

## Lower limb biomechanics during drop jump landing in individuals with chronic ankle instability

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## Lower limb biomechanics during drop jump landing on challenging surfaces in individuals with chronic ankle instability

### ABSTRACT

**Context:** Individuals with chronic ankle instability (CAI) exhibit impaired lower limb biomechanics during unilateral drop jump landing on a flat surface. However, lower limb biomechanical adaptations during unilateral drop jump landing on more challenging surfaces such as unstable or inclined are yet to be described.

**Objective:** Determine how unilateral drop jump landing surfaces (flat, unstable and inclined) influence lower limb EMG, kinematics and kinetics in individuals with CAI.

**Design:** Descriptive laboratory study.

**Setting:** Biomechanics laboratory.

**Patients or Other Participants:** Twenty-two young adults with CAI

**Interventions:** Participants completed five trials of unilateral drop jump landing from a 46 cm height platform on flat (DROP), unstable (FOAM) and laterally inclined (WEDGE) surfaces.

**Main outcome measure(s):** EMG of gluteus medius, vastus lateralis, gastrocnemius medialis, peroneus longus and tibialis anterior muscles were recorded. Knee and ankle angles and moments were calculated using a three-dimensional motion analysis system and a force plate. Biomechanical variables were compared between tasks using one-dimensional statistical nonparametric mapping.

**Results:** During DROP, greater ankle dorsiflexion angles, knee extension moments and vastus lateralis muscle activity (FOAM only) were observed compared to FOAM and WEDGE. Greater ankle inversion angles were observed during FOAM and WEDGE compared to DROP. Peroneus longus muscle activity was greater during DROP compared to FOAM. During FOAM, greater ankle inversion and knee extension angles, ankle inversion and internal rotation moments as well as smaller peroneus longus muscle activity were observed compared to WEDGE.

**Conclusions:** The greater ankle inversion and plantarflexion angles as well as the lack of increase in peroneus longus muscle activation during FOAM and WEDGE could increase the risk of recurrent LAS in individuals with CAI. The results of this study improve our understanding of lower limb biomechanics changes when landing on more challenging surfaces and will help clinicians better targeting deficits associated with CAI during rehabilitation.

**Keywords:** Electromyography; Kinematics; Kinetics; Neuromechanics

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**Key points:**

- Participants with CAI landed on FOAM and WEDGE with greater ankle inversion angles without changes in peroneus longus muscle activity which could predispose them to sustain recurrent LAS.

- Greater plantarflexion angles during FOAM and WEDGE represent a more vulnerable position in individuals with CAI during landing on more challenging surfaces.

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

Altered lower limbs biomechanics during high-velocity sport-specific movements, such as landing from a jump, could contribute to episodes of ankle giving way and recurrent LAS in individuals with CAI. These jump-landing tasks are commonly reported in previous studies quantifying biomechanical deficits in CAI as they impose large and rapid impulse loads to the ankle complex which could initiate the mechanism of LAS.<sup>8</sup>

During unilateral drop jump landing on a flat surface (DROP), individuals with CAI exhibit greater ankle dorsiflexion angles,<sup>9,10</sup> ankle inversion angles,<sup>11</sup> knee flexion angles<sup>9</sup> as well as less peroneus longus<sup>11,12</sup> and vastus lateralis<sup>13</sup> muscle activity (pre-landing) compared to healthy individuals. During landing on more challenging surfaces such as unstable<sup>13</sup> or inclined,<sup>13-15</sup> altered lower limb biomechanics could place individuals with CAI at greater risk of sustaining recurrent LAS. Indeed, previous studies that quantified lower limb biomechanics during unilateral drop jump landing on an inclined surface (WEDGE) showed a longer peroneus longus activation latency,<sup>14,15</sup> reduced peroneus longus activation,<sup>13,15,16</sup> reduced gluteus medius muscle activation<sup>13</sup> and greater ankle inversion angles<sup>14,15,17</sup> in individuals with CAI compared to healthy counterparts. During unilateral drop jump landing on an unstable surface (FOAM), greater ankle dorsiflexion angles were reported between participants with CAI and healthy controls.<sup>13</sup> Previous studies focused on the analysis of the lower limb biomechanical differences between individuals with CAI and healthy counterparts during DROP, WEDGE and FOAM. However, no study has yet determined how the biomechanics of the lower limb of individuals with CAI change when landing on different surfaces. Better understanding the lower limb changes when landing on different surfaces in individuals with CAI will help clinicians identify biomechanical risk factors that could predispose them to sustain recurrent LAS during sports including jump landing.

