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Lower Limb Biomechanics During Drop-Jump Landings on Challenging Surfaces in Individuals With Chronic Ankle Instability

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Context: Individuals with chronic ankle instability (CAI) exhibit impaired lower limb biomechanics during unilateral drop-jump landings on a flat surface. However, lower limb biomechanical adaptations during unilateral drop-jump landings on more challenging surfaces, such as those that are unstable or inclined, have not been described.

Objective: To determine how unilateral drop-jump landing surfaces (flat, unstable, and inclined) influence lower limb electromyography, kinematics, and kinetics in individuals with CAI.

Design: Descriptive laboratory study.

Setting: Biomechanics laboratory.

Patients or Other Participants: A total of 22 young adults (age = 24.9 ± 4.9 years, height = 1.68 ± 0.08 m, mass = 70.6 ± 11.4 kg) with CAI.

Intervention(s): Participants completed 5 trials each of unilateral drop-jump landings on a flat surface (DROP), an unstable surface (FOAM), and a laterally inclined surface (WEDGE).

Main Outcome Measure(s): Electromyography of the gluteus medius, vastus lateralis, gastrocnemius medialis, peroneus longus, and tibialis anterior muscles was recorded. Ankle and knee angles and moments were calculated using a 3-dimensional motion-analysis system and a force plate. Biomechanical variables were compared among tasks using 1-dimensional statistical nonparametric mapping.

Results: During DROP, greater ankle-dorsiflexion and knee-extension moments were observed than during FOAM and WEDGE and greater vastus lateralis muscle activity was observed than during FOAM. Greater ankle-inversion and plantar-flexion angles were noted during FOAM and WEDGE than during DROP. Peroneus longus muscle activity was greater during DROP than during FOAM. During FOAM, greater ankle-inversion and knee-extension angles and ankle-inversion and internal-rotation moments, as well as less peroneus longus muscle activity, were present than during WEDGE.

Conclusions: The greater ankle-inversion and plantar-flexion angles as well as the lack of increased peroneus longus muscle activation during the FOAM and WEDGE conditions could increase the risk of recurrent lateral ankle sprain in individuals with CAI. These findings improve our understanding of the changes in lower limb biomechanics when landing on more challenging surfaces and will help clinicians better target deficits associated with CAI during rehabilitation.

Key Words: electromyography, kinematics, kinetics, neuromechanics

Key Points

- Participants with chronic ankle instability landed on unstable and laterally inclined surfaces with greater ankle-inversion angles but without changes in peroneus longus muscle activity, which could predispose them to sustain recurrent lateral ankle sprains.
- Greater plantar-flexion angles during tasks on more challenging unstable and laterally inclined surfaces represented a more vulnerable position for individuals with chronic ankle instability.

Lateral ankle sprain (LAS) is a common lower limb musculoskeletal injury in sports populations, representing >15% of all injuries in National Collegiate Athletic Association athletes.[1] It is frequent in sports involving running and repetitive jump-landing movements, such as volleyball and basketball.[2] Approximately 40% of individuals who sustain an LAS will develop chronic ankle instability (CAI).[3] According to the Hertel and Corbett[4] model, individuals with CAI exhibit a spectrum of motor-behavioral, sensory-perceptual, and pathomechanical impairments after the initial LAS. Also, CAI is characterized by a propensity for recurrent LAS at least 1 year after the index LAS and persistent symptoms such as pain, recurrent episodes of the ankle giving way, swelling, limited motion, weakness, and diminished self-reported function.[4] These impairments place individuals with CAI at more risk of developing long-term joint degenerative sequelae, such as posttraumatic ankle osteoarthritis,[5] and decreased physical activity levels[6] and health-related quality of life.[7]

Altered biomechanics of the lower limbs during high-velocity sport-specific movements, such as landing from a jump, could contribute to episodes of the ankle giving way and recurrent LAS in individuals with CAI. These jump-landing tasks have been commonly reported by previous researchers[8] who quantified biomechanical deficits in CAI, which impose large and rapid impulse loads to the ankle complex that could initiate the mechanism of LAS. During a unilateral drop-jump landing on a flat surface (DROP), individuals with CAI exhibited greater ankle-dorsiflexion angles,[9,10] ankle-inversion angles,[11] and knee-flexion angles[9] as well as less peroneus longus[11,12] and vastus lateralis[13] muscle activity (prelanding) than healthy individuals. During landing on more challenging surfaces, such as those that are unstable[13] or inclined,[13–15] altered lower limb biomechanics could place individuals with CAI at a greater risk of sustaining recurrent LASs. Indeed, investigators who quantified lower limb biomechanics during unilateral drop-jump landings on an inclined surface (WEDGE) showed longer peroneus longus activation latency,[14,15] reduced peroneus longus activation,[13,15,16] reduced gluteus medius muscle activation,[13] and greater ankle-inversion angles[14,15,17] in individuals with CAI than their healthy counterparts. During a unilateral drop-jump landing on an unstable surface (FOAM), greater ankle-dorsiflexion angles were reported in participants with CAI.[13] Researchers have focused on the analysis of the lower limb biomechanical differences between individuals with CAI and their healthy counterparts during the DROP, FOAM, and WEDGE conditions. However, no one has determined how the biomechanics of the lower limb of individuals with CAI change when they land on different surfaces. Better understanding of the lower limb changes that occur when individuals with CAI land on different surfaces will help clinicians identify biomechanical risk factors that could predispose them to sustain recurrent LASs during sports involving jump landings.

