn z CAI moment siły mięśni obręczy biodrowej mierzony w warunkach izometrycznych i izokinetycznych jest obniżony w porównaniu z grupą kontrolną.
2. Moment siły mięśni obręczy biodrowej koreluje z równowagą dynamiczną, która jest zaburzona w grupie z CAI, oraz z subiektywnie zgłaszaną niestabilnością.

W badaniu wzięło udział 50 uczestników: 25 mężczyzn z CAI oraz 25 zdrowych mężczyzn w grupie kontrolnej (CON). Kwalifikacja do badania odbywała się na podstawie kryteriów włączenia i wyłączenia określonych przez IAC [34]. Kryteria włączenia do grupy CAI obejmowały: (1) płeć męską i wiek 18–30 lat; (2) co najmniej jedno istotne skręcenie stawu skokowego skutkujące bólem, obrzękiem i ograniczeniem aktywności przez minimum jeden dzień, które wystąpiło co najmniej 12 miesięcy przed rozpoczęciem badania; (3) co najmniej dwa epizody „uciekania” stawu skokowego w ciągu sześciu miesięcy poprzedzających rekrutację i/lub nawracające skręcenia i/lub subiektywne odczucie niestabilności; (4) potwierdzoną funkcjonalną niestabilność stawu skokowo-goleniowego w polskiej wersji kwestionariusza Cumberland Ankle Instability Tool (CAIT-PL) [55], określoną wynikiem ≤ 24 punktów. Do grupy CON kwalifikowano mężczyzn w wieku 18–30 lat, bez historii skręceń stawu skokowo-goleniowego oraz z potwierdzonym brakiem funkcjonalnej niestabilności ocenionej w kwestionariuszu CAIT-PL (28–30 punktów). Kryteria wyłączenia były wspólne dla obu grup i obejmowały przebyty zabieg chirurgiczny w obrębie struktur układu mięśniowo-szkieletowego kończyn dolnych, przebyty uraz złamania w okolicy kończyny dolnej wymagający repozycji oraz ostre uszkodzenia urazowe w okresie trzech miesięcy poprzedzających badanie, które mogły wpływać na integralność lub funkcję stawów kończyn dolnych.

U wszystkich uczestników wykonano następujące pomiary: (a) pomiary antropometryczne; (b) ocenę równowagi dynamicznej w teście Lower Quarter Y-Balance (YBT-LQ); (c) pomiar momentu siły mięśni obręczy biodrowej przy użyciu dynamometru Biodex Multi-Joint System 4 Pro (Biodex Medical Systems, Shirley, NY, USA) dla odwodzicieli i przywodzicieli stawu biodrowego oraz dynamometru ręcznego MicroFET2 (Hoggan Health Industries Inc., Salt Lake City, UT, USA) dla rotatorów zewnętrznych stawu biodrowego. Pomiary wykonywano w pozycji leżenia na boku (odwodziciele i przywodziciele) oraz w pozycji leżenia przodem (rotatory zewnętrzne). Do dalszych analiz wykorzystano szczytowe wartości momentów sił (peak torque) mierzone w warunkach izometrycznych i izokinetycznych, znormalizowane do masy ciała i wyrażone w jednostkach Nm/kg, a także stosunki momentów siły odwodzicieli do przywodzicieli stawu biodrowego, wyrażone w procentach.

Analizę statystyczną przeprowadzono z wykorzystaniem oprogramowania Statistica 13 (TIBCO Software Inc., Palo Alto, CA, USA). Różnice w zmiennych ciągłych pomiędzy grupami oceniano za pomocą testu t dla prób niezależnych, przy spełnieniu założeń normalności rozkładu (test Shapiro–Wilka) oraz homogeniczności wariancji (test Levene’a). W przypadku niespełnienia założenia homogeniczności wariancji, przy zachowanej normalności rozkładu, zastosowano test Welcha, natomiast przy naruszeniu normalności rozkładu wykorzystano test U Manna–Whitneya. Różnice w zmiennych nominalnych oceniano testem chi-kwadrat. Do oceny liniowych zależności pomiędzy zmiennymi ciągłymi zastosowano współczynnik korelacji Pearsona (dla zmiennych o rozkładzie normalnym) lub rang Spearmana (dla zmiennych o rozkładzie nienormalnym). Za poziom istotności statystycznej przyjęto $p < 0,05$.

Wyniki wykazały istotnie niższy stosunek izometrycznego momentu siły odwodzicieli do przywodzicieli w grupie CAI w porównaniu z grupą CON. Nie stwierdzono innych istotnych różnic między grupami w zakresie momentów sił mięśni obręczy biodrowej. Uczestnicy z CAI osiągnęli niższe wyniki w zasięgu tylnobocznym oraz w łącznym wyniku testu YBT-LQ. W grupie CAI odnotowano dodatnie umiarkowane korelacje pomiędzy równowagą dynamiczną w kierunkach tylnobocznym i tylnoprzódowym a momentami siły odwodzicieli stawu biodrowego, a także pomiędzy izometrycznym momentem siły odwodzicieli stawu biodrowego a subiektywnie zgłaszaną niestabilnością. Wyniki te mogą sugerować, że moment siły odwodzicieli stawu biodrowego jest istotnym czynnikiem, który należy uwzględnić przy diagnostyce oraz tworzeniu programów rehabilitacyjnych dla osób z CAI.



Isometric and isokinetic hip strength in males with chronic ankle instability and its relationship with dynamic balance and self-reported instability

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ABSTRACT

Objectives: To investigate isometric and isokinetic hip strength as well as dynamic balance in males with chronic ankle instability (CAI) and explore potential associations between hip strength, dynamic balance, and self-reported instability.

Design: Cross-sectional study.

Setting: University laboratory.

Participants: Fifty male participants (25 with CAI and 25 healthy controls).

Main outcome measures: Hip isometric and isokinetic torque normalized to body weight, Lower Quarter Y-balance Test (YBT-LQ), the Polish version of The Cumberland Ankle Instability Tool (CAIT-PL).

Results: Significant differences were observed only in the hip isometric abductors/adductors strength ratio ($p = 0.034$, $ES = 0.65$), which was lower in the CAI group. CAI participants showed reduced dynamic balance in posterolateral reach ($p = 0.006$, $ES = 0.92$) and composite score of YBT-LQ ($p = 0.012$, $ES = 0.91$). There was a moderate positive correlation between dynamic balance and hip abductors strength during posteromedial ($r = 0.40$, $p = 0.049$) and posterolateral ($r = 0.40$, $p = 0.048$) YBT-LQ reaches, and isometric hip abductors strength moderately positively correlated with self-reported instability ($r = 0.46$, $p = 0.021$) in the CAI group.

Conclusion: Males with CAI exhibit deficits in frontal plane hip isometric strength, specifically in the hip abductor/adductor ratio, while no deficits were observed in isokinetic strength. The relationships between hip abductors strength, dynamic balance, and self-reported ankle instability may suggest the importance of hip abductors isometric strength for functional outcomes in CAI-patients.

1. Introduction

Lateral ankle sprains (LASs) are the most prevalent musculoskeletal injuries among physically active individuals (Roos et al., 2017), with an incidence rate of 2–7 acute ankle sprains per 1000 person-years (Herzog et al., 2019). Gribble et al. (2016) summarized that LASs can contribute to \$6.2 billion in healthcare costs annually in the United States. It is reported that approximately 46% (ranging from 9% to 76%) of individuals with a history of ankle sprains will develop a condition called chronic ankle instability (CAI) (Lin et al., 2021). CAI is characterized by recurrent ankle sprains, ankle giving-way episodes, and feelings of ankle instability (Gribble et al., 2014). Individuals with CAI experience kinesiophobia and low self-reported ankle function (Watanabe et al., 2023),

which can be associated with limited physical activity levels (Hubbard-Turner & Turner, 2015) and reduced quality of life (Houston et al., 2014). Additionally, individuals with CAI may exhibit local symptoms such as ankle pain, ligamentous laxity (Kudo et al., 2023), restricted dorsiflexion range of motion (Hoch et al., 2012), decreased evor strength (Arnold et al., 2009), or impaired peroneal reaction time (Hoch & McKeon, 2014). However, in addition to distal impairments, proximal deficits are also observed in people with CAI (Dejong et al., 2020). It has been reported that individuals with CAI may exhibit reduced isometric strength of hip abductors (Khalaj et al., 2021; McCann et al., 2017), adductors (Khalaj et al., 2021), external rotators (McCann et al., 2017, 2018, 2019), flexors (Khalaj et al., 2021), and extensors (Kosik et al., 2020; McCann et al., 2018). On the other hand, some

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studies report no hip strength deficits in people with CAI (Bain et al., 2022; Gribble & Robinson, 2009; Mulligan & DeVahl, 2020). Most of the mentioned studies assessed hip strength exclusively isometrically when only two studies assessed hip strength in an isokinetic manner (Gribble & Robinson, 2009; Negahban et al., 2013). The study by Gribble and Robinson (2009) focused only on the isokinetic hip strength in the sagittal plane, while Negahban et al. (2013) examined all main hip muscle groups but exclusively in eccentric contraction. Moreover, in these studies, more females were recruited into the CAI groups (Bain et al., 2022; Khalaj et al., 2021; McCann et al., 2017, 2018, 2019; Negahban et al., 2013), or the male/female ratio was equal (Gribble & Robinson, 2009) or unknown (Kosik et al., 2020). The difference in the prevalence of CAI between genders varies depending on the population studied and it may be unclear. A large-scale epidemiological study by Hershkovich et al. (2015), which included a total of 829,791 subjects, reported that males had a 2.33-fold greater prevalence of mild CAI compared to females. However, no sex difference was observed in the prevalence of severe CAI. Conversely, other studies have found a higher prevalence of CAI among athletic females. For instance, Tanen et al. (2014) assessed 512 athletes and found a 32.1% prevalence of CAI in female athletes versus 17.4% in male athletes. Similarly, Donovan et al. (2020) examined a cohort of 1002 healthy adolescent athletes and reported a prevalence of CAI at 23.6% in female athletes compared to 16.3% in male athletes. These findings suggest that while males may be more affected by CAI in the general population, CAI appears to be more prevalent among female athletes.

This study focused exclusively on male participants to ensure group homogeneity, considering documented differences in hip abductors strength and functional performance between genders (Lu et al., 2022; Sugimoto et al., 2014), and the fact that males with CAI have not constituted the majority in any of the studies conducted to date assessing hip strength. This results in a lack of information in the scientific literature regarding hip strength deficits specific to this gender with CAI, especially in comparison to a male control group. It may allow for the creation of sex-specific evaluation and rehabilitation strategies (Lu et al., 2022) to be incorporated into the management for males with CAI.

The investigation aimed to assess isometric and isokinetic strength of the primary hip muscle groups in the frontal (abductors, adductors) and transverse planes (external rotators). These muscle groups were chosen because their strength differs significantly between males and females, unlike hip flexion and extension strength, where no sex-specific differences have been observed (Holmes et al., 2023). Lower limb movements in the frontal and transverse planes are closely linked to the mechanisms of ankle sprains and giving-way episodes. Li et al. (2019) reported that hip joint angles revealed distinct patterns mainly in the frontal and transverse planes during the ankle giving-way trials. It allows to speculate that adequate hip muscular strength in these planes could be beneficial for lower limb neuromuscular control and potentially reduce the risk of ankle sprains and giving-way episodes. Powers et al. (2017) further demonstrated that reduced isometric hip abductor strength more than doubled the risk of noncontact lateral ankle sprains in male soccer players.

Deficits in dynamic balance are common among individuals with CAI, often assessed using the Star Excursion Balance Test (SEBT) or Lower Quarter Y-Balance Test (YBT-LQ). A meta-analysis by Song et al. (2022) revealed impairments in all SEBT reach directions in individuals with CAI compared to healthy controls or their uninjured limb. Preliminary studies have also explored relationships between hip strength and dynamic balance in CAI (Khalaj et al., 2021; McCann et al., 2017; Mulligan & DeVahl, 2020), linking various muscle groups with SEBT/YBT-LQ reach performance. It suggests that hip strength may be considered a contributing factor to functional task performance in individuals with CAI, but it remains unclear which muscle groups and types of muscle contraction are most crucial for them. This vital information is necessary for developing comprehensive rehabilitation programs tailored to male CAI patients.

Therefore, the primary aim of this study was to determine whether isometric and isokinetic hip strength is impaired in males with CAI compared to the control group. Secondly, this study aimed to compare dynamic balance between groups, and to explore potential associations between hip strength, dynamic balance, and self-reported instability.

2. Methods

2.1. Participants

This study involved 25 male participants with CAI and 25 healthy controls. The sample size was determined in accordance with prior studies conducted within this topic, with groups consisting of approximately 20 individuals (Gribble & Robinson, 2009; Khalaj et al., 2021; McCann et al., 2018; Negahban et al., 2013). To recruit participants posters containing information about the research project were posted on social media and academic platforms as well they were hung on the university campus. Volunteers were individually assessed against inclusion and exclusion criteria using an online survey. Inclusion criteria for participants with CAI were based on recommendations from the International Ankle Consortium (Gribble et al., 2014) and included: 1) male sex and age between 18 and 30 years; 2) history of at least one significant ankle sprain resulting in pain, swelling, and activity limitation for at least one day, occurring at least 12 months prior to study enrolment; 3) history of at least two ankle ‘giving way’ episodes in the six months prior to study enrolment and/or history of recurrent ankle sprains and/or subjective feelings of ankle instability; 4) confirmed functional ankle instability with a score of ≤ 24 points on the Polish version of the Cumberland Ankle Instability Tool (CAIT-PL) (Olszewski et al., 2023). Inclusion criteria for the control group (CON) were: 1) male sex and age between 18 and 30 years; 2) no history of ankle sprain; 3) confirmed lack of functional ankle instability with the CAIT-PL questionnaire, with a score between 28 and 30 points. The exclusion criteria for all participants were: 1) history of surgeries to the musculoskeletal structures in either limb of the lower extremity; 2) history of fractures in either limb of the lower extremity requiring realignment; 3) acute injury to the musculoskeletal structures of the lower extremity in the three months prior to physical assessment affecting lower limb joint integrity or function.