The objective of this study was to identify lower limb kinematic, kinetic and EMG differences in individuals with CAI between DROP, FOAM and WEDGE. It was hypothesized that, based on the previously described feedforward alterations in

individuals with CAI, they would exhibit greater ankle inversion angles and no changes in peroneus longus muscle activation during WEDGE and FOAM compared to DROP.

## **METHODS**

### **Participants**

Twenty-two participants with CAI were recruited to take part to this cross-sectional laboratory-based study. This study is a secondary analysis of a subcohort of participants from previous studies.<sup>13, 18</sup> Participants who allowed their data to be kept in a database and used in other projects were included. As no previous study investigated the unilateral drop jump biomechanics on different challenging surfaces in healthy or injured participants, an a priori sample size calculation could not be performed. Thus, we analyzed the data for the variables of most interest (ankle sagittal, frontal and transverse angles and moments) of all participants of the convenience sample. As the statistical power was over 80% for these variables, we considered our sample size adequate to answer our study objectives.

Participants were recruited among the staff and students of the Université du Québec à Trois-Rivières (UQTR), Canada, and via advertisements on social media. Participants were recruited in accordance with the recommendations of the International Ankle Consortium.<sup>19</sup> Participants self-reported 1) a history of at least one or more LAS 2) a history of ankle giving way and/or recurrent sprains and/or feeling of ankle instability and 3) scored less than 90% and 80% of the Foot and Ankle Ability Measures-Activity of Daily Living (FAAM-ADL) and FAAM-Sports (FAAM-S) subscales, respectively.

Exclusion criteria were 1) a history of a lower limb musculoskeletal injury in the 3-month

period prior to the study onset, 2) a previous surgery to the lower limb musculoskeletal structures, 3) a history of a lower extremity fracture that needed surgical realignment and 4) neurological conditions. If participants had bilateral CAI, the less stable ankle, subjectively decided, was used in the analyses. All participants provided a written informed consent to a protocol approved by the Université du Québec à Trois-Rivières Ethics Committee (CER-18-243-07.14).

### **Instruments**

Lower limb kinematics was recorded using a three-dimensional motion analysis system (Optotrak Certus, Northern Digital, Waterloo, ON, Canada) with 9 cameras sampled at 100 Hz. Clusters of three infrared light-emitting markers were positioned on the sacrum, the distal one third of the thigh, the distal one third of the leg and on the posterior part of the calcaneus. For the calcaneus cluster, a heel plate and a wand previously described were used.<sup>13, 18</sup> The heel plate was secured directly on the posterior part of calcaneus with athletic tape. To allow the insertion of the wand into the heel plate, a standardized rectangular hole of 30 mm x 30 mm was cut into the shoes' heel counter (Rupert model, Athletic Works, China). During a calibration trial, 15 virtual kinematics markers were digitized on the tested lower extremity with a digitizing pointer on the following landmarks: bilateral anterior and posterior supra-iliac spines, greater trochanter, lateral and medial femoral epicondyles, lateral and medial malleoli, proximal and distal posterior part of the calcaneus, sustentaculum tali and fibular tubercle. Ground reaction forces, sampled at 2 000 Hz, were recorded with a force plate embedded in the floor (Bertec Corp, OH, USA). Kinematic marker trajectories and ground reaction forces

were used to identify ankle and knee joint centers and calculate joint moments using Newton–Euler inverse dynamic equation.