The purpose of our study was to identify lower limb electromyographic (EMG), kinematic, and kinetic differences in individuals with CAI among DROP, FOAM, and WEDGE. We hypothesized that, based on the previously described feed-forward alterations in individuals with CAI, they would exhibit greater ankle-inversion angles and no changes in peroneus longus muscle activation during FOAM and WEDGE compared with those during DROP.

METHODS

Participants

Twenty-two participants with CAI were recruited to take part in this cross-sectional, laboratory-based study (Table). This study is a secondary analysis of a subcohort of participants from earlier studies.[13,18] Participants who allowed their data to be kept in a database and used in other projects were included. Patient characteristics including age, height, mass, number of sustained sprains, the time since the first and last sprains, and the frequency of episodes of ankle giving way were registered before experimentation (Table). As no one has investigated the unilateral drop-jump biomechanics on different challenging surfaces in participants with and those without CAI, we could not calculate an a priori sample size. Thus, we analyzed the data for the variables of most interest (ankle sagittal-, frontal-, and transverse-plane angles and moments) of all participants of the convenience sample. Given that the statistical power was >80% for these variables, we considered our sample size adequate to answer our study objectives.

Table. Descriptive Data

Variable	Value[a]
Sex, No. of males/females	6/16
Age, y	24.9 ± 4.9
Height, m	1.68 ± 0.08
Mass, kg	70.6 ± 11.4
Sustained sprains, No.	3.5 ± 2.0
Episodes of ankle giving way, No./mo	5.9 ± 2.8
Time since first ankle sprain, y	5.8 ± 3.8
Time since last sprain, y	1.8 ± 1.9
Foot Posture Index	4.1 ± 3.0
Foot and Ankle Ability Measure, %	
Activities of Daily Living subscale	84.2 ± 5.5
Sports subscale	62.8 ± 7.9
International Physical Activity Questionnaire Short Form, metabolic equivalent task-min/wk	4210 ± 3354

[a] Values are mean ± SD unless otherwise specified.

Participants were recruited from among the staff and students of the Université du Québec à Trois-Rivières, Canada, and via advertisements on social media in accordance with the recommendations of the International Ankle Consortium.[19] Participants (1) self-reported a history of ≥1 LAS; (2) self-reported a history of the ankle giving way, recurrent sprains, or the perception of ankle instability or all of these; and (3) scored <90% and <80% on the Foot and Ankle Ability Measure (FAAM)-Activities of Daily Living and FAAM-Sports subscales, respectively. Exclusion criteria were (1) a history of a lower limb musculoskeletal injury in the 3-month period before the study, (2) previous surgery to the musculoskeletal structures of the lower limb, (3) a history of a lower extremity fracture that needed surgical realignment, and (4) a neurologic condition. If participants had bilateral CAI, the less stable ankle, subjectively decided, was used in the analyses. All participants provided written informed consent, and the study was approved by the Université du Québec à Trois-Rivières Ethics Committee (No. CER-18-243-07.14).

Instruments

Lower limb kinematics were recorded using a 3-dimensional motion-analysis system (model Optotrak Certus; Northern Digital Inc) with 9 cameras sampling at 100 Hz. Clusters of 3 infrared light-emitting diode markers were positioned on the sacrum, the distal one-third of the thigh, the distal one-third of the leg, and the posterior calcaneus. For the calcaneus cluster, a heel plate and a wand were used as described earlier.[13,18] The heel plate was secured to the posterior calcaneus using athletic tape. To allow insertion of the wand into the heel plate, we cut a standardized rectangular hole of 30 mm × 30 mm in the shoe's heel counter (model Rupert; Athletic Works). During a calibration trial, 13 virtual kinematics markers were digitized on the tested lower extremity using a digitizing pointer on the following landmarks: bilateral anterior- and posterior-superior iliac spines, greater trochanter, lateral and medial femoral epicondyles, lateral and medial malleoli, proximal and distal posterior calcaneus, sustentaculum tali, and fibular tubercles. Ground reaction forces, sampled at 2000 Hz, were recorded using a force plate (model FP-4550-08; Bertec Corp) embedded in the floor. Kinematic marker trajectories and ground reaction forces were used to identify ankle- and knee-joint centers and calculate joint moments using the Newton–Euler inverse-dynamic equation.

The EMG data were collected using rectangular wireless surface electrodes (Trigno Wireless, Delsys Inc) at a sampling rate of 2000 Hz with a gain of 1000. Electrodes (27 × 37 × 13 mm) were made of 99% silver contact material with a 4-bar formation. EMGworks software (version 4.7.3; Delsys Inc) was used for data acquisition. The skin was shaved, abraded using fine-grade sandpaper, and cleaned using alcohol swabs to reduce the local impedance over the electrode placement. Electrodes were positioned over the gluteus medius, the vastus lateralis and medialis, the tibialis anterior, and the peroneus longus muscles according to the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles recommendations.[20] The interelectrode spacing was 10 mm. The common mode rejection ratio of the amplifier was <80 dB, the maximal intraelectrode impedance was 6 kOhm, and a 16-bit analog-to-digital converter was used. A 3.8-cm × 3.8-cm foot switch (model Trigno 4-Channel FSR Adapter; Delsys Inc) was placed in the shoe, under the heel of the tested limb. Electromyography, kinematic, kinetic, and foot-switch data were synchronized using First Principle (Northern Digital Inc) software and Trigger Module (Delsys Inc).