2.2. Study design

In this cross-sectional study, participants were instructed to abstain from strenuous physical activities 24–48 h before testing and to ensure adequate sleep for optimal condition. Assessments were consistently scheduled between 11:00 a.m. and 4:00 p.m. to minimize potential circadian rhythm effects on measurements. In each subject, all variables were bilaterally assessed because this study was part of a larger research project focused on functional assessment in males with CAI. The order in which the limb (involved or uninvolved for the CAI group; ‘sham involved’ or ‘sham uninvolved’ for the CON group) started first in a given test was random. The YBT-LQ served as a dynamic warm-up for hip muscles before isometric and isokinetic tests, as well as the balance test itself. The participant’s dominant leg was determined as the preferred leg for kicking a ball. In the CAI group, the involved leg was analysed. If bilateral ankle instability was present, the limb with the lower CAIT-PL score and a greater number of giving-way episodes was chosen. For each control subject, limb matching to the CAI group was performed before the measurements began, assigning one limb as ‘sham involved’ and the other as ‘sham uninvolved’. Inspired by the protocol of Hubbard et al. (2007), this matching procedure was modified to align with the specific requirements of the study. This procedure ensured an equal proportion of dominant and non-dominant limbs were classified as involved and uninvolved in the CAI group and as ‘sham involved’ and ‘sham uninvolved’ in the CON group, thereby minimizing the potential

influence of limb dominance on the results. All measurements were conducted by one experienced researcher.

2.3. Cumberland Ankle Instability Tool

The Polish version of the Cumberland Ankle Instability Tool (CAIT-PL) (Olszewski et al., 2023) is a specific patient-reported outcome measure for chronic ankle instability. It was administered to participants in both the CAI and CON groups to assess self-reported ankle instability severity. The CAIT-PL questionnaire comprises 9 items with 3–6 possible answers each, from which participants select the one that best describes their ankle. Scores range from 0 (indicating extreme ankle instability) to 30 (indicating stable ankle). The CAIT-PL demonstrates adequate test-retest reliability ($ICC_{2,1} = 0.89$, 95% CI: 0.84–0.92) with minimal measurement error (SEM = 0.76 points, MDC = 2.10 points).

2.4. Godin Leisure Time Physical Activity scale

The Godin Leisure Time Physical Activity scale was utilized to gauge the current level of physical activity in both groups (Amireault & Godin, 2015). The International Ankle Consortium (Gribble et al., 2014) endorsed this scale as a measure of physical activity in controlled research involving individuals with CAI. This scale assesses physical activity across three categories: strenuous, moderate, and light. Participants reported the frequency of engaging in these activities for at least 15 min per session during a typical week. Scores were calculated by multiplying the frequency of each activity category (strenuous by 9, moderate by 5, light by 3) and then summing the results. The scores rank individuals by physical activity levels. The score range starts at 0 (no physical activity), with no upper limit, as respondents can report varying amounts of activity. Additionally, moderate-to-strenuous scores can classify respondents as active (≥ 24) or insufficiently active (≤ 23).

2.5. Anthropometric measurements

Body height was measured using the Seca 213 stadiometer (Seca GmbH & Co. Kg, Germany). Body mass and composition were assessed using the BC-418 analyzer (Tanita, Japan). Body mass index (BMI) was calculated as weight in kilograms divided by height in meters squared. Limb length and the arm of force measurement were recorded using a measuring tape (TK Gruppe Klingler, China) to the nearest 0.5 cm.

2.6. Lower Quarter Y-balance test

Participants completed 3 familiarization and 3 testing trials (Jagger et al., 2020) in each of 3 directions: anterior (ANT), posteromedial (PM), and posterolateral (PL) for both legs using the Y-Balance test kit (Move2Perform, USA). Before trials, participants received verbal instructions and a visual demonstration of the test. The YBT-LQ was performed barefoot with a single-leg stance, positioning behind the red line

on the starting block. Participants aimed to reach as far as possible in each direction: ANT, PM, and PL (Fig. 1). Attempts were discarded if the participant: 1) lost hand contact from the pelvis; 2) lifted the heel during ANT reach; 3) kicked the indicator box; 4) failed to return to the starting position with maintained balance; or 5) supported balance with the reaching leg touching the floor or bearing weight on the indicator box. If any of these errors occurred, the participant had to repeat the attempt in the given direction until successful. The mean distance from the 3 testing trials in each direction was used for further analysis. Average scores were normalized to the subject's lower limb length, measured in the supine position from the anterior superior iliac spine to the medial malleolus (Neelly et al., 2013). The composite score of the YBT-LQ was calculated as the sum of the average reaches in each of the 3 directions divided by three leg lengths and multiplied by 100% (Bulow et al., 2019).

2.7. Hip muscle strength measurements

2.7.1. Hip external rotators strength

Isometric hip external rotator strength was measured using the MicroFET2 handheld dynamometer (Hoggan Health Industries Inc., USA), following the protocol described by Mendonça et al. (2018). Participants were positioned in a prone position with 90° of knee flexion, hip neutral rotation (0°), and their pelvis was stabilized to the treatment table with a rigid strap. The dynamometer was placed proximally to the medial malleolus (Willy & Davis, 2011) (Fig. 2). The force arm length represented the linear distance from the dynamometer placement to the hip axis of rotation. Each subject performed one sub-maximal familiarization contraction and three maximal isometric contractions for 5 s with 15-s rest intervals (Thorborg et al., 2010). The mean of the three measurements was considered for analysis. The average force value was multiplied by the force arm length and normalized to body mass (Nm/kg). This clinical assessment of hip external rotator strength using a handheld dynamometer has been shown to be reliable (Thorborg et al., 2010). The strength of hip ER was measured exclusively isometrically due to the documented high variability in hip rotational ROM and morphology among individuals (Chadayammuri et al., 2016). For instance, Olszewski et al. (2024) reported significant differences in ER ROM even between the dominant and non-dominant legs of the same individual in a healthy male population. Isokinetic testing requires consistent ROM limits, which must be identical for all participants to ensure standardized conditions. For this reason, isokinetic testing of this muscle group was excluded.

2.7.2. Hip abductors and adductors strength

Hip abductors and adductors strength were measured using an isokinetic dynamometer (Biodex Multi-Joint System 4 Pro; Biodex Medical Systems, Shirley, NY). Each measurement was conducted in a side-lying position, which has been shown to be the most reliable for hip abductors strength (Widler et al., 2009). In this position, the non-tested limb was

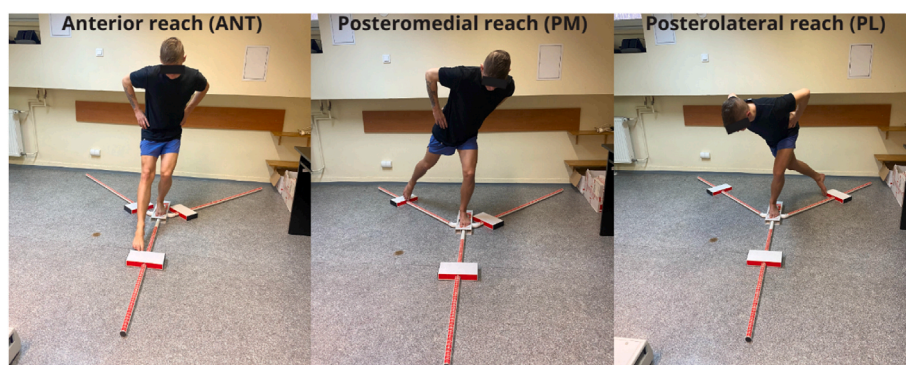


Fig. 1. Lower quarter Y-balance test.



Fig. 2. Hip external rotators strength measurement using handheld dynamometer.

flexed at the hip and knee to 90°, while the tested limb was set with neutral (0°) hip alignment in the frontal plane, full extension in the knee joint and slight hip extension (10°) to limit torque generation of anterior hip muscles and to prevent entering the hip flexion position during the test (Francis et al., 2018). A rigid belt was placed tightly above the pelvis to ensure a stable position. The dynamometer axis of rotation was aligned with the greater trochanter of the hip (Gerodimos et al., 2015). The pad, where participants produced force, was placed above the



Fig. 3. Hip abductors and adductors strength measurement using isokinetic dynamometer.

popliteal fossa. The setup of the subject during testing is shown in Fig. 3. Once the mentioned position was stabilized, the participant was instructed to relax the tested limb in the frontal plane, with the knee extended, to introduce a gravitational correction. Every participant was verbally encouraged to exert their maximum capacity during the test. The participant's peak torque normalized to body mass (Nm/kg) and abductors/adductors ratio of each test were the variables considered for further analysis. Two different protocols were applied: 1) isometric strength of hip abductors/adductors and 2) isokinetic strength of hip abductors/adductors.

2.7.2.1. Isometric protocol. The isometric protocol for hip abductors and adductors strength consisted of two familiarization trials with 50% and 80% of the participant's perceived maximal torque, followed by 30 s of rest and three testing trials with maximal voluntary contraction (MVC) for both muscle groups. Each isometric contraction lasted 5 s with 15-s rest intervals (Thorborg et al., 2010). Isometric contractions were performed in neutral (0°) hip alignment in the frontal plane.

2.7.2.2. Isokinetic protocol. The isokinetic protocol (concentric/concentric) for hip abductors and adductors strength consisted of two different angular velocities. Based on a systematic review by Castro et al. (2020) about hip isokinetic strength, the most common velocities for assessing frontal plane isokinetic hip strength (30°/s and 60°/s) were selected. Concentric contraction was chosen as to date, no studies have evaluated hip concentric abductor and adductor strength in the CAI population. Each isokinetic set contained five repetitions for both muscle groups. The range of motion for the tests was set from 0° (neutral position) to 30° of hip abduction (Venable et al., 2022). Before maximal trials with MVCs, subjects performed five familiarization trials at each angular velocity. Familiarization and maximal trials were separated by a 30-s rest interval. The reliability of isokinetic hip strength testing in a side-lying position is good for abductors (ICC = 0.83; 95% CI: 0.75–0.91) as well as for adductors (ICC = 0.82; 95% CI: 0.75–0.90) (Contreras-Diaz et al., 2022).

2.8. Statistical analysis

Statistical analysis was performed using Statistica 13 software (TIBCO Software Inc., Palo Alto, CA, USA). Differences in continuous variables between groups were assessed using independent groups t-tests, ensuring the assumptions of data normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) were met. Welch's test was employed if homogeneity of variances was not satisfied while maintaining data normality, and the Mann-Whitney U test was used if normality assumptions were violated. The chi-square test determined statistical significance in differences between nominal variables. Pearson's correlation coefficient evaluated linear relationships between continuous variables if both met the normal distribution assumption; otherwise, Spearman's correlation coefficient was applied. Interpretation of correlation coefficients was as follows: very weak (0.0–0.2), weak (0.2–0.4), moderate (0.4–0.6), strong (0.6–0.8), and very strong (0.8–1.0). Post-hoc effect size calculations, categorized as small (<0.2), medium (0.2–0.5), or large (>0.5), were conducted using G*Power (Franz Faul, Universität Kiel, Germany). The statistical significance threshold was set at a p-value below 0.05.

3. Results

Between-group comparisons of basic characteristics are presented in Table 1. There were no significant differences between groups for age, height, body mass, fat-free mass, body mass index, or leg dominance. However, the CAI group exhibited a significantly greater number of ankle sprains, a greater number of ankle giving-way episodes, and lower CAIT-PL scores than the CON group.

Table 1
Characteristics of study population.

	CAI group (n = 25)	CON group (n = 25)	p-value
Age [years]	23.1 ± 3.6	21.7 ± 2.8	0.112
Body height [m]	1.81 ± 0.07	1.78 ± 0.07	0.179
Body mass [kg]	78.2 ± 12.8	77.5 ± 10.4	0.734
Fat-free mass [kg]	66.4 ± 8.1	66.6 ± 6.6	0.587
BMI [kg/m ²]	23.9 ± 3.3	24.5 ± 2.7	0.404
Dominant leg, L/R	3 (12%)/22 (88%)	3 (12%)/22 (88%)	1.000
Involved limb ^{SI} , D/ND	16 (64%)/9 (36%)	16 (64%)/9 (36%)	1.000
# of ankle sprains	3 (2–4)	0 (0–0)	<0.001*
# of ankle giving-way ep.	2 (1–4)	0 (0–0)	<0.001*
CAIT-PL [0–30 pt]	20 (18–22)	30 (30–30)	<0.001*
GODIN [pt.]	60.5 ± 24.2	59.8 ± 30.0	0.926

Data are expressed as mean ± SD, median (Q₁–Q₃) or n (%).

p-value – probability of type I error, * statistically significant difference, SD – standard deviation, Q1–Q3 – 1st and 3rd quartiles, BMI – body mass index, pt. – points, # – number, ankle giving way ep. – episodes within last 6 months, L – left, R – right, ^{SI} – for the control group “sham involved” limb, D – dominant, ND – non dominant, CAI – chronic ankle instability, CON – control, CAIT-PL – the Polish version of the Cumberland Ankle Instability Tool, GODIN – Godin Leisure Time Physical Activity scale.

The CAI group had significantly lower performance in YBT-LQ posterolateral reach and the composite score compared to the CON group. No significant differences between the groups were found for YBT-LQ anterior and posteromedial reach (Table 2).

The CAI group exhibited a significantly lower hip isometric abductors/adductors strength ratio compared to the CON group. No other significant differences were observed in the strength of hip external rotators, abductors, adductors, and abductors/adductors ratios at various angular velocities (Table 3).

Moderate positive correlations have been observed between the peak torque of isometric hip abductors, self-reported ankle instability, and the posterolateral reach of the YBT-LQ in the CAI group. Moreover, the peak torque of isokinetic hip abductors at a velocity of 30°/s has been moderately positively correlated with the posteromedial reach of the YBT-LQ. No other significant correlations have been observed (Table 4).

4. Discussion

This study is the first to examine hip strength exclusively in male individuals with CAI, evaluating it in comparison to healthy controls. Before comparing our results with other studies, it's crucial to note that the vast majority of previous research included between 71% and 91% female participants (Bain et al., 2022; Khalaj et al., 2021; McCann et al., 2017, 2018, 2019; Negahban et al., 2013). Additionally, the study is unique in comparing both isometric and isokinetic hip strength in individuals with CAI and uninjured controls. Significant differences were identified only in the ratio of hip abductors to adductors isometric strength, which was lower in the CAI group. The study also investigated dynamic balance and explored potential associations between hip strength, dynamic balance, and self-reported instability in individuals with CAI. The CAI group showed lower dynamic balance performance and a moderate positive correlation between isokinetic (30°/s) and

Table 2
YBT-LQ performance.

	CAI group	CON group	p-value	Effect size
Anterior reach [%]	63.8 ± 5.8	66.8 ± 6.7	0.094	0.48 (medium)
Posteromedial reach [%]	110.6 ± 7.7	114.7 ± 6.9	0.056	0.55 (large)
Posterolateral reach [%]	106.9 ± 7.4	112.7 ± 6.2	0.006*	0.92 (large)
Composite score [%]	93.8 ± 6.2	98.1 ± 5.3	0.012*	0.91 (large)

Data expressed as mean ± SD.

p-value – probability of type I error, * statistically significant difference, % – reach distance normalized to lower limb length, CAI – chronic ankle instability, CON – control.

Table 3
Isometric and Isokinetic hip strength.