EMG data were collected using rectangular wireless surface electrodes (Trigno Wireless; Delsys Inc., Boston, MA, United States) at a sampling rate of 2 000 Hz with a gain of 1 000. Electrodes (27 x 37 x 13 mm) were made of 99% silver contact material with a four-bar formation. The interelectrode spacing was 10 mm. Delsys EMGworks software (Delsys Inc., Boston, MA, United States) was used for the data acquisition. Electrodes were positioned over the gluteus medius, the vastus lateralis and medialis, the tibialis anterior and the peroneus longus muscles according to the SENIAM recommendations.<sup>20</sup> The skin was shaved, abraded with fine-grade sandpaper and cleaned with alcohol swabs to reduce the local impedance over the electrode placement. The common mode rejection ratio of the amplifier was >80 dB, the maximal intraelectrode impedance was 6 kOhm and a 16-bit A/D converter was used during the experimentation. A 3.8 cm x 3.8 cm foot switch (Trigno 4-Channel FSR Adapter, Boston, USA) was placed in the shoes, under the heel of the tested limb. Kinematic, kinetic, EMG and foot switch data were synchronized using First Principle software and Delsys Trigger Module.

## **Procedures**

Participants completed the validated French version of the FAAM-ADL and FAAM-S<sup>21</sup> as well as the short version of the International Physical Activity Questionnaire (IPAQ)<sup>22</sup> to respectively quantify foot and ankle disability and the physical activity level. Participants' mass, height and age as well as the number of sustained sprains, the time since first and last sprains and the frequency of episodes of ankle giving way were registered before the experimentation (see Table 1). During the experimental



protocol, participants had to complete five unilateral drop jump landings from a 46 cm high platform on three different surfaces, namely a flat surface (DROP), a 10 cm foam block with a density of 1 kg/ft<sup>3</sup> (FOAM) and a 25-degree laterally inclined platform (WEDGE) (see Supplementary material). 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 tasks, participants stood on the high platform on their contralateral limb, hands on their waist and were instructed to step forward and land on their tested limb. The foam block and the inclined platform surfaces were designed to fit on the force plate. The order of the conditions was randomly decided across participants using a random number table. Participants performed familiarization trials before each task until they felt comfortable safely completing the experimental protocol.

### **Data processing**

EMG, kinematic and kinetic data were extracted and processed using Visual 3D software (C-Motion, Germantown, MD, United States). EMG data were full wave rectified and filtered using a zero-phase lag, bidirectional, 20-450 Hz fourth-order bandpass Butterworth filter. The root mean square (RMS) amplitude was calculated using a 100 ms moving window average. RMS data of all muscles, for all tasks, were normalized with the mean peak RMS amplitude of all trials during DROP. EMG data were analyzed during the preactivation and landing phases. Ankle and knee angles and moments as well as vertical ground reaction forces (expressed as percent of the body weight (%BW)) were only calculated during the landing phase. Data were resampled and normalized to 100 points with the beginning of the preactivation phase being the heel off from the initial platform and the ending being the initial contact with the surface. The

landing phase started with the initial contact with the surface and ended with the maximal knee flexion. Joint angles were calculated for the knee and ankle 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 used for demographic data. Kinematic, kinetic and EMG data were compared across conditions for each percent of the phase using a one-dimensional statistical parametric approach, based on the random field theory.<sup>23</sup> D'Agostino-Pearson K2 tests were used to evaluate the distribution of the lower limb EMG, kinetic and kinematic data. As data were not normally distributed, each normalized point of the curves was compared using the nonparametric version of the statistical parametric mapping one-way ANOVA (SnPM(f)). When significant differences were observed with the SnPM(f), experimental conditions were compared with the nonparametric version of the dependent t-test (SnPM(t)). The threshold of significance was set at  $\alpha \leq 0.01$  for all SnPM(t) analyses. Peak difference (PD) between conditions were calculated for each significant result. All SnPM analyses were implemented using the open access SPM1D code ([www.spm1d.org](http://www.spm1d.org)) in Matlab R2020b (The Mathworks Inc., Boston, MA, USA).

## RESULTS

EMG, joint angles, joint moments and vertical ground reaction forces results are reported in Fig.1, Fig.2, Fig.3 and Fig.4, respectively. Mean between-task differences for each biomechanical variable are also reported in Supplementary materials.