Procedures

Participants completed the validated French version of the FAAM-Activities of Daily Living and FAAM-Sports subscales[21] as well as the International Physical Activity Questionnaire Short Form[22] to quantify their foot and ankle disability and physical activity level, respectively. During the experimental protocol, participants had to complete 5 unilateral drop-jump landings from a 46-cm-high platform to 3 surfaces: a flat surface (DROP), a 10-cm foam block with a density of 1 kg/ft^3 (FOAM), and a 25° laterally inclined platform (WEDGE; Supplemental Figure 1, available online at https://doi.org/10.4085/1062-6050-0399.21.S1). The jump platform was positioned on wood blocks to maintain a height of 46 cm between the platform and the landing surface across conditions. During the tasks, participants stood on the high platform on their contralateral limb with their hands on their waist and were instructed to step forward and land on the test limb. The foam block and inclined platform surfaces were designed to fit on the force plate. Order of the conditions was randomly decided across participants using a random number table (Excel 2016; Microsoft Corp). Participants performed familiarization trials before each task until they were comfortable safely completing the experimental protocol.

Data Processing

The EMG, kinematic, and kinetic data were extracted and processed using Visual 3D software (version 6.01.36; C-Motion, Inc). The EMG data were full-wave rectified and filtered using a zero-phase lag, bidirectional, 20- to 450-Hz, fourth-order, bandpass Butterworth filter. The root mean square amplitude was calculated using a 100-millisecond moving window average. The root mean square data for all muscles and all tasks were normalized with the mean peak root mean square amplitude of all trials during DROP. We analyzed the EMG data during the preactivation phase (PP) and landing phase (LP). Ankle and knee angles and moments as well as vertical ground reaction forces (expressed as a percentage of the body weight [% BW]) were calculated only during the LP. Data were resampled and normalized to 100 points, with the beginning of the PP being the heel off the initial platform and the ending being initial contact with the surface. The LP started with initial contact with the surface and ended with maximal knee flexion. We computed joint angles for the ankle and knee using a Cardan sequence of X-Y-Z. Force-plate data were low-pass filtered using a dual-pass, fourth-order Butterworth filter with a cut-off frequency of 50 Hz. Joint moments were normalized to body mass.

Statistical Analysis

Descriptive statistics were applied to the descriptive data. Electromyographic, kinematic, and kinetic data were compared across conditions for each percentage of the phase using a 1-dimensional statistical parametric approach, based on the random field theory.[23] We performed the D'Agostino–Pearson K^2 test to evaluate the distribution of the lower limb EMG, kinematic, and kinetic data. Given that the data were not normally distributed, we compared normalized points of the curves using the nonparametric version of the statistical parametric mapping 1-way analysis of variance (SnPM{f}). When the SnPM{f} revealed differences, we compared experimental conditions using the nonparametric version of the dependent *t* test (SnPM{t}). The threshold of significance was set at $\alpha \leq .01$ for all SnPM{t} analyses. Peak difference (PD) between conditions was calculated for each result that was different. All SnPM analyses were implemented in MATLAB (version R2020b; The MathWorks, Inc).

RESULTS

The results for EMG, joint angles, joint moments, and vertical ground reaction forces are reported in Figures 1 through 4. Mean between-task differences for each biomechanical variable are provided in Supplemental Figure 2 (available online at https://doi.org/10.4085/1062-6050-0399.21.S2).

The DROP Versus FOAM Condition

Electromyography. During the PP, more gluteus medius, vastus lateralis, and peroneus longus muscle activity was observed from 95% to 100% ($P < .001$, PD = 24.9% at 100% of the PP), 90% to 100% ($P < .001$, PD = 25.4% at 100% of the PP), and 65% to 96% ($P < .001$, PD = 19.5% at 93% of the PP), respectively, for DROP.

During the LP, more gluteus medius, vastus lateralis, and peroneus longus muscle activity was noted from 0% to 58% ($P < .001$, PD = 33.8% at 12% of the LP), 0% to 45% ($P < .001$, PD = 31.0% at 11% of the LP), and 0% to 57% ($P < .001$, PD = 25.6% at 21% of the LP), respectively, for DROP. No difference was found for other muscles during PP and LP.