	CAI group	CON group	p-value	Effect size
External rotators [Nm/kg]				
Isometric	0.87 ± 0.13	0.89 ± 0.14	0.519	0.15 (small)
Abductors Peak Torque [Nm/kg]				
Isometric	1.92 ± 0.36	2.10 ± 0.38	0.089	0.49 (medium)
Isokinetic (30°/s)	1.69 ± 0.36	1.77 ± 0.35	0.430	0.23 (medium)
Isokinetic (60°/s)	1.54 ± 0.31	1.62 ± 0.30	0.363	0.26 (medium)
Adductors Peak Torque [Nm/kg]				
Isometric	1.25 ± 0.25	1.23 ± 0.22	0.316	0.08 (small)
Isokinetic (30°/s)	1.46 ± 0.27	1.52 ± 0.27	0.378	0.22 (medium)
Isokinetic (60°/s)	1.45 ± 0.31	1.47 ± 0.32	0.771	0.06 (small)
Abductors/adductors ratio [%]				
Isometric	155.7 ± 23.9	174.8 ± 33.7	0.034*	0.65 (large)
Isokinetic (30°/s)	116.3 ± 15.3	117.8 ± 24.1	0.803	0.07 (small)
Isokinetic (60°/s)	108.4 ± 15.6	113.1 ± 22.8	0.393	0.24 (medium)

Data expressed as mean ± SD.

p-value – probability of type I error, * statistically significant difference, CAI – chronic ankle instability, CON – control.

Table 4
The correlation between hip strength, dynamic balance, and self-reported ankle instability in the CAI group (n = 25).

Independent variables		Dependent variables				
		CAIT _{PL}	YBT _{ANT}	YBT _{PM}	YBT _{PL}	YBT _{CS}
External Rotators	r	0.13 ^S	0.29	0.29	0.35	0.35
	p	0.523	0.167	0.166	0.083	0.087
Abductors Isometric Peak Torque	r	0.46^S	0.35	0.24	0.40	0.37
	p	0.021*	0.086	0.246	0.048*	0.069
Abductors Isokinetic Peak Torque (30°/s)	r	0.25 ^S	0.27	0.40	0.34	0.39
	p	0.211	0.190	0.049*	0.097	0.056
Abductors Isokinetic Peak Torque (60°/s)	r	0.22 ^S	0.10 ^S	0.20 ^S	0.14 ^S	0.20 ^S
	p	0.121	0.486	0.161	0.349	0.169
Adductors Isometric Peak Torque	r	0.37 ^S	0.13	0.17	0.09	0.15
	p	0.065	0.539	0.423	0.656	0.481
Adductors Isokinetic Peak Torque (30°/s)	r	0.19 ^S	0.23	0.39	0.32	0.36
	p	0.363	0.277	0.056	0.118	0.077
Adductors Isokinetic Peak Torque (60°/s)	r	0.13 ^S	0.12	0.24	0.15	0.20
	p	0.531	0.565	0.242	0.482	0.343

Data are expressed as Pearson or Spearman correlation coefficients (r).

p – probability of type I error, ^S – Spearman correlation coefficient, * statistically significant correlation, CAI – chronic ankle instability, CAIT-PL – The Polish version of the Cumberland Ankle Instability Tool, YBT – Y-Balance Test, ANT – anterior reach, PM – posteromedial reach, PL – posterolateral reach, CS – composite score, PT – peak torque.

isometric hip abductors strength and balance during PM and PL reaches. Additionally, greater isometric hip abductors strength had a moderate positive association with lower self-reported ankle instability.

The study revealed significant differences in the isometric abductors to adductors ratio, which was lower in the CAI group. However, no significant differences were found in abductors, adductors and external rotators isometric strength. Noticeable but not statistically significant differences were observed in isometric hip abductors strength, which was lower in the CAI group (p = 0.089; ES = 0.49). Additionally, small but inverse differences were noted in adductors strength, which was slightly higher in the CAI group (p = 0.316; ES = 0.08). Consequently, significant differences in the isometric abductor to adductor ratio were observed. An imbalance in the agonist to antagonist strength ratio at the hip can diminish joint stability (Hoglund et al., 2024) and predispose

individuals to injuries in the joint area, such as groin pain (Kekeleki et al., 2024; Rodríguez, 2020). However, the importance of an optimal frontal plane hip strength ratio may extend beyond the hip joint area itself. Two studies have reported similar findings, indicating that both the hip eccentric abductor to adductor ratio (de Marche Baldon et al., 2009) and the isometric ratio (Magalhães et al., 2013) are impaired in individuals with patellofemoral pain syndrome (PFPS). Specifically, individuals with PFPS exhibited a lower abduction strength component and a higher adduction strength component in their ratios compared to healthy controls. No previous study has evaluated this ratio in the CAI population, but it seems it should be interpreted as a non-beneficial compensation. Although other studies have evaluated frontal plane hip strength ratios in healthy or sports populations, it is difficult to compare our findings due to a lack of consistent normative values. The remaining findings are partially consistent with existing evidence when some studies have found impaired isometric strength of hip abductors (Khalaj et al., 2021; McCann et al., 2018), adductors (Khalaj et al., 2021), and external rotators (McCann et al., 2017, 2018, 2019) compared to healthy controls. However, Bain et al. (2022) and Mulligan and DeVahl (2020) reported no deficits in isometric hip strength in individuals with CAI. The isometric strength of the hip abductors in the current study did not show a statistically significant difference compared to the control group, which contrasts with previous studies (Khalaj et al., 2021; McCann et al., 2018). Although the obtained p -value ($p = 0.089$) did not meet traditional criteria for statistical significance, the results may have potential clinical relevance, as suggested by a medium effect size of 0.49 and correlation findings discussed in subsequent sections. This study also did not confirm deficits in external rotator strength, which is inconsistent with three previous studies (McCann et al., 2017, 2018, 2019). A possible explanation for this discrepancy could be the differing testing positions for the external rotator muscles. In this study, testing was performed in the prone position with a neutral hip, whereas the other studies used a seated position with the hip flexed.

In our study, isokinetic strength of the frontal plane hip musculature did not significantly differ between males with CAI and controls. These findings align with two previous studies assessing hip isokinetic strength in individuals with CAI. Gribble and Robinson (2009) found no differences in concentric hip flexor and extensor torque. Negahban et al. (2013) examined eccentric strength of the hip muscles in both frontal and sagittal planes, and reported deficits only in eccentric hip flexor torque ($60^\circ/\text{s}$). These reports suggest that isokinetic hip muscle work may not represent the functional demands placed on these muscles in everyday activities among individuals with CAI. It is speculated that during most functional activities, such as the single limb support phase during walking, the role of frontal plane hip musculature is closer to isometric contraction, as it requires pelvic stabilization while resisting gravitational forces (Neumann, 2010).

A meta-analysis by (Khalaj et al., 2020) included only three studies related to hip strength in CAI, yielding inconclusive results. While two studies examined isokinetic hip strength (Gribble & Robinson, 2009; Negahban et al., 2013), only one investigated it isometrically (McCann et al., 2017). Since then, the results may have the potential for updates, particularly regarding isometric hip strength, though the findings might still be equivocal. A recent cross-sectional study with prospective follow-up by Khalaj et al. (2022) found that individuals after first-time lateral ankle sprains did not demonstrate decreased hip and knee strength within the first 3 months post-injury, suggesting that potential deficits in proximal lower limb musculature strength may manifest later, during chronic ankle conditions. This may possibly be due to repeated ankle sprains, associated with joint effusion (Hopkins et al., 2001), pain, and damage to mechanoreceptors from periarticular soft tissues (Palmieri et al., 2004). One hypothesis explaining these changes involves reorganization of the central nervous system (CNS), particularly spinal and cortical pathways (Ward et al., 2015), which may affect voluntary muscle activation, strength, and lead to biomechanical

changes such as compensatory motor strategies (Pietrosimone et al., 2012). It's worth noting that neuromuscular deficits after unilateral ankle trauma can occur bilaterally (Hu et al., 2024; Pietrosimone & Gribble, 2012; Simpson et al., 2019), supporting the hypothesis of CNS reorganization rather than purely biomechanical explanations.

It appears that there could be a positive relationship between the isometric strength of the hip abductors and self-reported ankle instability. A moderate positive correlation suggests that individuals with more severe ankle instability may also have lower hip abductors isometric strength. A similar association between hip abductors strength and CAIT scores has been reported, but only in a female cohort (Lu et al., 2022). Increasing isometric hip abductors strength could potentially benefit those with severe CAI in terms of self-reported ankle function. There is evidence that hip strengthening programs targeting the abductors, lateral rotators and extensors have been shown to improve patient-reported outcomes in other musculoskeletal conditions, such as PFPS, as supported by meta-analyses (Alammari et al., 2023; Na et al., 2021).

Our study also confirms existing dynamic balance deficits in males with CAI. Large effect sizes were observed when comparing PL reach and composite score of YBT-LQ to the control group. Differences in ANT and PM reach were noticeable but not statistically significant. Only hip abductors strength showed a moderate positive correlation with PM and PL reach performance. Specifically, isokinetic strength ($30^\circ/\text{s}$) of hip abductors positively correlated with the PM reach, while isometric hip abductors strength positively correlated with the PL reach. No correlations were observed for hip abductor isokinetic strength at an angular velocity of $60^\circ/\text{s}$. This may be because the YBT-LQ was performed in a slow and controlled manner, which for the hip abductors may more closely match the velocity of $30^\circ/\text{s}$ than $60^\circ/\text{s}$. Overall, these findings suggest that hip abductors strength is associated with posterior directions performance of YBT-LQ/SEBT, consistent with reports on CAI patients (McCann et al., 2017) as well as in healthy male population (Olszewski et al., 2024). However, neuromuscular strategies responsible for balance control may differ between individuals with CAI, LAS copers, and uninjured controls (Doherty et al., 2015; Rios et al., 2015). Decreased ankle muscles activation and increased hip and spine muscles activation during single leg postural control tasks have been found in individuals with CAI (Rios et al., 2015). Increased ankle-hip linked coordination during static postural tasks has also been reported in CAIs compared to LAS copers and controls (Doherty et al., 2015). These findings suggest that individuals with CAI may use more hip-dominant strategy to compensate distal ankle deficits and maintain stability, but due to existing neuromuscular deficits, this may not be fully optimal. Although hip strength and hip muscle activation are distinct concepts, they may both be related to lower limb functional performance during different tasks (Lanza et al., 2022; Neamatallah et al., 2020). This could explain why higher hip abductors isometric strength may be associated with lower self-reported ankle instability.

The implications of our study are significant. Knowing that individuals with CAI have a reduced hip abductors/adductors isometric strength ratio, improving it will rely mainly on increasing the isometric strength of the hip abductors. Additionally, the positive relationship between hip abductors strength and dynamic balance and self-reported ankle instability suggests that the strength of these muscles may impact the functional status of patients with CAI. A study by Smith et al. (2018) on a 4-week hip strengthening program in people with CAI supports our findings, as improvements in dynamic balance, strength, and self-reported function were noted. Moreover, Kosik et al. (2017) reported that CAI subjects with lower self-reported function will benefit more from implementing hip exercises, which aligns with the results of our correlation. A novel study by Suttmitter et al. (2024) reported that 8-week balance training and hip strengthening programs can both improve posterolateral hip strength, perceived ankle function, disability, balance self-efficacy, and injury-related fear in individuals with CAI, with balance training identified as the more effective

intervention. Nevertheless, the study did not evaluate the effectiveness of combining both interventions. These studies remain the only ones on the topic of hip strengthening in managing CAI symptoms. However, there are studies on individuals with PFPS that suggest incorporating hip strengthening exercises alongside knee exercises may offer additional benefits compared to exercises targeting knee alone (Alammari et al., 2023; Nascimento et al., 2018; Şahin et al., 2016). These findings raise the possibility that a similar approach could be effective for CAI, where combining hip strengthening exercises with the gold standard interventions such as balance training (Mollà-Casanova et al., 2021), might provide additional functional benefits for patients with CAI.

Our study also has certain limitations. It has been reported that hip abductors strength and functional performance differ between males and females with CAI, so caution is needed when generalizing the results of this study (Lu et al., 2022; Sugimoto et al., 2014). Due to the cross-sectional design, it is challenging to determine when exactly hip strength deficits can occur in individuals with CAI. Recent study suggest that this may not happen until at least 3 months post first-time lateral ankle sprain (Khalaj et al., 2022). Further longitudinal studies are needed to investigate the precise mechanisms and timeframe of forming these types of neuromuscular deficits. Additionally, there are limitations in the application of hip interventions in managing CAI symptoms. Limited available data suggests caution in their implementation across the broader CAI population. Further experimental studies are necessary to understand the role of hip strength in CAI rehabilitation and to optimize the integration of hip-targeted exercises into treatment plans.

5. Conclusions

Males with CAI exhibit deficits in frontal plane hip isometric strength, specifically in the isometric hip abductor/adductor ratio, while no deficits were observed in isokinetic strength. Existing moderate positive relationships between hip abductors strength, dynamic balance, and self-reported ankle instability may suggest that hip abductors isometric strength is an important factor to consider in rehabilitation programs for CAI. It is speculated that interventions focused on hip strengthening may improve functional outcomes in CAI patients. However, further experimental studies are needed to confirm these assumptions.

CRedit authorship contribution statement

Maciej Olszewski: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Joanna Golec:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Bartosz Zajac:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Piotr Krężalek:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Ethical approval

The participants were informed about the research protocol in detail and provided their written informed consent to participate in the study. All procedures were performed in accordance with the 1964 Helsinki declaration and its later amendments. The approval of the Bioethics Committee at the Regional Medical Chamber in Kraków (No. 11/KBL/OIL/2022) was obtained for this study.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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4.3. Publikacja 3

Olszewski, M.; Krężałek, P.; Golec, J. Multisegmented Foot and Lower Limb Kinematics During Gait in Males with Chronic Ankle Instability: Exploring Links with Hip Abductor Strength. J Clin Med 2025, 14, 5977, doi:10.3390/jcm14175977.

Głównym celem tej pracy była ocena wielosegmentowej kinematyki stopy oraz pozostałych stawów kończyny dolnej podczas całego cyklu chodu u mężczyzn z CAI w porównaniu z grupą kontrolną. Celem dodatkowym była ocena związków między momentem siły odwodzicieli stawu biodrowego a kinematyką stawu skokowo-goleniowego podczas chodu. Sformułowano następujące hipotezy badawcze:

1. Mężczyźni z CAI wykazują zmienioną kinematykę segmentów stopy i stawów proksymalnych w trakcie cyklu chodu, w szczególności zwiększoną inwersję tyłostopia oraz przywiedzenie biodra, w porównaniu z grupą kontrolną.
2. Ujemne korelacje występują pomiędzy momentem siły odwodzicieli stawu biodrowego a maksymalną inwersją stawu skokowo-goleniowego oraz jego zakresem ruchu w płaszczyźnie czołowej, co może wskazywać na potencjalną rolę tych mięśni w stabilizacji poprzez redukcję nadmiernych ruchów stawu skokowo-goleniowego.