### **DROP compared to FOAM**

#### *EMG*

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

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

#### *Kinematics*

During DROP, ankle dorsiflexion angles were greater from 0 to 70% ( $p < .001$ , PD=9.3° at 20%LP) and ankle inversion angles were smaller from 0 to 47% ( $p < .001$ , 3.5° at 23%LP) of the landing phase. Smaller and greater ankle external rotation angles were respectively observed from 0 to 30% ( $p < .001$ , PD=3.6° at 18%LP) and 50 to 100% ( $p < .001$ , PD=2.4° at 72%LP) of the landing phase during DROP. Finally, knee flexion angles were greater from 0 to 100% ( $p < .001$ , PD=12.7° at 32%LP) of the landing phase

during DROP. No significant difference was found for knee frontal and transverse plane angles.

### *Kinetics*

During DROP, smaller ankle plantarflexion moments were observed from 0 to 37% ( $p < .001$ , PD=1.91 Nm/kg at 21%LP), 48 to 54% ( $p = .002$ , PD=0.44 Nm/kg at 50%LP) and from 73 to 100% ( $p < .001$ , PD=0.35 Nm/kg at 100%LP) of the landing phase. Smaller ankle inversion moments from 0 to 3% ( $p = .003$ , PD=0.14Nm/kg at 1%LP) and ankle internal rotation moments from 9 to 16% ( $p < .001$ , 0.34 Nm/kg at 15%LP) of the landing phase were observed during DROP. Participants exhibited greater knee extension moments from 0 to 11% ( $p < .001$ , PD=0.79 Nm/kg at 6%LP) and 18 to 40% ( $p < .001$ , PD=0.82 Nm/kg at 31%LP) of the landing phase. Furthermore, smaller knee adduction moments were observed from 0 to 13% ( $p = .003$ , PD=0.44 Nm/kg at 13%LP) of the landing phase. Greater and smaller vertical ground reaction forces were observed from 1 to 28% ( $p=.001$ , PD=149 %BW at 22%LP) and from 58 to 99% ( $p=.001$ , PD= 58%BW at 64%LP) of the landing phase, respectively. No other significant difference was found for the knee and ankle moments.

### **DROP compared to WEDGE**

#### *EMG*

No significant difference was found for all muscles during the preactivation and landing phases.

### *Kinematics*

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

### *Kinetics*

During DROP, ankle dorsiflexion moments were smaller from 4 to 100% ( $p < .001$ , PD=0.85 Nm/kg at 34%LP) and ankle inversion and internal rotation moment were respectively greater from 9 to 100% ( $p < .001$ , PD=2.94 Nm/kg at 28%LP) and 67 to 100% ( $p < .001$ , PD=0.84 Nm/kg at 67%LP) of the landing phase. Knee extension moments were greater from 0 to 4 % ( $p = .003$ , PD=0.34 Nm/kg at 4%LP) and smaller from 83 to 100 % ( $p < .001$ , PD=0.34 Nm/kg at 100%LP) of the landing phase. Furthermore, greater knee adduction moments were observed from 13 to 100% ( $p < .001$ , 2.48 Nm/kg at 29%LP) of the landing phase during DROP. Finally, knee internal rotation moments were greater from 0 to 6% ( $p = .002$ , PD=0.13 Nm/kg at 6%LP) and smaller from 27 to 35% ( $p=.001$ , 0.99 Nm/kg at 29%LP) and 40 to 100% ( $p < .001$ , 0.76 at 61%LP) of the landing phase during DROP. No difference in vertical ground reaction forces were observed.

### **FOAM compared to WEDGE**

### *EMG*

During the preactivation phase, vastus lateralis, peroneus longus and gluteus medius muscle activity were respectively smaller from 92 to 100% ( $p < .001$ , PD=-14.5%

at 99%PP), 55 to 100% ( $p < .001$ , PD=-32.1% at 100%PP) and 95 to 100% ( $p < .001$ , PD=-23.0% at 100%PP) during FOAM.

During the landing phase, gluteus medius, vastus lateralis and peroneus longus muscle activity were respectively decreased from 0 to 56 % ( $p < .001$ , PD=33.9% at 12%LP), 0 to 31% ( $p < .001$ , PD=19.3% at 13%LP) and 0 to 76% ( $p < .001$ , PD=39.8% at 15%LP) during FOAM. No significant difference was found for all other muscles during the preactivation and landing phases.