Kinematics. During DROP, ankle-dorsiflexion angles were greater from 0% to 70% ($P < .001$, PD = 9.3° at 20% of the LP), and ankle-inversion angles were smaller from 0% to 47% ($P < .001$, 3.5° at 23% of the LP) of the LP. We

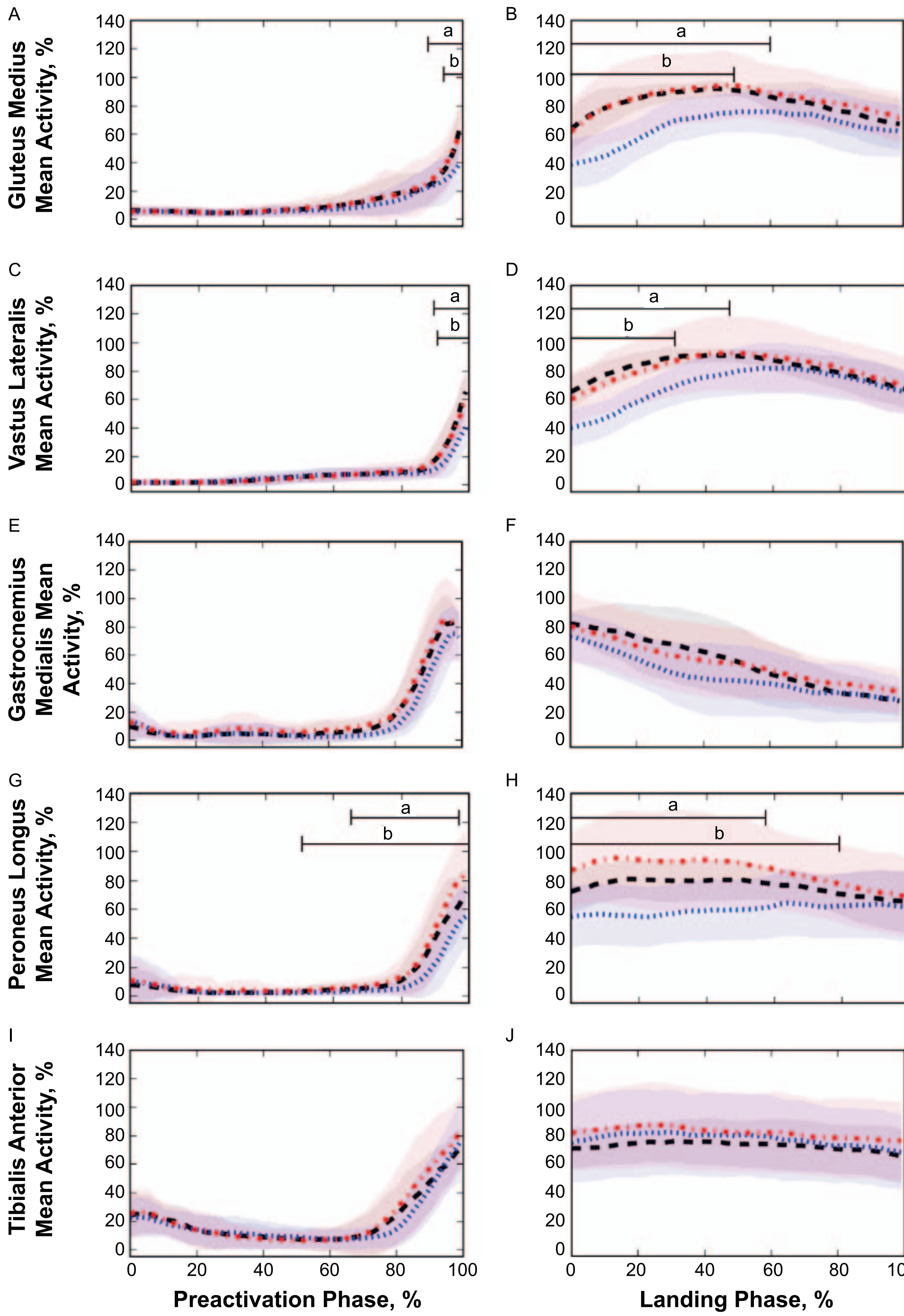

Figure 1. Electromyographic differences between unilateral drop-jump landing on a flat surface (DROP), unstable surface (FOAM), and laterally inclined surface (WEDGE). Gluteus medius mean activity during, A, preactivation and, B, landing phases. Vastus lateralis mean activity during, C, preactivation and, D, landing phases. Gastrocnemius medialis mean activity during, E, preactivation and, F, landing phases. Peroneus longus mean activity during, G, preactivation and, H, landing phases. Tibialis anterior mean activity during, I, preactivation and, J, landing phases. Dotted lines and shaded regions represent the means and SDs, respectively, of DROP (black), FOAM (blue), and WEDGE (red) tasks. [a] Difference between DROP and FOAM conditions. [b] Difference between FOAM and WEDGE conditions.

detected smaller ankle external-rotation angles from 0% to 30% ($P < .001$, PD = 3.6° at 18% of the LP) and greater ankle external-rotation angles from 50% to 100% ($P < .001$, PD = 2.4° at 72% of the LP) of the LP during DROP. Finally, knee-flexion angles were greater from 0% to 100% ($P < .001$, PD = 12.7° at 32% of the LP) of the LP during DROP. No difference was present for knee frontal- and transverse-plane angles.