W badaniu wzięło udział 25 zdrowych mężczyzn oraz 25 mężczyzn z CAI. Kwalifikacja uczestników odbywała się na podstawie kryteriów włączenia i wyłączenia określonych przez IAC [34]. Kryteria te szczegółowo opisano w rozdziale 4.2 (Publikacja 2). Badani uczestniczyli w następujących pomiarach: (a) pomiary antropometryczne; (b) trójwymiarowa analiza chodu przy użyciu systemu BTS SMART (BTS Bioengineering, Milan, Italy) wraz z platformą dynamometryczną (Advanced Mechanical Technology, Inc. (AMTI), Watertown, USA); (c) pomiar izometrycznego momentu siły odwodzicieli stawu biodrowego przy użyciu dynamometru Biodex Multi-Joint System 4 Pro (Biodex Medical Systems, Shirley, NY, USA).

Przed rozpoczęciem analizy chodu markery odbłaskowe rozmieszczono na ciele badanego zgodnie z modelem Simple Davis [56], obejmującym punkty anatomiczne: kość krzyżową, kolce biodrowe przednie górne, krętarz większy, kłykieć boczny kości udowej, głowę strzałki i kostkę boczną, a także sztywne wysięgniki na środkowej części uda i podudzia. Ruchy segmentów stopy analizowano przy użyciu zmodyfikowanej wersji modelu Rizzoli Foot Model [57]. Markery umieszczono na punktach anatomicznych stopy: tylna część kości piętowej, guzek strzałkowy kości piętowej, podpórka skokowa kości piętowej, guzowatość

kości łódkowatej, podstawy II i V kości śródstopia, głowy I i V kości śródstopia oraz paliczek bliższy palucha.

Zbieranie danych kinematycznych rozpoczęto od próby w pozycji stojącej, która posłużyła do normalizacji danych chodu. Podczas rejestracji kinematyki kończyn dolnych uczestnicy chodzili boso z preferowaną prędkością po 8-metrowej ścieżce. Do dalszej analizy kinematycznej i czasowo-przestrzennej wykorzystano średnią z trzech powtarzalnych cykli chodu. Po zakończeniu oceny chodu uczestnicy poddani zostali pomiarowi momentu siły mięśni odwodźcicieli stawu biodrowego. Dalszą obróbkę danych kinematycznych przeprowadzono w oprogramowaniu BTS Smart Analyzer (BTS Bioengineering, Milan, Italy). Cykl chodu zdefiniowano jako okres od pierwszego kontaktu pięty (0%) do kolejnego kontaktu pięty tej samej kończyny (100%). Zdarzenia charakterystyczne identyfikowano manualnie, wspierając się zsynchronizowanymi danymi sił reakcji podłoża z platformy dynamometrycznej.

Analizy statystyczne wykonano w środowisku Python 3.13 z wykorzystaniem bibliotek pandas, spm1d, NumPy, SciPy oraz Matplotlib (wersja 3.10.3). Do analizy zmiennych opisowych zastosowano test t dla prób niezależnych (przy spełnionej normalności rozkładu i homogeniczności wariancji), test t Welcha (przy spełnionej normalności, ale nierówności wariancji) lub test U Manna–Whitneya (przy niespełnionej normalności). Normalność rozkładu sprawdzano testem Shapiro–Wilka, a jednorodność wariancji testem Levene’a. Różnice międzygrupowe w zakresie ciągłych przebiegów kinematycznych analizowano metodą Statistical Parametric Mapping (SPM), wykorzystując test t dla dwóch prób niezależnych. Metoda ta analizuje cały znormalizowany czasowo przebieg fali i identyfikuje te odcinki cyklu chodu, w których statystyka testowa przekracza wartość krytyczną, kontrolując ryzyko błędu I rodzaju zgodnie z teorią pól losowych [58]. Dla każdego istotnego odcinka raportowano odpowiadający mu przedział czasowy cyklu chodu, wartość p, średnią różnicę (Mean Difference – MD) oraz wielkość efektu (Cohen’s d). Do oceny liniowych zależności pomiędzy zmiennymi ciągłymi o rozkładzie normalnym zastosowano współczynnik korelacji Pearsona, a w przypadku niespełnienia tego założenia – współczynnik korelacji rang Spearmana. Za poziom istotności statystycznej przyjęto $p < 0,05$.

Mężczyźni z CAI wykazywali większe odwiedzenie tyłostopia w płaszczyźnie poprzecznej podczas końcowej fazy wymachu cyklu chodu w porównaniu ze zdrowymi uczestnikami z grupy kontrolnej. Nie stwierdzono istotnych różnic w innych segmentach stopy ani w kinematyce proksymalnych segmentów kończyny dolnej, w tym stawu biodrowego i kolanowego. Wyniki mogą wspierać praktykę kliniczną, szczególnie w ocenie chodu

i planowaniu rehabilitacji. Wskazują one, że klinicyści powinni rozważać rolę wszystkich segmentów stopy oraz całej kończyny dolnej, zamiast skupiać się wyłącznie na stawie skokowo-goleniowym podczas diagnostyki i planowania interwencji terapeutycznych. Ponadto nie odnotowano istotnych korelacji pomiędzy izometrycznym momentem siły odwodzicieli stawu biodrowego a kinematyką stawu skokowo-goleniowego w płaszczyźnie czołowej. Może to sugerować, że potencjalna korzystna rola siły mięśni odwodzicieli stawu biodrowego u osób z CAI realizowana jest poprzez inne mechanizmy, które powinny być przedmiotem dalszych badań.

Article

Multisegmented Foot and Lower Limb Kinematics During Gait in Males with Chronic Ankle Instability: Exploring Links with Hip Abductor Strength

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Abstract

Background/Objectives: Although considerable progress has been made in understanding lateral ankle sprains (LAS) and chronic ankle instability (CAI), recurrent injury rates remain high. This highlights the need to explore additional contributors such as comprehensive lower-limb gait analysis, including multisegmented foot models and proximal joint kinematics and strength. This study aimed to assess multisegmented foot and lower-limb kinematics throughout the gait cycle in individuals with CAI compared to healthy controls. Additionally, associations between hip abductor strength and frontal plane ankle kinematics were examined. **Methods:** Fifty males (25 with CAI and 25 healthy controls) participated in this cross-sectional study. Gait analysis was conducted using a BTS SMART 3D motion capture system to assess multisegmented foot and proximal joint kinematics. Isometric hip strength was measured using a Biodex dynamometer. Statistical Parametric Mapping (SPM) was used to assess group differences, and correlations were calculated between hip abductor strength and ankle kinematics. **Results:** The CAI group demonstrated significantly greater calcaneus abduction relative to the shank in the transverse plane between 88% and 93% of the gait cycle (MD = -3.50° , 95% CI [-5.60 , -1.40], $d = -0.95$, $p = 0.037$). No other statistically significant between-group differences in hip, knee, or foot segment kinematics were detected. Furthermore, correlations between hip abductor strength and ankle frontal plane kinematics were not significant. **Conclusions:** Males with CAI demonstrated altered rearfoot kinematics in the transverse plane during the terminal swing phase. The multisegmented foot model was valuable in detecting subtle deviations and emphasized the importance of including the swing phase. Hip abductor strength was not associated with ankle kinematics, suggesting that its potential role in CAI may involve other mechanisms. These findings may support clinical gait assessment and rehabilitation planning by highlighting the importance of evaluating all foot segments and the entire lower limb, rather than focusing solely on the ankle joint. Segment-specific deviations, particularly those emerging during the swing phase, may help guide targeted interventions aimed at improving foot positioning in males with CAI.

Keywords: chronic ankle instability; multisegmented foot model; gait analysis; lower limb biomechanics; hip abductor strength



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1. Introduction

Lateral ankle sprains (LAS) are among the most common musculoskeletal injuries, affecting over two million individuals annually in the United States alone [1]. Alarming, only 11% of LAS patients undergo supervised physical therapy following injury [2]. Improper or insufficient management often leads to residual impairments, with approximately 46% of LAS cases progressing to chronic ankle instability (CAI) [3], which is characterized by recurrent ankle sprains, giving-way episodes, and self-reported dysfunction [4]. Although substantial progress has been made in understanding the pathomechanics and pathophysiology of LAS and CAI, there is still no clear evidence that the incidence of recurrent injuries is decreasing. This may, in part, reflect limitations in diagnostic accuracy and suboptimal treatment strategies, highlighting the need to investigate additional factors influencing functional status and to further optimize physical therapy approaches.

Despite extensive research conducted in the CAI population, there is still a lack of detailed biomechanical studies that focus not only on the injured joint but also comprehensively evaluate the entire kinematic chain. Most studies treat the foot as a single rigid segment, thereby ignoring relevant intersegmental interactions that may contribute to functional deficits in this population. This approach is inconsistent with the complex anatomy and biomechanics of the foot, which consists of multiple articulations allowing relative movement between segments. Overlooking intersegmental foot motion can mask subtle dysfunctions in foot control, potentially leading to impaired balance, altered load distribution, and increased risk of injury recurrence. Moreover, such simplification may limit the precision of rehabilitation strategies by overlooking segment-specific impairments that require targeted interventions. Studies have shown that inversion injuries such as LAS can also damage structures beyond the ankle, including the midfoot and forefoot [5]. Søndergaard [6] demonstrated that these regions are frequently affected during inversion ankle sprains, an observation that may be underrecognized by many clinicians and researchers. To better understand foot mechanics, several multisegmented foot models have been proposed [7], typically dividing the foot–ankle complex into shank, rearfoot, midfoot, medial/lateral forefoot, and hallux. Although these models offer a more detailed representation of foot function, their application in CAI-related research has been relatively limited. To date, most studies on gait analysis in individuals with CAI have used single-segment foot models and reported differences such as increased foot inversion [8] and plantarflexion [9]. These findings may be present during terminal swing, initial contact [10,11], or throughout the entire gait cycle [12] in people with CAI compared to controls.

Only a limited number of studies have evaluated gait in individuals with CAI using a multisegmented foot model. Fraser et al. [13] found increased rearfoot inversion during midstance (from 34% to 91% of the stance phase) compared to healthy controls, with a mean difference (MD) of 3.6° . In that study, no other differences were found in foot–ankle complex segments. Dingenen et al. [14] reported decreased dorsiflexion during the loading response and a more inverted rearfoot during the initial swing phase in individuals with CAI. They also did not find any differences in the midfoot and forefoot segments. In De Ridder's study [15], a multisegmented foot model was also compared with a rigid foot model during walking and running. The authors revealed different findings than others, specifically a more everted rigid foot position from 11% to 73% of the stance phase, while no significant differences were found for the rearfoot during walking, which contradicts findings from multiple studies [8,9]. This discrepancy may arise from the absence of normalization to reference values or differences in participants' specific characteristics. In that study, the medial forefoot showed increased inversion ($MD = 9.4^\circ$) from 87% to 98% of the stance phase in the CAI group compared to controls. In two of the above-mentioned studies [13,15], foot kinematics were analysed only during the stance phase of gait. This disregards

the swing phase, which also appears to be significant for people with CAI. Previous studies [10,11] reported that individuals with CAI exhibit a more inverted foot position even before heel strike. Koldenhoven et al. [16] indicated greater hip joint adduction during the swing phase across three different walking speeds in CAI participants compared to copers, which may be linked to altered ankle positioning. In addition, Huang et al. [17] found greater frontal plane hip variability during gait in individuals with CAI compared to healthy controls. However, none of the studies using multisegmented foot models incorporated kinematic data from proximal lower limb joints, which may hinder comprehensive gait evaluation in the CAI population.

Hip abductor strength deficits and diminished isometric hip extensor strength have been confirmed by a recent meta-analysis in individuals with CAI, while no decrease in isokinetic strength was noted [18]. Similar impairments may also be present during gait and functional movements. Activity of the gluteus medius, which is the primary hip abductor, may be decreased in this population, as reported by ultrasound studies [19–21]. Isometric strength of the hip abductor has also been shown to predict ankle sprains in soccer players [22]. While the role of this muscle group in CAI continues to be explored, little is still known about how it influences the function of distal lower limb segments. One possible explanation may lie in observed relationships between isometric hip abductor strength and dynamic balance [23–26], which is commonly impaired in the CAI population [27]. It is also speculated that optimal hip abductor function may contribute to improved control of frontal plane ankle motion, for example by reducing excessive inversion or enhancing mediolateral postural stability [28]. Foot placement is adjusted in response to changes in the centre of mass (CoM) state, primarily through modulation of hip abductor activity during the swing phase. This control mechanism relies on sensory input, including visual, vestibular, and proprioceptive signals, and is regulated through both spinal and supraspinal pathways. Proprioceptive feedback from the hip muscles may help the central nervous system estimate hip position in the frontal plane and activate the appropriate muscles to correct deviations, supporting stable mediolateral foot placement and overall gait stability [29,30]. Holmes et al. [31] reported that greater hip abductor strength may be associated with a greater foot progression angle in healthy males, although such a relationship was not found in females. To date, no studies have focused on exploring the direct relationship between hip abductor strength and frontal plane ankle kinematics during gait. Consistent with this, our previous study found that isometric hip abductor strength was associated with self-reported instability and dynamic balance performance [23]. On this basis, this variable was selected for the correlation analysis in the present study, as such information may aid in better understanding the biomechanical role of hip musculature in individuals with CAI.

Despite promising results from existing multisegmented foot models, their limited application in CAI research, particularly without the inclusion of proximal joint kinematics and full gait cycle analysis, continues to hinder a comprehensive understanding of broader biomechanical adaptations in this population. Therefore, the primary aim of this study was to assess multisegmented foot and lower limb kinematics throughout the entire gait cycle in males with CAI, compared to healthy controls. It was hypothesised that males with CAI would demonstrate altered foot segment and proximal joint kinematics across the gait cycle, particularly increased rearfoot inversion and hip adduction relative to healthy controls. Secondly, the study aimed to examine whether hip abductor strength is associated with ankle kinematics during gait. It was hypothesised that moderate negative correlations would be observed between hip abductor strength and both peak ankle inversion and frontal plane range of motion, indicating a potential role in limiting ankle excursion. This comprehensive evaluation may help clinicians better understand how CAI influences the

biomechanics of the entire lower limb kinematic chain. The findings may support the optimisation of rehabilitation strategies for males with CAI.