### *Kinematics*

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

### *Kinetics*

During FOAM, ankle dorsiflexion, inversion and internal rotation moments were respectively greater from 0 to 29% ( $p < .001$ , PD=1.23 Nm/kg at 21%LP), 5 to 100% ( $p < .001$ , PD=2.57 Nm/kg at 26%LP) and 69 to 100% ( $p < .001$ , PD=0.74 Nm/kg at 72%LP) of the landing phase. Furthermore, greater knee flexion and adduction moments were respectively observed from 1 to 39% ( $p < .001$ , 0.85 Nm/kg at 31%LP) and 8 to 100% ( $p < .001$ , PD=1.86 Nm/kg at 25%LP) of the landing phase during FOAM. Finally, greater

and smaller knee internal rotation moments were respectively observed from 1 to 7% ( $p = .002$ , PD=0.11 Nm/kg at 5%LP) and 27 to 100% ( $p = .001$ , PD= 0.85 Nm/kg at 28%LP) of the landing phase. Smaller and greater vertical ground reaction forces were observed from 1 to 28% ( $p= .001$ , PD=161%BW at 23%LP) and 56 to 99% ( $p= .001$ , PD= 59%BW at 63%LP) of the landing phase, respectively.

## DISCUSSION

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

The main finding of our study was the greater ankle inversion angles during FOAM and WEDGE compared to DROP. Ankle inversion is an important movement leading to LAS during dynamic tasks. Fong et al.<sup>24</sup> reported that increased ankle inversion from 9 to 15° (+6°) was enough to cause a LAS during a sport-maneuver task. In our study, we identified increased maximal ankle inversion angles of 6.3° during WEDGE and 3.5° during FOAM compared to DROP (see Fig.1 and Supplementary materials). During WEDGE, loads on lateral ankle structures were a lot greater compared to DROP as highlighted by the increased ankle eversion moments from 9 to 100% of the landing phase (PD=2.94 Nm/kg at 28%LP). Greater ankle inversion angles and eversion

moments (WEDGE only) increase the physiological demands to the ankle evtor muscles, especially peroneus longus and its EMG activity should thereby have been increased during these tasks. However, compared to DROP, no change was observed during WEDGE and peroneus longus muscle activity was smaller during FOAM (preactivation and landing phases). Peroneus longus muscle stabilizes the ankle and plays an important role in reducing the risk of episodes of giving way or recurrent LAS during dynamic tasks.<sup>25</sup> Reduced peroneus longus muscle activity before and after the initial foot impact during FOAM and lack of increased activity during WEDGE could represent altered feed-forward and feedback motor control mechanisms caused by damages to mechanoreceptors located in ankle ligaments.<sup>4</sup> These alterations are believed to trigger inadequate proximal lower limb joints movements, decrease evtor muscle strength and reduced control of ankle musculature during dynamic tasks.<sup>4</sup> 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 episodes of ankle giving way or recurrent ankle sprains.

The second main finding of our study was that participants with CAI exhibited greater ankle plantarflexion angles during the beginning of the landing phase during FOAM and WEDGE compared to DROP. As the anterior part of the talar trochlea is wider than the posterior part,<sup>26</sup> ankle intra-articular pressure is increased in a dorsiflexed position<sup>27</sup> and thus joint stability is greater. This ankle close-packed position is believed to be protective in individuals with CAI during jump landing tasks.<sup>8</sup> Greater ankle plantarflexion angles during FOAM and WEDGE could represent a vulnerable position in individuals with CAI and may perhaps increase the risk of reinjury during challenging



jump landing tasks. The greater ankle plantarflexion angles during the first part of the landing phase during FOAM could also explain the greater ankle inversion and internal rotation angles compared to WEDGE. However, even though from a biomechanical standpoint the ankle is more vulnerable in a plantarflexed position, LAS are not always sustained in that position.<sup>24, 28</sup> LAS can be sustained with the ankle in an inverted, internally rotated and dorsiflexed or plantarflexed position.<sup>24, 28</sup> Further large-scale studies determining the prevalence of each mechanism of injuries are needed.