Kinetics. During DROP, smaller ankle plantar-flexion moments were observed from 0% to 37% ($P < .001$, PD = 1.91 Nm/kg at 21% of the LP), 48% to 54% ($P = .002$, PD = 0.44 Nm/kg at 50% of the LP), and 73% to 100% ($P < .001$, PD = 0.35 Nm/kg at 100% of the LP) of the LP. Smaller ankle-inversion moments from 0% to 3% ($P = .003$, PD = 0.14 Nm/kg at 1% of the LP) and ankle internal-rotation moments from 9% to 16% ($P < .001$, 0.34 Nm/kg

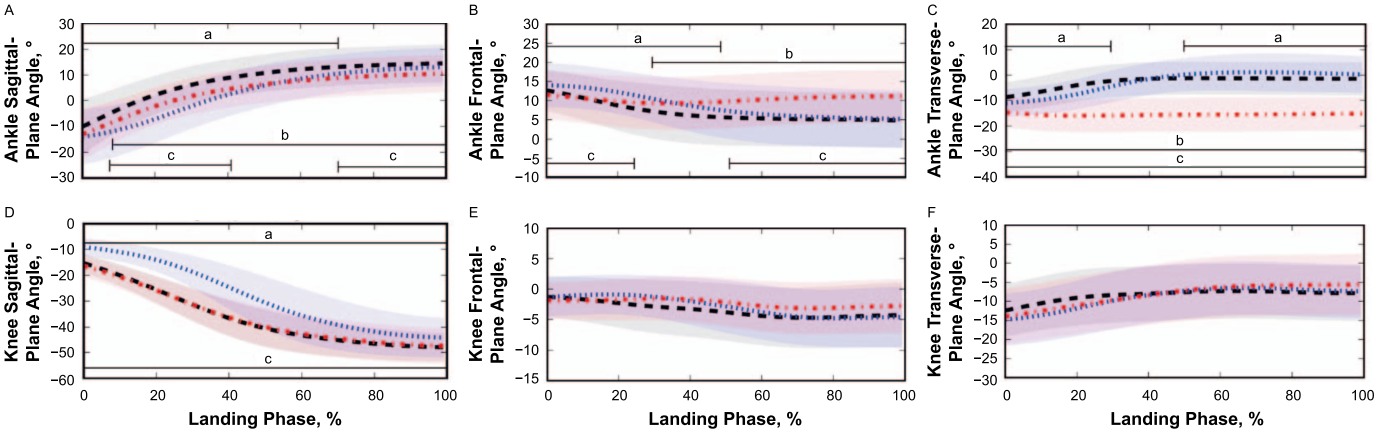

Figure 2. Kinematic differences between unilateral drop-jump landing on a flat surface (DROP), unstable surface (FOAM), and laterally inclined surface (WEDGE). A, Ankle sagittal-plane angle (positive values = dorsiflexion, negative values = plantar flexion). B, Ankle frontal-plane angle (positive values = inversion, negative values = eversion). C, Ankle transverse-plane angle (positive values = internal rotation, negative values = external rotation). D, Knee sagittal-plane angle (positive values = extension, negative values = flexion). E, Knee frontal-plane angle (positive values = adduction, negative values = abduction). F, Knee transverse-plane angle (positive values = internal rotation, negative values = external rotation). Dotted lines and shaded regions represent the means and SDs, respectively, of DROP (black), FOAM (blue), and WEDGE (red) tasks. [a] Difference between DROP and FOAM conditions. [b] Difference between DROP and WEDGE conditions. [c] Differences between FOAM and WEDGE conditions.

at 15% of the LP) of the LP were evident during DROP. Participants exhibited greater knee-extension moments from 0% to 11% ($P < .001$, PD = 0.79 Nm/kg at 6% of the LP) and 18% to 40% ($P < .001$, PD = 0.82 Nm/kg at 31% of the LP) of the LP during DROP. Furthermore, smaller knee-adduction moments were demonstrated from 0% to 13% ($P = .003$, PD = 0.44 Nm/kg at 13% of the LP) of the LP. We found greater vertical ground reaction forces from 1% to 28% ($P = .001$, PD = 149% BW at 22% of the LP) and smaller vertical ground reaction forces from 58% to 99% ($P = .001$, PD = 58% BW at 64% of the LP) of the LP during DROP. No other difference occurred for the ankle and knee moments.

The DROP Versus WEDGE Condition

Electromyography. During the PP and LP, no differences were seen for any muscles.

Kinematics. During DROP, greater ankle-dorsiflexion and internal-rotation angles were noted from 7% to 100% ($P < .001$, PD = 4.4° at 59% of the LP) and 0% to 100% ($P < .001$, PD = 14.3° at 51% of the LP), respectively, of the LP. Ankle-inversion angles were greater from 28% to 100% ($P < .001$, PD = 6.3° at 100% of the LP) of the LP during WEDGE. No differences were present for knee sagittal-, frontal-, and transverse-plane angles.

Kinetics. During DROP, ankle-dorsiflexion moments were smaller from 4% to 100% ($P < .001$, PD = 0.85 Nm/kg at 34% of the LP), ankle-inversion moments were