2. Materials and Methods

2.1. Participants

The study enrolled 25 males with CAI and 25 healthy male controls. Participants were recruited through posters shared on social media, academic platforms, and displayed on campus. Volunteers completed an online survey to determine eligibility based on inclusion and exclusion criteria. The inclusion criteria for participants with CAI were established in accordance with the recommendations of the International Ankle Consortium [32] and included the following: (1) male sex and an age range of 18 to 30 years; (2) a history of at least one significant ankle sprain that caused pain, swelling, and activity limitation for at least one day, occurring no less than 12 months prior to study enrolment; (3) at least two episodes of the ankle “giving way” in the six months preceding participation and/or a history of recurrent ankle sprains and/or subjective sensations of ankle instability; (4) confirmed functional ankle instability, indicated by a score of ≤ 24 points on the Polish version of the Cumberland Ankle Instability Tool (CAIT-PL) [33]. The inclusion criteria for the control group (CON) were as follows: (1) male sex and an age between 18 and 30 years; (2) no prior history of ankle sprains; (3) no signs of functional ankle instability, confirmed by a CAIT-PL score between 28 and 30 points. Exclusion criteria for all participants included the following: (1) a history of surgeries involving musculoskeletal structures in either lower limb; (2) a history of fractures in either lower limb that required realignment; (3) any acute musculoskeletal injury to the lower limb within the three months preceding the physical assessment, affecting joint integrity or function.

2.2. Ethical Approval

The participants were informed about the research protocol in detail and provided their written informed consent to participate in the study. All procedures were performed in accordance with the 1964 Helsinki declaration and its later amendments. The approval of the Bioethics Committee at the Regional Medical Chamber in Krakow (No. 11/KBL/OIL/2022) was obtained for this study.

2.3. Study Protocol

Before the measurements, participants provided detailed information about their history of ankle sprains and instability episodes. All volunteers were asked to complete the CAIT-PL questionnaire [33] to determine the severity of CAI, as well as the Godin Leisure-Time Physical Activity Scale [34] to assess their current level of physical activity. Anthropometric data were then collected for each participant. This included measurements of body height using the Seca 213 stadiometer (Seca GmbH & Co. KG, Hamburg, Germany), body mass using the BC-418 analyser (Tanita Corporation, Tokyo, Japan), and foot posture using the Foot Posture Index [35]. For gait analysis, pelvis width, pelvis depth, lower limb length, knee width, and ankle width were measured using a measuring tape to the nearest 0.5 cm or a thickness compass to the nearest 0.1 cm. Subsequently, retroreflective markers were placed on the participant’s lower limbs according to the BTS Simple Davis protocol [36] and on the feet in accordance with the modified Rizzoli foot model [37]. All markers were applied by the same experienced examiner to ensure consistency.

Collection of kinematic data began with a static standing posture trial, which served as a reference for normalising gait data. To record lower limb kinematics during gait, participants walked barefoot at a self-selected speed along an 8 m walkway. The warm-up consisted of five minutes of walking to familiarise participants with the testing environ-

ment and ensure repeatability of the gait cycle. All participants received identical verbal instructions regarding gait performance to standardise the conditions. The mean from three consistent gait cycles was used for further kinematic and spatiotemporal analysis. Upon completion of the gait assessment, participants underwent hip strength testing. All measurements were conducted by a team of two experienced researchers.

The participant's dominant leg was identified as the preferred leg for kicking a ball. In the CAI group, the involved limb was analysed. In cases of bilateral ankle instability, the limb with the lower CAIT-PL score and a higher number of giving-way episodes was selected. In the control group, limbs were matched prior to measurements by assigning one as "sham involved" and the other as "sham uninvolved", which was used for subsequent analysis. This procedure ensured the same proportion of dominant and non-dominant limbs across groups, minimizing the influence of limb dominance on the results [23,38].

2.4. Foot Posture Index

The Foot Posture Index is a six-item scale used to assess rearfoot, midfoot, and forefoot posture in the three cardinal body planes. It was designed to quantify variation in foot position easily and quickly in a clinical setting [35]. It consists of the assessment of the following: (1) talar head palpation; (2) curves above and below the lateral malleolus; (3) inversion and eversion of the calcaneus; (4) bulge in the region of the talonavicular joint; (5) congruence of the medial longitudinal arch; and (6) abduction and adduction of the forefoot on the rearfoot (the too-many-toes sign). The scoring system uses a five-point Likert-type scale, where each item is scored from -2 to $+2$. The overall score is the sum of all six items. Scores between -1 and -4 indicate a supinated foot posture, while scores from -5 to -12 indicate significant supination. Values from 0 to $+5$ represent a neutral foot posture, scores from $+6$ to $+9$ indicate pronation, and values above $+10$ suggest significant pronation. The Foot Posture Index demonstrates excellent intra-rater reliability ($ICC = 0.945$) and moderate inter-rater reliability ($ICC = 0.575$) [39].

2.5. Kinematic Analysis

Kinematic data were collected during walking trials using a three-dimensional (3D) optoelectronic motion capture system (BTS SMART, BTS Bioengineering, Milan, Italy), equipped with six infrared cameras (sampling frequency: 70 Hz) and a piezoelectric force platform (Advanced Mechanical Technology, Inc. (AMTI), Watertown, USA). All equipment was calibrated prior to data collection [36]. The gait cycle was defined as the period from initial contact (0%) to the subsequent ipsilateral initial contact (100%). Events were manually identified with the support of synchronized force platform data.

Reflective markers were placed according to the Simple Davis Model [36] for tracking the pelvis, thigh, and shank, including anatomical landmarks on the anterior superior iliac spines, greater trochanter, lateral femoral condyle, fibular head, and lateral malleolus, as well as rigid bars placed mid-thigh and mid-shank.

Foot motion was analysed using a modified version of the Rizzoli Foot Model [37]. Markers were placed on the following landmarks of the right foot: the posterior aspect of the calcaneus, the peroneal tubercle, the sustentaculum tali, the navicular tuberosity, the bases of the 2nd and 5th metatarsals, the heads of the 1st and 5th metatarsals, and the proximal phalanx of the hallux. A modification to the original model was introduced: instead of a single marker on the 2nd metatarsal head, a virtual marker was calculated post hoc as the midpoint between the heads of the 1st and 5th metatarsals. This change was made to improve the symmetry and stability of the forefoot coordinate system. The forefoot spreads mediolaterally during stance, and individual marker placement is prone to error. Using the midpoint virtual marker provides a more reliable and symmetrical reference for

defining forefoot direction and also reduces the risk of marker occlusion or overlap with the 1st metatarsal marker, particularly in participants with narrower feet or closely spaced metatarsal heads [40]. The Simple Davis and Rizzoli models were integrated at the shank segment, defined using common markers (fibular head, lateral malleolus, and mid-shank).

The following rigid segments were defined for the calculation of foot and lower limb kinematics:

- Shank: fibular head, lateral malleolus, mid-shank marker
- Foot: posterior calcaneus, 1st and 5th metatarsal heads, virtual metatarsal head
- Calcaneus: posterior calcaneus, peroneal tubercle, sustentaculum tali
- Midfoot: navicular tuberosity, 2nd and 5th metatarsal bases
- Metatarsus: 2nd metatarsal base, 1st and 5th metatarsal heads
- Toe: 1st metatarsal head, proximal phalanx of the hallux

Segment coordinate systems were defined following the convention proposed by Leardini et al. [37], with the X-axis aligned with the longitudinal axis of the segment (proximal to distal), the Z-axis oriented mediolaterally, and the Y-axis defined as orthogonal to X and Z, directed dorsally in the standing position.

Relative orientations between segments were calculated as Cardan angles using the Z–X–Y rotation sequence, corresponding to the following: Z-axis: dorsiflexion/plantarflexion, X-axis: inversion/eversion, Y-axis: adduction/abduction.

2.6. Hip Abductor Strength Measurement

Hip abductor isometric strength was measured using a Biodex Multi-Joint System 4 Pro dynamometer (Biodex Medical Systems, Shirley, MA, USA). Participants were positioned in a side-lying position with a strap placed around their pelvis to provide support. The isometric examination consisted of two familiarization trials at 50% and 80% of the participant's perceived maximal torque, followed by a 30 s rest. Then, three maximal isometric contractions were performed, each lasting 5 s, with 15 s rest intervals between them [41]. The testing protocol was described in detail in our previous publication [23]. In the present study, only the isometric peak torque of the hip abductor, normalised to body mass (Nm/kg), was included as an independent variable for correlation analysis with gait-related kinematic parameters.

2.7. Statistical Analysis

Statistical analysis was conducted using Python 3.13 with the libraries pandas, spm1d, NumPy, SciPy, and Matplotlib version 3.10.3. For descriptive statistics of the studied population, the independent samples *t*-test (assuming normal distribution in both groups and homogeneity of variances), Welch's *t*-test (assuming normal distribution but unequal variances), or the Mann–Whitney *U* test (when the assumption of normality was not met in at least one group) was used. The assumption of normality was verified using the Shapiro–Wilk test, and homogeneity of variances was assessed using Levene's test.

Between-group differences in continuous kinematic waveforms were assessed using Statistical Parametric Mapping (SPM) two-sample *t*-tests. This method analyses the entire time-normalised waveform as a whole and detects continuous sections of the gait cycle where the test statistic exceeds the critical value for statistical significance, with the overall risk of type I error controlled according to Random Field Theory [42]. For each significant section, the corresponding gait time interval and *p*-value were reported, along with the mean difference (MD) in kinematic variables and the corresponding mean Cohen's *d* effect size within that interval.

Effect sizes were interpreted according to conventional thresholds: small ($|d| \approx 0.2$), medium ($|d| \approx 0.5$), and large ($|d| \geq 0.8$) [43]. Regions with medium ($|d| \geq 0.50$) and

large ($|d| \geq 0.80$) effect sizes were shaded on the plots to indicate differences that, although not statistically significant or not meeting the predefined threshold for a large effect, may still have biomechanical relevance and serve as a basis for further research considerations.

Pearson's correlation coefficient was used to assess linear relationships between continuous variables that followed a normal distribution. If at least one variable did not meet the normality assumption, Spearman's rank correlation coefficient was applied instead. Correlation strength was interpreted as follows: very weak (0.0–0.2), weak (0.2–0.4), moderate (0.4–0.6), strong (0.6–0.8), and very strong (0.8–1.0).

Power analysis indicated that a minimum of 25 participants per group would be required to detect a large effect size (Cohen's $d = 0.80$) with a statistical power of 0.80 and $\alpha = 0.05$. This estimation was based on the large variability observed in rearfoot eversion kinematics in a multisegmented model [44]. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Characteristics of Study Population

Participant characteristics and spatiotemporal gait parameters are presented in Table 1. No significant differences were observed between the CAI and CON groups in terms of age, body mass, fat-free mass, height, BMI, or physical activity level. The CAI group demonstrated significantly lower Foot Posture Index scores, indicating a slightly more supinated static foot posture ($p = 0.01$), lower CAIT-PL scores, indicating greater functional ankle instability ($p < 0.001$), and reported a higher number of giving-way episodes in the last six months and more ankle sprains ($p < 0.001$). Spatiotemporal gait parameters, including stance phase, swing phase, stride time, and walking velocity, did not differ significantly between groups.

Table 1. Descriptive statistics of the studied population.

	CAI Group ($n = 25$)	CON Group ($n = 25$)	p -Value
Age [years]	23.1 (3.6)	21.8 (2.9)	0.139
Body mass [kg]	78.2 (12.8)	77.2 (10.3)	0.786
Body height [m]	1.81 (0.07)	1.78 (0.07)	0.153
BMI [kg/m^2]	23.9 (3.4)	24.4 (2.7)	0.473
GODIN	60.5 (24.3)	58.6 (30.3)	0.809
Foot Posture Index	1.8 (3.8)	4.6 (3.4)	0.01 *
CAIT-PL	20 (18–22)	30 (30–30)	<0.001 *
# of ankle sprains	3 (2–4)	0 (0–0)	<0.001 *
# of ankle giving-way	2 (1–4)	0 (0–0)	<0.001 *
Spatiotemporal parameters			
Stance Phase [%]	60.0 (1.7)	59.9 (1.0)	0.934
Swing Phase [%]	40.0 (1.7)	40.1 (1.0)	0.959
Stride time [s]	1.1 (0.1)	1.1 (0.1)	0.316
Velocity [m/s]	1.2 (0.2)	1.2 (0.1)	0.900

Data are expressed as mean (SD) or median (Q_1 – Q_3). p -value—probability of type I error, * statistically significant difference, SD—standard deviation, Q_1 – Q_3 —1st and 3rd quartiles, BMI—body mass index, #—number, CAIT-PL—the Polish version of the Cumberland Ankle Instability Tool, GODIN—Godin Leisure Time Physical Activity scale.

3.2. Curve Analyses

Statistical Parametric Mapping (SPM) was used to compare the continuous kinematic waveforms between groups across the entire gait cycle (0–100%). Kinematics for all analysed joints and segments are presented in Figures 1 and 2.

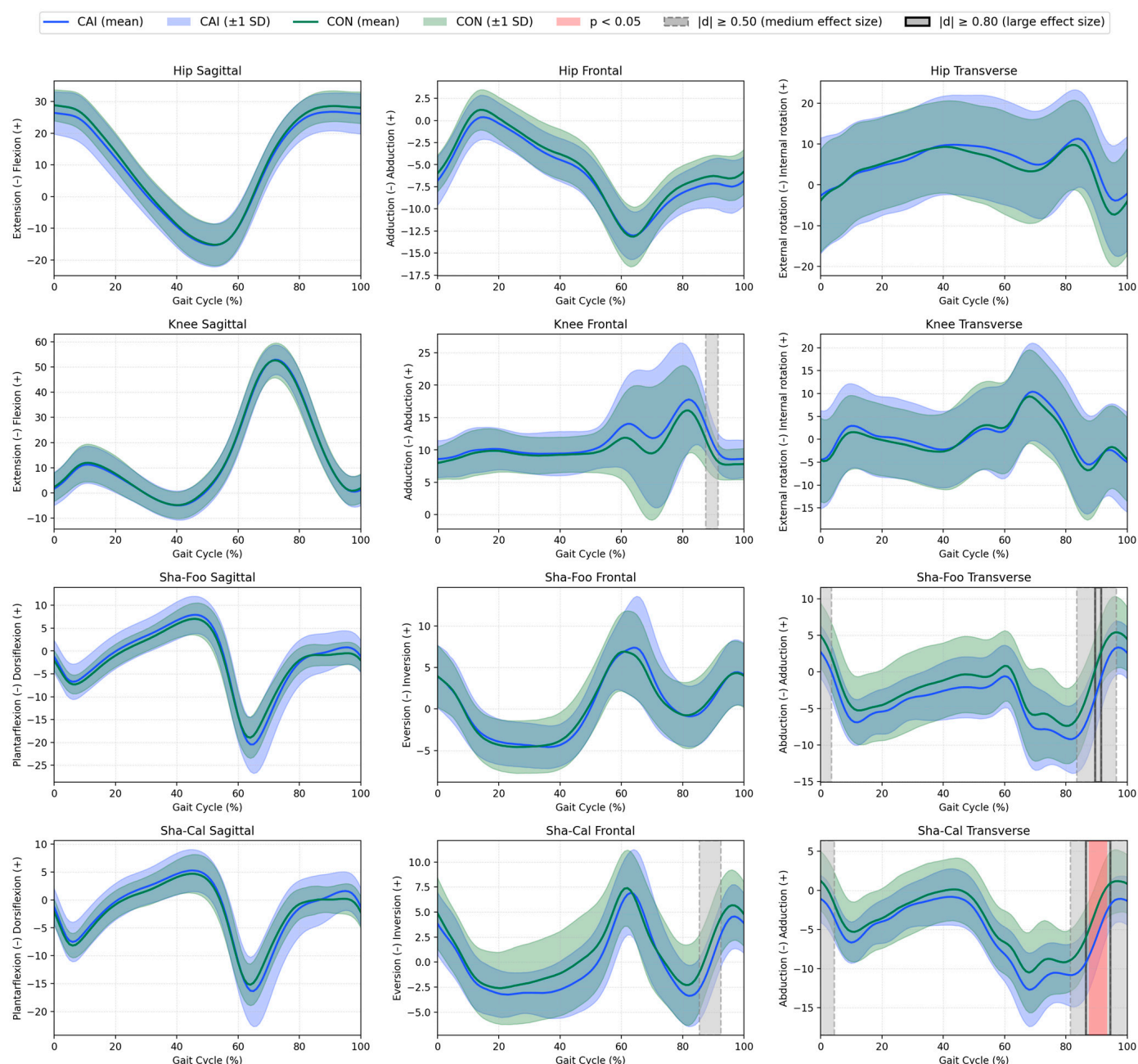


Figure 1. Mean kinematics (solid lines) ± 1 SD (shaded areas) for the CAI group (blue) and control group (green) for the hip, knee, Sha-Foo, and Sha-Cal segments throughout the gait cycle (%). The gait cycles are time-normalized to 100%, with initial contact at 0% and toe-off at ~60%. Grey shading indicates medium effect sizes ($|d| \geq 0.50$), black bold outline indicates large effect sizes ($|d| \geq 0.80$), and red shading indicates statistically significant differences ($p < 0.05$) between groups, as determined by Statistical Parametric Mapping (SPM).

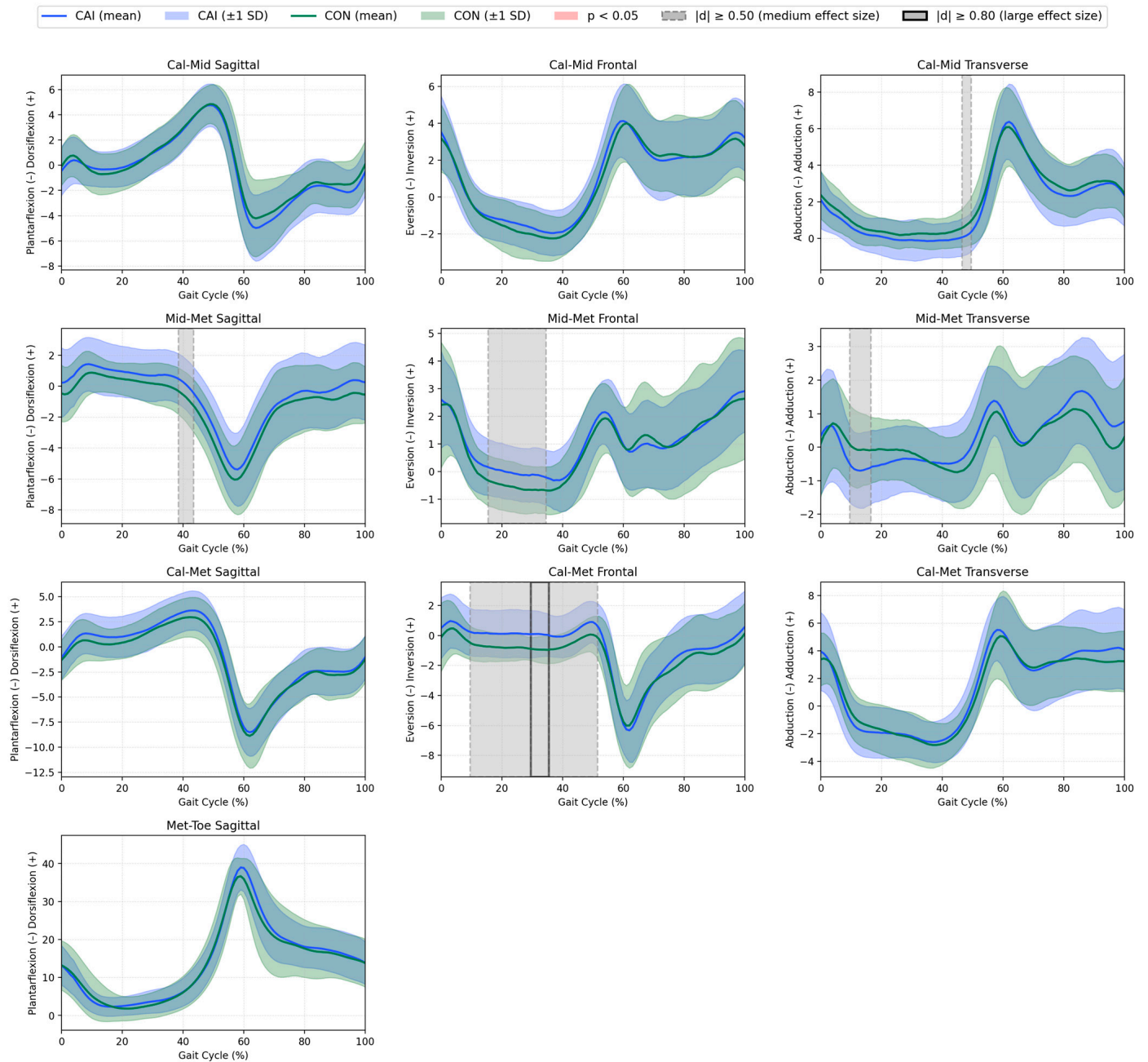


Figure 2. Mean kinematics (solid lines) ± 1 SD (shaded areas) for the CAI group (blue) and control group (green) for the Cal-Mid, Mid-Met, Cal-Met, and Met-Toe segments throughout the gait cycle (%). The gait cycles are time-normalized to 100%, with initial contact at 0% and toe-off at ~60%. Grey shading indicates medium effect sizes ($|d| \geq 0.50$), black bold outline indicates large effect sizes ($|d| \geq 0.80$), and red shading indicates statistically significant differences ($p < 0.05$) between groups, as determined by Statistical Parametric Mapping (SPM).

Sha–Cal (calcaneus relative to the shank). In the transverse plane, the CAI group demonstrated significantly greater calcaneus abduction than the CON group between 88% and 93% of the gait cycle (MD = -3.50° , 95% CI [-5.60 , -1.40], $d = -0.95$, $p = 0.037$), as indicated by red shading in Figure 1. No other statistically significant between-group differences were observed at any time point in the frontal or sagittal planes.

All other joints and segments. No statistically significant between-group differences were detected in the hip, knee, Sha–Foo (foot relative to the shank), Cal–Mid (midfoot relative to the calcaneus), Mid–Met (metatarsus relative to the midfoot), Cal–Met (metatarsus relative to the calcaneus) and Met–Toe (toe relative to the metatarsus) at any time point in the sagittal, frontal, or transverse planes. Although medium ($|d| \geq 0.50$) and large ($|d| \geq 0.80$) effect sizes were observed in some variables (as illustrated by grey shading and black outlines in Figures 1 and 2), these did not reach statistical significance in the SPM analysis.

3.3. Correlation Analysis

Data on hip strength in the CAI and CON groups were recently published [23]. In the present study, these variables were included solely as independent factors to examine their relationship with gait-related outcomes. No statistically significant correlations were found between hip abductor isometric strength and either the peak inversion angle or frontal plane ROM (i.e., the angular range between maximum inversion and maximum eversion) in the Sha–Foo or Sha–Cal segments during the gait cycle in either group. All observed correlations were weak or very weak (r ranging from -0.26 to 0.13 ; $p > 0.05$), with predominantly negative directions (Table 2).

Table 2. Correlations between hip abductor isometric strength and ankle kinematics throughout the gait cycle.

Independent Variable		Dependent Variables							
		Sha–Foo Peak Inversion		Sha–Foo F-ROM		Sha–Cal Peak Inversion		Sha–Cal F-ROM	
		CAI	CON	CAI	CON	CAI	CON	CAI	CON
Hip Abductor Isometric strength [Nm/kg]	r	−0.09	−0.23	−0.26	−0.11	0.13	−0.19	−0.03	−0.20
	p	0.68	0.28	0.22	0.60	0.52	0.37	0.88	0.33

Data are expressed as Pearson’s or Spearman’s correlation coefficients (r). p —probability of type I error; Sha–Foo—foot relative to the shank; Sha–Cal—calcaneus relative to the shank; F-ROM—frontal plane range of motion; CAI—chronic ankle instability; CON—controls.

4. Discussion

This study aimed to compare multisegmented foot and lower limb kinematics throughout the entire gait cycle between individuals with chronic ankle instability and healthy controls. Contrary to the initial hypothesis, increased inversion of the foot (Sha–Foo) or rearfoot (Sha–Cal) relative to the shank was not observed. Instead, the CAI group demonstrated greater abduction of the rearfoot during the terminal swing phase, which may reflect altered foot positioning. In addition, this study identified other non-significant but potentially interesting differences during the gait cycle as indicated by medium and large effect sizes in the knee, Sha–Foo, Sha–Cal, Cal–Mid, Mid–Met and Cal–Met. These findings may indicate that subtle alterations in segmental foot coordination in individuals with CAI are not captured by conventional single-segment foot models typically used in earlier studies. The use of a multisegmented foot model (e.g., Sha–Cal) enabled the identification of more numerous and statistically significant between-group differences in the transverse plane compared to the single-segment approach (e.g., Sha–Foo). These

differences were characterised by larger effect sizes across the gait cycle, which may underscore the greater potential of multisegmented modelling in detecting nuanced kinematic deviations associated with CAI.

To date, only a few studies have examined multisegmented foot kinematics during gait in populations with CAI and compared them to healthy individuals. Fraser et al. [13] reported only increased rearfoot inversion during midstance. Dingenen et al. [14] observed decreased foot dorsiflexion during loading response and a more inverted rearfoot during the initial swing phase in individuals with CAI. De Ridder et al. [15] reported increased rigid foot eversion from 11% to 73% of the stance phase, but no differences in the rearfoot were noted during walking in CAI participants. Results of this study did not confirm previous findings indicating neither inversion [8,9,12,13] nor eversion [15] was significantly increased in the CAI group. However, a slight tendency toward increased rearfoot eversion was reported during terminal swing phase with a medium effect size but without reaching statistical significance. These discrepancies may be explained by significant differences in foot posture between the CAI and CON groups, potentially associated with greater peak rearfoot eversion and abduction in cavus feet compared to normal or planus feet [45].

Although mean Foot Posture Index (FPI) values were classified as “normal” in both groups, the CAI group presented lower FPI scores, indicating a tendency toward a more cavus/supinated foot posture. The increased Sha–Cal abduction in the CAI group occurred primarily during the terminal swing phase, a period responsible for preparing the foot for initial contact. This pattern may reflect an altered pre-positioning strategy, potentially aimed at avoiding excessive inversion upon landing. Research suggests that inappropriate foot positioning may increase susceptibility to subsequent sprains in previously sprained ankles [46]. Such compensatory abduction could represent an attempt to stabilise the ankle joint in anticipation of ground contact, but it may also contribute to lateral foot strike or uneven loading during heel contact. This pre-positioning strategy may depend on swing-phase muscle modulation in response to the mechanical state of the contralateral leg, which represents a control mechanism potentially altered in individuals with impaired neuromuscular control [47]. Biomechanically, the tibialis posterior muscle eccentrically controls excessive rearfoot eversion and abduction. Although its peak activity occurs during the stance phase [48], coordination with the peroneus longus and brevis muscles is responsible for foot alignment in the frontal and transverse planes throughout the swing phase of gait [49]. While dysfunction of the tibialis posterior may potentially be present in individuals with CAI, no studies to date have directly linked it with CAI or LAS during gait. Available research on muscle strength has only reported significant deficits in invertor concentric torque [50] and in eccentric everter–invertor strength ratios [51].

While only the Sha–Cal segment in the transverse plane showed a statistically significant difference between groups, several other variables exhibited medium-to-large effect sizes. Although these differences did not reach statistical significance in the SPM analysis and should therefore be interpreted with caution, they may reflect subtle biomechanical deviations associated with CAI. These trends included greater knee abduction in the frontal plane, foot abduction in the transverse plane, rearfoot eversion in the frontal plane, midfoot abduction in the transverse plane, and forefoot dorsiflexion, abduction, and inversion in the sagittal, transverse, and frontal planes, respectively, in the CAI group compared to controls and were observed during both the stance and swing phases of gait. Similar alterations in forefoot kinematics have been reported by De Ridder et al. [15], who found increased medial forefoot inversion from 87% to 98% of the stance phase in individuals with CAI with a mean difference (MD) of 9.42°. In the present study, increased inversion was observed in the Mid–Met and Cal–Met segments during comparable phases of gait, albeit with smaller mean differences. Methodological differences between studies, such

as dividing the forefoot into two segments rather than a single segment and the absence of static posture normalisation in the previous work, may partially explain the discrepancies in magnitude. One possible explanation for these inversion trends could involve altered muscle function, such as impaired peroneus longus activity [52–54], or changes in rearfoot–forefoot biomechanical coupling, which have been proposed in previous CAI research. If confirmed, such deviations could alter the position of the forefoot, potentially affecting foot loading patterns and contributing to the risk of recurrent ankle sprains, and may therefore be clinically relevant. These observations could also inform rehabilitation strategies targeting forefoot positioning and control and warrant further investigation with larger sample sizes or under different locomotor conditions.

In this study, hip and knee kinematics were also assessed alongside multisegmented foot motion to verify whether potential impairments in the foot–ankle region might be associated with alterations in proximal lower-limb joints. No significant differences were observed in proximal joint kinematics, which is consistent with the findings of most previous studies [10,11]. Increased knee abduction in the frontal plane, which was not statistically significant but demonstrated a medium effect size, was observed in the CAI group compared to controls. However, this deviation may correspond to rearfoot findings during terminal swing, as it occurred at the same point in the gait cycle. Frontal-plane knee motion may influence rearfoot positioning through lower-limb joint coupling [55]. Only the study by Koldenhoven et al. [16] reported greater hip adduction during the swing phase in individuals with CAI, possibly linked to more inverted ankle positioning at initial contact. Nevertheless, the present findings did not support this result.