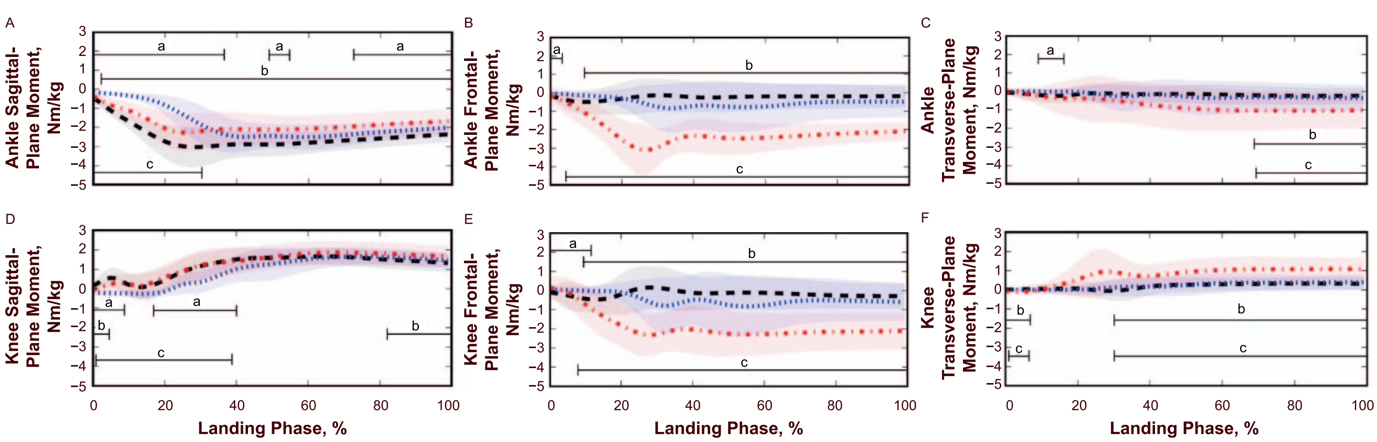

Figure 3. Kinetic differences between unilateral drop-jump landing on a flat surface (DROP), unstable surface (FOAM), and laterally inclined surface (WEDGE). A, Ankle sagittal-plane moment (positive values = dorsiflexion, negative values = plantar flexion). B, Ankle frontal-plane moment (positive values = inversion, negative values = eversion). C, Ankle transverse-plane moment (positive values = internal rotation, negative values = external rotation). D, Knee sagittal-plane moment (positive values = extension, negative values = flexion). E, Knee frontal-plane moment (positive values = adduction, negative values = abduction). F, Knee transverse-plane moment (positive values = internal rotation, negative values = external rotation). Dotted lines and shaded regions represent the means and SDs, respectively, of DROP (black), FOAM (blue), and WEDGE (red) tasks. [a] Difference between DROP and FOAM conditions. [b] Difference between DROP and WEDGE conditions. [c] Differences between FOAM and WEDGE conditions.

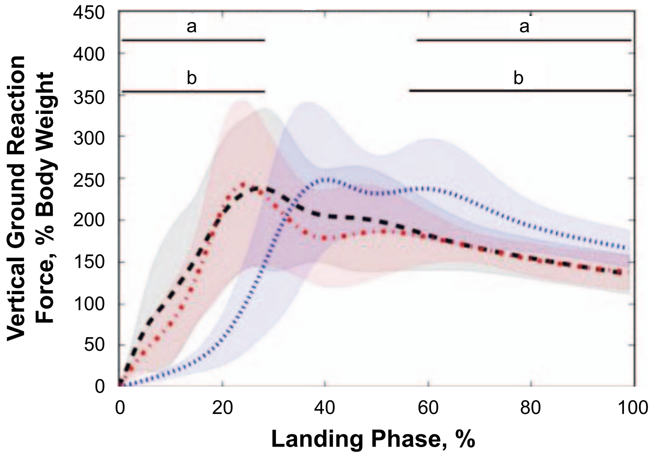

Figure 4. Vertical ground reaction force differences between unilateral drop-jump landing on a flat surface (DROP), unstable surface (FOAM), and laterally inclined surface (WEDGE). Dotted lines and shaded regions represent means and SDs, respectively, of DROP (black), FOAM (blue), and WEDGE (red) tasks. [a] Difference between DROP and FOAM conditions. [b] Difference between DROP and WEDGE conditions.

greater from 9% to 100% ($P < .001$, PD = 2.94 Nm/kg at 28% of the LP), and ankle internal-rotation moments were greater from 67% to 100% ($P < .001$, PD = 0.84 Nm/kg at 67% of the LP) of the LP. Knee-extension moments were greater from 0% to 4% ($P = .003$, PD = 0.34 Nm/kg at 4% of the LP) and smaller from 83% to 100% ($P < .001$, PD = 0.34 Nm/kg at 100% of the LP) of the LP during DROP. Furthermore, greater knee-adduction moments were observed from 13% to 100% ($P < .001$, 2.48 Nm/kg at 29% of the LP) of the LP during DROP. Finally, knee internal-rotation moments were greater from 0% to 6% ($P = .002$, PD = 0.13 Nm/kg at 6% of the LP) and smaller from 27% to 35% ($P = .001$, 0.99 Nm/kg at 29% of the LP) and 40% to 100% ($P < .001$, 0.76 at 61% of the LP) of the LP during DROP. No difference in vertical ground reaction forces was evident.

The FOAM Versus WEDGE Condition

Electromyography. During the PP, vastus lateralis, peroneus longus, and gluteus medius muscle activity was less from 92% to 100% ($P < .001$, PD = –14.5% at 99% of the PP), 55% to 100% ($P < .001$, PD = –32.1% at 100% of the PP), and 95% to 100% ($P < .001$, PD = –23.0% at 100% of the PP), respectively, during FOAM.

During the LP, less gluteus medius, vastus lateralis, and peroneus longus muscle activity was demonstrated from 0% to 56% ($P < .001$, PD = 33.9% at 12% of the LP), 0% to 31% ($P < .001$, PD = 19.3% at 13% of the LP), and 0% to 76% ($P < .001$, PD = 39.8% at 15% of the LP), respectively, during FOAM. No difference occurred for any other muscles during the PP and LP.

Kinematics. During FOAM, ankle plantar-flexion angles were greater from 6% to 41% ($P < .001$, PD = 5.0° at 20% of the LP), and ankle-dorsiflexion angles were greater from 72% to 100% ($P = .003$, PD = 2.6° at 100% of the LP) of the LP. Ankle-inversion angles were greater from 0% to 24% ($P = .002$, PD = 2.9° at 12% of the LP) and smaller from 52% to 100% ($P < .001$, PD = 6.0° at 100% of the LP) of the LP during FOAM. Ankle internal-rotation ($P < .001$, PD = 16.6° at 69% of the LP) and knee-extension ($P < .001$, PD = 12.7° at 31% of the LP) angles were greater from 0% to 100% of the LP during FOAM. No difference was found for knee frontal- and transverse-plane angles.

Kinetics. During FOAM, ankle-dorsiflexion, ankle-inversion, and internal-rotation moments were greater from 0% to 29% ($P < .001$, PD = 1.23 Nm/kg at 21% of the LP), 5% to 100% ($P < .001$, PD = 2.57 Nm/kg at 26% of the LP), and 69% to 100% ($P < .001$, PD = 0.74 Nm/kg at 72% of the LP), respectively, of the LP. Furthermore, greater knee-flexion and -adduction moments were seen from 1% to 39% ($P < .001$, 0.85 Nm/kg at 31% of the LP) and 8% to 100% ($P < .001$, PD = 1.86 Nm/kg at 25% of the LP), respectively, of the LP during FOAM. Finally, larger and smaller knee internal-rotation moments were exhibited from 1% to 7% ($P = .002$, PD = 0.11 Nm/kg at 5% of the LP) and 27% to 100% ($P = .001$, PD = 0.85 Nm/kg at 28% of the LP), respectively, of the LP during FOAM. Smaller and larger vertical ground reaction forces were present from 1% to 28% ($P = .001$, PD = 161% BW at 23% of the LP) and 56% to 99% ($P = .001$, PD = 59% BW at 63% of the LP), respectively, of the LP during FOAM.

DISCUSSION

The aim of this study was to compare lower limb biomechanics in individuals with CAI during DROP, FOAM, and WEDGE conditions. Participants with CAI displayed important lower limb biomechanical differences during FOAM and WEDGE that could put them at greater risk of sustaining recurrent LASs. Our main hypothesis was that individuals with CAI would exhibit more at-risk lower limb biomechanics, including greater ankle-inversion angles, and no changes in peroneus longus muscle activation during FOAM and WEDGE than during DROP. Our results fully support these hypotheses.

The first main finding of our study was the greater ankle-inversion angles during FOAM and WEDGE than during DROP. Ankle inversion is an essential movement leading to LAS during dynamic tasks. Fong et al[24] reported that increased ankle inversion from 9° to 15° (ie, 6° increase) was enough to cause an LAS during a sport-maneuver task. We identified increased maximal ankle-inversion angles of 6.3° during WEDGE and 3.5° during FOAM compared with DROP (Figure 2 and Supplementary Materials). During WEDGE, the loads on the lateral ankle structures were much greater than during DROP, as highlighted by the increased ankle-eversion moments from 9% to 100% of the LP (PD = 2.94 Nm/kg at 28% of the LP). Greater ankle-inversion angles and -eversion moments (WEDGE only) increase the physiological demands on the ankle-evertor muscles, especially the peroneus longus, and its EMG activity should therefore have increased during these tasks. However, compared with DROP, no change occurred during WEDGE, and peroneus longus muscle activity was smaller during FOAM (PP and LP). The peroneus longus muscle stabilizes the ankle and plays a critical role in reducing the risk of giving way or recurrent LAS during dynamic tasks.[25] Reduced peroneus longus muscle activity before and after the initial foot impact during FOAM and a lack of increased activity during WEDGE could represent altered feed-forward and feedback motor-control mechanisms caused by damage to mechanoreceptors in the ankle ligaments.[4] These alterations are believed to trigger inadequate movement of the proximal lower limb joints, decrease evertor muscle strength, and reduce the control of the ankle musculature during dynamic tasks.[4] This combination of impairments contributes to placing the foot and ankle in a vulnerable position during landing on more challenging surfaces and could lead individuals with CAI to experience ankle giving way or recurrent ankle sprains (or both).

The second main finding of our study was that participants with CAI exhibited greater ankle plantar-flexion angles at the beginning of the LP during FOAM and WEDGE than during DROP. Given that the anterior part of the talar trochlea is wider than the posterior part,[26] ankle intra-articular pressure is increased in the dorsiflexed position,[27] and thus, joint stability is greater. This ankle close-packed position is believed to be protective in individuals with CAI during jump-landing tasks.[8] A greater ankle plantar-flexion angle during FOAM and WEDGE could represent a vulnerable position in individuals with CAI and may increase the risk of reinjury during challenging jump-landing tasks. The greater ankle plantar-flexion angle during the first part of the LP during FOAM could also explain the greater ankle-inversion and internal-rotation angles compared with those during WEDGE. However, although the ankle is more vulnerable in a plantar-flexed position from a biomechanical standpoint, that position does not always result in an LAS,[24,28] whereas LAS can result with the ankle in an inverted, internally rotated, and dorsiflexed or plantar-flexed position.[24,28] Further large-scale studies in which researchers determine the prevalence of each mechanism of injury are needed.