The secondary aim of this study was to evaluate the relationship between hip abductor strength and ankle kinematics during walking. Although the initial hypothesis predicted moderate negative correlations between isometric hip abductor strength and both peak inversion and frontal plane range of motion in the Sha–Foo and Sha–Cal segments, it was not confirmed. Correlations ranged from very weak to weak, were predominantly negative in direction, but were not statistically significant in either the CAI or CON groups. This may suggest that no meaningful association exists between hip abductor strength and frontal plane ankle kinematics or that any potential relationship is not linear. Interestingly, in our previous study [23], we observed a significant association between hip abductor strength and self-reported instability and dynamic balance performance in individuals with CAI, which is not reflected in the current findings. Based on current scientific evidence, the role of the hip abductor in CAI may be more closely related to variable postural control strategies [28,56]. However, as this is the first study to attempt to link hip strength with ankle movement during gait in individuals with CAI, further research is warranted to verify these findings.

The results of this study have important clinical implications. Gait training interventions may improve biomechanical outcomes, such as optimising plantar pressure distribution or increasing peroneus longus activity in individuals with CAI [57]. Gait retraining may also reduce rearfoot eversion [58], particularly when associated with a decreased foot progression angle [59]. Based on our findings, exercises aimed at controlling rearfoot abduction may be beneficial. These may include swing phase control drills using visual or auditory biofeedback to improve foot positioning during gait. In addition, implementing other interventions aimed at enhancing tibialis posterior and peroneus longus function, such as resistance training, may be justified [60,61]. In this context, progressive strengthening of foot and ankle stabilisers (e.g., banded eversion and inversion exercises), as well as eccentric strengthening, endurance training, and balance activities performed on inclined platforms, where foot position sense can also be challenged and trained, may be particularly effective in improving muscle function and foot mechanics in individuals with CAI.

Moreover, it has been speculated that optimal coordination between invertor and evtor muscles may influence rearfoot, midfoot, and forefoot positioning during walking [49].

The current study also has several limitations. Only males with CAI were included in order to minimise sex-specific differences in gait performance [62]. Thus, caution is warranted when generalising the results to females with CAI. Limb dominance, which may potentially affect study outcomes, was controlled by matching the dominance status of the tested limb between groups, resulting in the same proportion of dominant and non-dominant limbs in the CAI and control groups. Therefore, it was unlikely to have influenced the results. As all joint angles were normalised to a static standing trial, the observed changes represent deviations from each participant's neutral position, rather than absolute segment orientations. Since the CAI group demonstrated significantly different foot posture compared to controls, these functional differences should be interpreted cautiously, as they may be influenced by initial alignment. Further discussion is warranted regarding when and how to normalise foot kinematic data in light of morphological variability between individuals. In the literature, angles have been reported as non-normalised values, or normalised either to a quiet standing trial or to a defined "neutral" foot position. This distinction is important, as each approach may produce different outcomes [63]. Therefore, future studies should aim to establish clear guidelines on how multisegmented foot kinematics should be presented in the CAI population. Although possible muscle activity was speculated based on kinematic patterns, electromyographic (EMG) data were not collected and marker placement reliability was not assessed, which limits direct conclusions about neuromuscular control and may affect the accuracy of kinematic measurements. Despite the fact that multisegmented foot models provide a more detailed representation of foot motion, they may also be more susceptible to measurement errors, which can constitute a limitation of this approach. Anatomical marker misplacement and soft tissue artifacts are considered the two main sources of measurement error that can affect segment coordinate systems and, consequently, joint kinematics. These errors are particularly relevant in multisegmented foot kinematics, where inter-marker distances are much smaller than in proximal body segments [40,64]. The correlation analyses between hip strength and frontal plane ankle kinematics were performed separately within each group to account for potentially different underlying mechanisms. However, they may have been underpowered to detect small-to-moderate correlations ($r < 0.5$). Therefore, these results should be interpreted with caution and confirmed in future studies with larger samples and sufficient statistical power.

5. Conclusions

Males with CAI demonstrated greater rearfoot abduction in the transverse plane during the terminal swing phase of the gait cycle compared to healthy controls. No significant differences were observed in other foot segments as well as in proximal lower limb kinematics, including those of the hip and knee. The use of a multisegmented foot model may support the identification of subtle segment-to-segment interactions that could underlie functional impairments associated with CAI. The exclusion of swing phase analysis in multisegmented foot kinematics, as seen in much of the current literature, appears unjustified, as this study highlights its potential value in enhancing our understanding of foot–ankle complex function in individuals with CAI. The results of this study may support clinical practice, particularly in gait assessment and rehabilitation planning. Specifically, they encourage clinicians to consider the role of all foot segments and the entire lower limb, rather than focusing solely on the ankle joint during examination and intervention design. This broader perspective may lead to more comprehensive rehabilitation strategies that address altered foot segment coordination and improve functional gait outcomes in

individuals with CAI. Lastly, no significant relationships were found between isometric hip abductor strength and frontal plane ankle kinematics during walking. This may suggest that the potential beneficial role of hip strength in individuals with CAI operates through alternative mechanisms, which should be further explored in future research.

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Data Availability Statement: The datasets used and analysed in this study are available from the corresponding author upon reasonable request.

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Abbreviations

BMI	Body Mass Index
CAI	Chronic Ankle Instability
CAIT-PL	The Polish version of the Cumberland Ankle Instability Tool
CON	Control group/Controls
CoM	Centre of Mass
Cal-Met	Metatarsus (forefoot) relative to the calcaneus (rearfoot)
<i>d</i>	Cohen’s <i>d</i> (effect size)
EMG	Electromyographic
FPI	Foot Posture Index
F-ROM	Frontal Plane Range of Motion
ICC	Intraclass Correlation Coefficient
LAS	Lateral Ankle Sprain
MD	Mean Difference
Met-Toe	Toe relative to the metatarsus
Mid-Met	Metatarsus (forefoot) relative to the midfoot
PL	Peroneus Longus
ROM	Range of Motion
Sha-Cal	Calcaneus (rearfoot) relative to the shank
Sha-Foo	Foot in relation to the shank
SD	Standard Deviation
SPM	Statistical Parametric Mapping

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5. Podsumowanie

Podsumowując, przeprowadzone badania, zaprezentowane w postaci cyklu trzech publikacji naukowych, pozwoliły scharakteryzować istniejące deficyty w populacji z przewlekłą niestabilnością stawu skokowo-goleniowego. Na ich podstawie określono potencjalną rolę siły mięśni obręczy biodrowej w ocenie klinicznej, funkcjonalnej i biomechanicznej CAI. Każda z publikacji stanowiła istotny wkład w realizację kolejnych etapów badań, a w konsekwencji przyczyniła się do osiągnięcia głównego celu niniejszej rozprawy doktorskiej. Publikacja nr 1 stanowiła fundament do rozpoczęcia dalszych badań nad CAI, zgodnie z międzynarodowymi kryteriami ustalonymi przez International Ankle Consortium. W jej ramach opracowano i zwalidowano pierwsze polskojęzyczne narzędzie specyficzne do oceny stopnia nasilenia funkcjonalnej niestabilności stawu skokowo-goleniowego (CAIT-PL). Narzędzie to wypełniło istotną lukę diagnostyczną i może być szeroko wykorzystywane w praktyce klinicznej oraz w badaniach naukowych obejmujących polską populację z CAI. Publikacja nr 2 była centralnym punktem przeprowadzonych badań, gdyż pozwoliła precyzyjnie określić wartości momentów sił mięśni obręczy biodrowej w warunkach izometrycznych i izokinetycznych u osób z CAI. Ponadto scharakteryzowano istniejące zależności między momentami siły odwodzicieli stawu biodrowego a równowagą dynamiczną i subiektywnie zgłaszaną niestabilnością stawu skokowo-goleniowego. Wyniki tej pracy zostały następnie uwzględnione w pierwszej metaanalizie dotyczącej siły mięśni obręczy biodrowej u osób z CAI [27], która wykazała deficyty izometrycznej siły mięśni odwodzicieli i prostowników stawu biodrowego, przy jednoczesnym braku obniżenia siły w badaniach izokinetycznych. Nasze badanie zostało włączone do 5 z 8 analiz, a w 3 przypadkach było jedną z zaledwie dwóch prac, co podkreśla jego znaczenie i wskazuje na istotny wkład w rozwój wiedzy oraz tworzenie najwyższej jakości dowodów naukowych w tym obszarze. W publikacji nr 3 określono zaburzenia biomechaniczne podczas cyklu chodu u osób z CAI w porównaniu z grupą kontrolną. Wartości izometrycznego momentu siły mięśni odwodzicieli stawu biodrowego wykorzystano do analizy ich potencjalnych związków z kinematyką stawu skokowo-goleniowego. Nie okazały się one istotne statystycznie, co może sugerować, że zależność nie istnieje lub nie ma charakteru liniowego, a potencjalna korzystna rola siły mięśni obręczy biodrowej obejmuje inne mechanizmy związane ze strategiami kontroli nerwowo-mięśniowej. Podkreśla to potrzebę dalszej eksploracji roli siły mięśni obręczy biodrowej w CAI, szczególnie w przyszłych badaniach interwencyjnych aplikujących uzyskane wyniki w programach terapeutycznych. W długoterminowej perspektywie pozwoli to umocnić

i scharakteryzować rolę siły mięśni obręczy biodrowej we współczesnej nauce i praktyce klinicznej, podobnie jak miało to miejsce w leczeniu zespołu bólu rzepkowo-udowego. Należy pamiętać, że przeprowadzone badania mają zarówno mocne strony, jak i pewne ograniczenia. Ich atutem było zastosowanie nowoczesnych metod oceny, natomiast ograniczenia dotyczyły jednorodności badanych prób, przekrojowego charakteru analiz oraz wybranych aspektów metodologicznych. Szczegółowe omówienie ograniczeń zawarto w pełnych tekstach poszczególnych publikacji.

6. Wnioski

Poniżej przedstawiono wnioski, które są odpowiedziami na postawione pytania badawcze:

1. Polska wersja narzędzia Cumberland Ankle Instability Tool (CAIT-PL) jest rzetelnym i trafnym narzędziem do oceny stopnia nasilenia przewlekłej niestabilności stawu skokowo-goleniowego.
2. Osoby z przewlekłą niestabilnością stawu skokowo-goleniowego wykazywały niższy stosunek izometrycznego momentu siły odwodzicieli do przywodzicieli w porównaniu z grupą kontrolną. Nie odnotowano innych istotnych statystycznie różnic między grupami w zakresie momentów sił mięśni obręczy biodrowej mierzonych w warunkach izometrycznych oraz izokinetycznych.
3. Zaobserwowano dodatnie związki między momentami siły mięśni odwodzicieli stawu biodrowego a równowagą dynamiczną oraz subiektywnie zgłaszaną niestabilnością stawu skokowo-goleniowego.
4. Osoby z przewlekłą niestabilnością stawu skokowo-goleniowego wykazywały zwiększone odwiedzenie tyłostopia w płaszczyźnie poprzecznej podczas końcowej fazy przenoszenia cyklu chodu w porównaniu z grupą kontrolną. Nie zaobserwowano istotnych różnic w pozostałych segmentach stopy ani w innych płaszczyznach jej ruchu, a także w zakresie kinematyki stawu skokowo-goleniowego, biodrowego i kolanowego.
5. Nie stwierdzono istotnych związków między izometrycznym momentem siły mięśni odwodzicieli stawu biodrowego a kinematyką stawu skokowo-goleniowego u osób z przewlekłą niestabilnością tego stawu.

7. Zastosowania aplikacyjne

1. Polska wersja narzędzia Cumberland Ankle Instability Tool (CAIT-PL) może być stosowana w celach klinicznych i badawczych do oceny stopnia nasilenia funkcjonalnej niestabilności stawu skokowo-goleniowego w polskojęzycznej populacji.
2. Ocena momentów siły mięśni obręczy biodrowej w populacji z przewlekłą niestabilnością stawu skokowo-goleniowego powinna stanowić element kompleksowej diagnostyki funkcjonalnej w tej grupie pacjentów. Na podstawie wyników niniejszej pracy i dostępnych dowodów naukowych zaleca się wykonywanie tej oceny w warunkach izometrycznych, ponieważ pozwala ona zidentyfikować więcej zaburzeń niż ocena w warunkach izokinetycznych.
3. Interwencje ukierunkowane na zwiększenie momentu siły mięśni odwodźcicieli stawu biodrowego mogą przyczynić się do poprawy stanu funkcjonalnego pacjentów z CAI, w szczególności równowagi dynamicznej oraz subiektywnie ocenianej stabilności stawu skokowo-goleniowego.
4. Podczas oceny wielosegmentowej kinematyki stopy analiza fazy przenoszenia cyklu chodu może dostarczyć dodatkowych informacji biomechanicznych. Brak jest uzasadnionych powodów, dla których w większości prac naukowych faza ta jest pomijana, a autorzy koncentrują się wyłącznie na fazie podporu.
5. Interwencje skupione na poprawie pozycjonowania stopy podczas chodu mogą być zasadne w celu optymalizacji biomechaniki kompleksu stopy i stawu skokowo-goleniowego u pacjentów z CAI.
6. Rola siły mięśni obręczy biodrowej w przewlekłej niestabilności stawu skokowo-goleniowego prawdopodobnie bazuje na mechanizmach związanych z funkcjonalnymi strategiami kontroli nerwowo-mięśniowej. Nie stwierdzono zależności wskazujących na bezpośredni biomechaniczny potencjał tych mięśni w ograniczaniu nadmiernych ruchów stawu skokowo-goleniowego podczas chodu.
7. Wskazane są dalsze badania eksperymentalne aplikujące wyniki niniejszej rozprawy. W szczególności należy zweryfikować, czy dodanie ćwiczeń wzmacniających mięśnie obręczy biodrowej do interwencji uznawanych za złoty standard w leczeniu CAI, takich jak trening równowagi, zapewnia pacjentom dodatkowe korzyści kliniczne, funkcjonalne i biomechaniczne.

8. Streszczenie

Urazy skrętne stawu skokowo-goleniowego w mechanizmie inwersyjnym (LAS) należą do najczęstszych uszkodzeń mięśniowo-szkieletowych u osób młodych i aktywnych fizycznie, stanowiąc 25–30% wszystkich kontuzji sportowych. Brak odpowiedniego leczenia pierwszorazowego LAS może zwiększać ryzyko kolejnych skręceń i progresji do przewlekłej niestabilności stawu skokowo-goleniowego (CAI), która rozwija się u około 46% osób po pierwszym LAS. Głównymi objawami CAI są nawracające skręcenia, epizody „uciekania” stawu oraz subiektywne poczucie niestabilności. Według przeglądów systematycznych najskuteczniejsze leczenie zachowawcze obejmuje trening nerwowo-mięśniowy i trening równowagi. Jednak wciąż brakuje jednoznacznych dowodów na zmniejszenie częstości nawracających urazów skrętnych stawu skokowo-goleniowego. Protokoły rehabilitacyjne często pomijają proksymalne elementy łańcucha kinematycznego, co może ograniczać ich skuteczność. W tym kontekście celem pracy było zbadanie roli siły mięśni obręczy biodrowej w CAI z uwzględnieniem oceny klinicznej, funkcjonalnej i biomechanicznej.