The third main finding of this study was the difference in knee biomechanics and above-knee muscles between landing tasks. During FOAM, the smaller demand for dampening of impact forces due to the soft surface may have changed knee biomechanics. To dampen ground reaction forces during landing, individuals with CAI need to flex the knee and thus activate the knee-extensor and hip-abductor muscles.[18] However, considering the softness of the unstable FOAM surface, individuals with CAI landed with a less-flexed knee joint than during DROP (and WEDGE) because of a reduced demand for dampening of ground reaction forces during the first part of the LP (PD = 149% BW at 22% of the LP). Consistent with this result, greater knee-extension angles during bilateral landing on an unstable surface were also previously observed.[29,30] Smaller knee-flexion angles during FOAM may explain the decreased activity of the vastus lateralis and gluteus medius muscles as well as the smaller knee-extension and -abduction moments than during DROP. These findings are consistent with those of researchers who also reported decreased EMG activity of the knee extensors in healthy participants during bilateral landings on an unstable compared with a stable surface.[30,31] Greater knee frontal- and sagittal-plane angles[29] and lower limb EMG activity[32] during bilateral landing from a drop jump were demonstrated when the height of the initial drop-jump platform was increased. Given that the initial platform was relatively high (ie, 46 cm) in our study, it may have induced changes to the biomechanics of the lower limbs of our participants during landing that would perhaps decrease if they landed from a lower initial platform.

Clinical Implications

Athletic demands impose external demands, and athletes must often land and stabilize on challenging surfaces in sport-specific contexts. The biomechanical changes that participants with CAI exhibited during landing on these surfaces could place them at a greater risk of sustaining recurrent LASs. The most concerning finding was the lack of increased peroneus longus muscle activity despite greater ankle-inversion angles during FOAM and WEDGE. Interventions should emphasize modifying the landing strategy of patients with CAI during these challenging landing tasks. To avoid injury, we also suggest being cautious when including jump-landing exercises on challenging surfaces in the rehabilitation of patients with CAI.

Limitations

The first limitation of this study was that hip movements and moments were not assessed because of technical limitations with the capture volume of our motion-analysis system. Differences in hip angles and moments could have been present between tasks but not observed using our experimental setup. The second limitation was that participants may have experienced fatigue during data collection. However, they were allowed rest periods as needed and after each task. The third limitation was that participants were aware of the surface on which they were landing, and data collection took place in a highly controlled environment. Because LASs are mostly sustained during unexpected perturbations, our results should be interpreted with caution. The fourth limitation was the sex distribution of participants (16 females, 6 males). Our results may therefore be more generalizable to females. The fifth limitation was related to the interpretation of the EMG differences during the PP. Changes may have reflected immediate postadaptation motor strategies in response to surface conditions. Familiarization trials were provided to participants, so EMG differences during the PP could have been due to a learning effect and thus were perhaps not representative of the motor-control strategy during the initial trials. Readers should interpret these results accordingly.

CONCLUSIONS

Lower limb kinetics, kinematics, and EMG differences among DROP, FOAM, and WEDGE were observed in individuals with CAI. The greater ankle-inversion and plantar-flexion angles as well as the lack of increase in peroneus longus muscle activation during FOAM and WEDGE could place individuals with CAI at greater risk of sustaining recurrent LAS. Better understanding of the lower limb biomechanical differences during jump landings on different surfaces will help clinicians target deficits associated with CAI during rehabilitation and eventually contribute to preventing the recurrence of LAS and the development of CAI.

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SUPPLEMENTAL MATERIAL

Supplemental Figure 1.

Execution of unilateral drop-jump landing on, A and B, flat; C and D, unstable; and, E and F, laterally inclined surfaces.

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Supplemental Figure 2.

Mean between-task differences. A, Gluteus medius preactivation phase. B, Gluteus medius landing phase. C, Vastus lateralis preactivation phase. D, Vastus lateralis landing phase. E, Gastrocnemius medialis preactivation phase. F, Gastrocnemius medialis landing phase. G, Peroneus longus preactivation phase. H, Peroneus longus landing phase. I, Tibialis anterior preactivation phase. J, Tibialis anterior landing phase. K, Ankle sagittal-plane angle. L, Ankle frontal-plane angle. M, Ankle transverse-plane angle. N, Knee sagittal-plane angle. O, Knee frontal-plane angle. P, Knee transverse-plane angle. Q, Ankle sagittal-plane moment. R, Ankle frontal-plane moment. S, Ankle transverse-plane moment. T, Knee sagittal-plane moment. U, Knee frontal-plane moment. V, Knee transverse-plane moment. W, Vertical ground reaction force. Red line indicates the difference between unilateral drop-jump landing on a flat surface (DROP) and a laterally inclined surface (WEDGE; positive indicates DROP is greater). Black line indicates the difference between DROP and unilateral drop-jump landing on an unstable surface (FOAM; positive indicates DROP is greater). Blue line indicates the difference between FOAM and WEDGE (positive indicates FOAM is greater).

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