Niniejsza rozprawa doktorska obejmuje cykl trzech publikacji naukowych. W pierwszej publikacji opracowano i zaadaptowano do realiów polskiej kultury narzędzie Cumberland Ankle Instability Tool (CAIT-PL), a następnie oceniono jego właściwości psychometryczne zgodnie ze standardami COSMIN. W drugiej publikacji porównano wartości momentów siły mięśni obręczy biodrowej w warunkach izometrycznych i izokinetycznych, analizując także powiązania między tymi zmiennymi a równowagą dynamiczną oraz subiektywnie zgłaszaną niestabilnością. W trzeciej publikacji oceniono kinematykę stopy, stawu skokowo-goleniowego, kolanowego i biodrowego podczas chodu, z wykorzystaniem wielosegmentowego modelu stopy (MFM), a także potencjalne związki kinematyki stawu skokowo-goleniowego z momentem siły mięśni odwodzicieli stawu biodrowego.

Narzędzie CAIT-PL uzyskało odpowiednią rzetelność i trafność, potwierdzając jego przydatność kliniczną i badawczą. U mężczyzn z CAI stwierdzono obniżony stosunek momentu siły odwodzicieli do przywodzicieli oraz gorsze wyniki równowagi dynamicznej. Wykazano także umiarkowane dodatnie korelacje pomiędzy momentem siły odwodzicieli stawu biodrowego a równowagą dynamiczną i subiektywnie zgłaszaną niestabilnością. Analiza chodu wykazała zwiększone odwiedzenie tyłostopia w płaszczyźnie poprzecznej w końcowej fazie przenoszenia, bez istotnych różnic w pozostałych segmentach stopy ani w kinematyce stawów proksymalnych. Nie stwierdzono korelacji między momentem siły mięśni odwodzicieli stawu biodrowego a kinematyką stawu skokowo-goleniowego.

Wyniki wskazują, że CAIT-PL jest rzetelnym i trafnym narzędziem diagnostycznym i badawczym w populacji polskojęzycznej. Moment siły mięśni odwodźcicieli stawu biodrowego ma związek z równowagą dynamiczną i subiektywnie odczuwaną niestabilnością, co podkreśla jego znaczenie w ocenie klinicznej i funkcjonalnej. Zmienione wzorce kinematyczne stopy potwierdzają potrzebę kompleksowej analizy biomechanicznej całej kończyny dolnej. Uzyskane wyniki podkreślają wagę uwzględnienia siły mięśni obręczy biodrowej w diagnostyce i terapii CAI, a dalsze badania interwencyjne mogą potwierdzić jej rolę w procesach rehabilitacyjnych. W długoterminowej perspektywie pozwoli to lepiej scharakteryzować i ugruntować znaczenie siły mięśni obręczy biodrowej w nauce i praktyce klinicznej, podobnie jak ma to miejsce w leczeniu zespołu bólu rzepkowo-udowego.

9. Abstract

Lateral ankle sprains (LAS) are among the most common musculoskeletal injuries in young and physically active individuals, accounting for 25–30% of all sports-related injuries. Inadequate treatment of a first-time LAS may increase the risk of recurrent sprains and progression to chronic ankle instability (CAI). CAI develops in approximately 46% of individuals who have experienced an initial LAS. The main symptoms of CAI include recurrent ankle sprains, repeated episodes of the ankle “giving way”, and subjective feelings of instability. According to systematic reviews, the most effective conservative treatment strategies for CAI are neuromuscular training and balance training. Nevertheless, there is still no conclusive evidence for reducing the incidence of recurrent ankle sprains. Existing rehabilitation protocols often neglect the proximal elements of the lower limb and pelvic kinetic chain, which may limit their effectiveness. In this context, the main aim of the dissertation was to investigate the role of hip muscle strength in CAI, considering clinical, functional, and biomechanical aspects.

This doctoral dissertation comprises a series of three thematically related scientific publications addressing the main objective. In the first stage, the Cumberland Ankle Instability Tool was adapted to the Polish cultural context (CAIT-PL) to assess the severity of functional ankle instability. Its psychometric properties were then evaluated in accordance with COSMIN standards. In subsequent stages, males with CAI and healthy controls were examined. The second publication compared isometric and isokinetic hip muscle strength values as well as dynamic balance, and analyzed potential associations between hip strength, dynamic balance, and self-reported instability in the CAI group. The third publication assessed foot, ankle, knee, and hip kinematics during the gait cycle, using a multisegmented foot model (MFM), and explored potential associations between ankle kinematics and hip abductor strength.

The CAIT-PL demonstrated satisfactory reliability and validity, confirming its clinical and research applicability in the Polish-speaking CAI population. In males with CAI, a reduced hip abductor/adductor strength ratio and poorer dynamic balance performance were observed, along with moderate positive correlations between hip abductor strength, dynamic balance, and self-reported instability. In gait analysis using MFM, males with CAI exhibited increased transverse-plane abduction of the rearfoot during the terminal swing phase, without significant differences in other foot segments or proximal joints. No significant correlations were found between hip abductor strength and ankle kinematics.

These findings indicate that the Polish version of the CAIT-PL is a reliable and valid tool for assessing the severity of functional ankle instability and can be effectively used in both research and clinical practice. Hip abductor strength is associated with dynamic balance and self-reported instability, highlighting its importance in the clinical and functional assessment of CAI. Altered foot kinematic patterns during gait, identified with MFM, confirm the need for a comprehensive biomechanical evaluation of the entire lower limb in this population. The findings emphasize the importance of incorporating hip muscle strength into diagnostic and therapeutic processes in CAI. However, further research is warranted to explore the role of hip muscle strength in CAI, particularly in interventional studies applying these results to rehabilitation programs. In the long term, this may help better define and establish the role of hip muscle strength in scientific literature and clinical practice, similar to the progress achieved in the management of patellofemoral pain syndrome.

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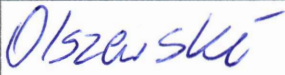
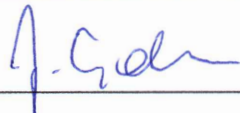
11. Załączniki

1. Oświadczenie o wkładzie w powstawaniu publikacji nr 1 (str. 70)
2. Oświadczenie o wkładzie w powstawaniu publikacji nr 2 (str. 71)
3. Oświadczenie o wkładzie w powstawaniu publikacji nr 3 (str. 72)
4. Zgoda komisji bioetycznej na przeprowadzenie badań (str. 73–74)

Oświadczenie o wkładzie w powstawaniu publikacji

Oświadczenie dotyczy publikacji:

Olszewski, M.; Zając, B.; Golec, J. Cross Cultural Adaptation, Reliability and Validity of the Polish Version of the Cumberland Ankle Instability Tool. Disabil Rehabil 2024, 46, 2926–2932, doi:10.1080/09638288.2023.2232719.

L.p.	Imię i Nazwisko	Wkład procentowy	Podpis współautora
1.	mgr Maciej Olszewski	60%	
2.	mgr Bartosz Zając	30%	
3.	prof. dr hab. Joanna Golec	10%	

Wkład opisowy współautorów:

Maciej Olszewski: przygotowanie manuskryptu – przygotowanie wersji oryginalnej, przegląd i edycja; wizualizacja, walidacja, oprogramowanie, zasoby, administracja projektu, metodologia, badania, pozyskiwanie funduszy, analiza formalna, opracowanie danych, konceptualizacja.

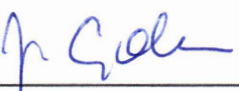
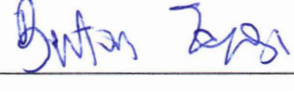
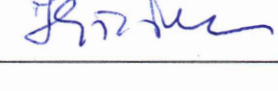
Bartosz Zając: przygotowanie manuskryptu – przygotowanie wersji oryginalnej, przegląd i edycja; walidacja, oprogramowanie, metodologia, badania, analiza formalna, opracowanie danych, konceptualizacja.

Joanna Golec: przygotowanie manuskryptu – przegląd i edycja, nadzór, administracja projektu, metodologia, pozyskiwanie funduszy, konceptualizacja.

Oświadczenie o wkładzie w powstawaniu publikacji

Oświadczenie dotyczy publikacji:

Olszewski, M.; Golec, J.; Zając, B.; Kręzątek, P. Isometric and Isokinetic Hip Strength in Males with Chronic Ankle Instability and Its Relationship with Dynamic Balance and Self-Reported Instability. Physical Therapy in Sport 2025, 72, 9–17, doi:10.1016/j.ptsp.2024.12.007.

L.p.	Imię i Nazwisko	Wkład procentowy	Podpis współautora
1.	mgr Maciej Olszewski	65%	
2.	prof. dr hab. Joanna Golec	20%	
3.	mgr Bartosz Zając	10%	
4.	dr Piotr Kręzątek	5%	

Wkład opisowy współautorów:

Maciej Olszewski: przygotowanie manuskryptu – przygotowanie wersji oryginalnej, przegląd i edycja; wizualizacja, walidacja, oprogramowanie, zasoby, administracja projektu, metodologia, badania, pozyskiwanie funduszy, analiza formalna, opracowanie danych, konceptualizacja.

Joanna Golec: przygotowanie manuskryptu – przegląd i edycja, nadzór, administracja projektu, metodologia, konceptualizacja.

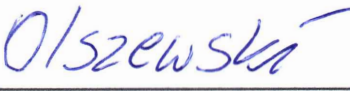
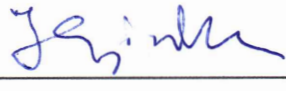
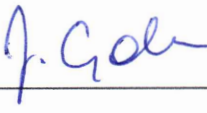
Bartosz Zając: przygotowanie manuskryptu – przegląd i edycja, oprogramowanie, metodologia, badania, opracowanie danych.

Piotr Kręzątek: przygotowanie manuskryptu – przegląd i edycja, nadzór, metodologia, opracowanie danych, konceptualizacja.

Oświadczenie o wkładzie w powstawaniu publikacji

Oświadczenie dotyczy publikacji:

Olszewski, M.; Kręzątek, P.; Golec, J. Multisegmented Foot and Lower Limb Kinematics During Gait in Males with Chronic Ankle Instability: Exploring Links with Hip Abductor Strength. J Clin Med 2025, 14, 5977, doi:10.3390/jcm14175977

L.p.	Imię i Nazwisko	Wkład procentowy	Podpis współautora
1.	mgr Maciej Olszewski	55%	
2.	dr Piotr Kręzątek	33%	
3.	prof. dr hab. Joanna Golec	12%	

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Maciej Olszewski: przygotowanie manuskryptu – przygotowanie wersji oryginalnej, przegląd i edycja; wizualizacja, walidacja, oprogramowanie, zasoby, administracja projektu, metodologia, badania, analiza formalna, opracowanie danych, konceptualizacja, pozyskiwanie funduszy.

Piotr Kręzątek: przygotowanie manuskryptu – przygotowanie wersji oryginalnej, przegląd i edycja; wizualizacja, walidacja, oprogramowanie, metodologia, badania, analiza formalna, opracowanie danych, zasoby, konceptualizacja.

Joanna Golec: przygotowanie manuskryptu – przegląd i edycja; nadzór, metodologia, konceptualizacja, pozyskiwanie funduszy.



Komisja Bioetyczna
przy Okręgowej Izbie Lekarskiej
w Krakowie

Nr 11/KBL/OIL/2022 z dnia 11 lutego 2022 r.

Na posiedzeniu w dniu 11 lutego 2022 r. Komisja zapoznała się z wnioskiem (dokumentacja w załączeniu) złożonym przez :

Koordinator Badania: mgr Maciej Olszewski

Akademia Wychowania Fizycznego, Szkoła Doktorska, Al. Jana Pawła II 78, 31-571 Kraków

Tytuł badania: Ocena związku wydolności mięśni obręczy biodrowej z funkcją kompleksu stawu skokowo- goleniowego i stopy u osób z przewlekłą niestabilnością stawu skokowo-goleniowego

Do wniosku dołączono:

- Wniosek w sprawie wyrażenia zgody na przeprowadzenie eksperymentu medycznego
- Protokół badania
- Streszczenie protokołu
- Życiorys głównego badacza
- Informacja dla pacjenta
- Formularz Świadomej Zgody Pacjenta z klauzulą o „Ochronie Danych Osobowych”
- Kserokopia polisy ubezpieczeniowej OC lekarza nadzorującego badanie
- Kserokopia polisy ubezpieczeniowej Ośrodka, w którym będzie realizowane badanie
- Zgoda Dyrektora jednostki na przeprowadzenie badań.

Komisja wyraża zgodę na przeprowadzenia badania na warunkach przedstawionych we wniosku.

Zgoda Komisji dla Ośrodka jest ważna do dnia ważności Polisy Ubezpieczeniowej Skład i działanie Komisji zgodne z zasadami Dobrej Praktyki Klinicznej (GCP) oraz wymogami lokalnymi

Lista członków Komisji biorących udział w posiedzeniu stanowi załącznik do niniejszego dokumentu.

Pouczenie: W ciągu 14 dni od otrzymania niniejszej opinii Wnioskodawcy przysługuje prawo odwołania do Komisji Odwoławczej za pośrednictwem Komisji Bioetycznej przy OIL w Krakowie

Kraków, dnia 25.02.2022 r.

**Przewodniczący Komisji Bioetycznej
przy OIL w Krakowie**

Dr Mariusz Janikowski



Komisja Bioetyczna
przy Okręgowej Izbie Lekarskiej
w Krakowie

Lista obecności członków Komisji Bioetycznej
przy Okręgowej Izbie Lekarskiej w Krakowie
na posiedzeniu w dniu 11 lutego 2022r.

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I Klinika Chorób Wewnętrznych i Gerontologii
Szpitala Uniwersyteckiego w Krakowie

mgr Jerzy Bilek

mgr farmacji

ks. dr hab. Jerzy Brusilo

Uniwersytet Papieski Jana Pawła II
duchowny, etyk

dr Mirosława Noppenberg

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SPZOZ im. Śniadeckiego w Nowym Sączu

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prof. dr hab. med. Zbigniew Kojs

specjalista ginekologii i położnictwa
Szpital Specjalistyczny im. L. Rydygiera Krakowie

Lek. dent. Dariusz Kościelniak

Specjalista stomatologii ogólnej i ortodoncji
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prof. dr hab. Janusz Raglewski

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