The third main finding of this study was the differences in knee biomechanics and above-knee muscles between landing tasks. During FOAM, the smaller demand in impact forces dampening due to the softness of the surface may have changed knee biomechanics. To dampen ground reaction forces during landing, individuals with CAI need to flex the knee and thus activate knee extensors and hip abductor muscles.<sup>18</sup> However, considering the softness of the unstable surface (during FOAM), individuals with CAI land with a less flexed knee joint compared to DROP (and WEDGE) due to reduced demand in ground reaction forces dampening during the first part of the landing phase (PD=149 %BW at 22%LP). Consistent with this result, greater knee extension angles during bilateral landing on an unstable surface was also previously observed.<sup>29, 30</sup> Smaller knee flexion angles during FOAM may explain the decreased vastus lateralis and gluteus medius muscles activity as well as the smaller knee extension and abduction moments compared to DROP. These findings are consistent with those of previous studies also reporting decreased EMG activity of knee extensors during bilateral landing on an unstable compared to a stable surface in healthy participants.<sup>30, 31</sup> Greater knee frontal and sagittal angles<sup>29</sup> and lower limb EMG activity<sup>32</sup> during bilateral landing from

a drop jump were previously reported when increasing the height of the initial drop-jump platform. As the initial platform was relatively high (i.e., 46 cm) in our study, it may have induced changes to the biomechanics of the lower limbs of our participants during landing that could perhaps be lessened when landing from a lower initial platform.

### **Clinical implications**

Athletic demands impose external demands and athletes often have to 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 greater risk of sustaining recurrent LAS. The most concerning finding is the lack of increased peroneus longus muscle activity despite greater ankle inversion angles during FOAM and WEDGE. Interventions should emphasize on modifying the landing strategy of patients with CAI during these challenging landing tasks. We also suggest being cautious when including jump-landing exercises on challenging surfaces in the rehabilitation of patients with CAI to avoid injuries.

### **Limitations**

The first limitation of this study is that hip movements and moments were not assessed due to technical limitations with the volume of capture 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 perhaps have experienced fatigue during data collection. However, rest periods were given to participants as needed and after each task. The third limitation is that participants were aware of the surface they were landing on and the data collection

took place in a highly controlled environment. As LAS are mostly sustained during unexpected perturbations, our results should be interpreted with caution. The fourth limitation is the sex distribution of included participants (16F/6M). Our results may be more generalizable to females. The fifth limitation is related to the interpretation of the EMG differences during the preactivation phase. Changes may be related to immediate post-adaptation motor strategies in response to surface conditions. As familiarization trials were provided to participants, EMG differences during the preactivation phase could be due to a learning effect and thus perhaps not be representative of the motor control strategy during the initial trials. Readers should interpret these results with caution.

## **CONCLUSION**

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

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### Legends to figures

Fig.1. Kinematic differences between DROP, FOAM and WEDGE. Means of DROP (black), FOAM (blue) and WEDGE (red) tasks are represented by dotted lines and standard deviations are observed in the shaded region. †: Significant differences between DROP VS FOAM, ††: Significant differences between DROP VS WEDGE, ‡: Significant differences between FOAM VS WEDGE.

Fig.2. Kinetic differences between DROP, FOAM and WEDGE. Means of DROP (black), FOAM (blue) and WEDGE (red) tasks are represented by dotted lines and standard deviations are observed in the shaded region †: Significant differences between DROP VS FOAM, ††: Significant differences between DROP VS WEDGE, ‡: Significant differences between FOAM VS WEDGE.

Fig.3. EMG differences between DROP, FOAM and WEDGE. Means of DROP (black), FOAM (blue) and WEDGE (red) tasks are represented by dotted lines and standard deviations are observed in the shaded region †: Significant differences between DROP VS FOAM, ††: Significant differences between DROP VS WEDGE, ‡: Significant differences between FOAM VS WEDGE.

Fig.4. Vertical ground reaction forces differences between DROP, FOAM and WEDGE. Means of DROP (black), FOAM (blue) and WEDGE (red) tasks are represented by dotted lines and standard deviations are observed in the shaded region †: Significant

differences between DROP VS FOAM, ††: Significant differences between DROP VS WEDGE, ‡: Significant differences between FOAM VS WEDGE.

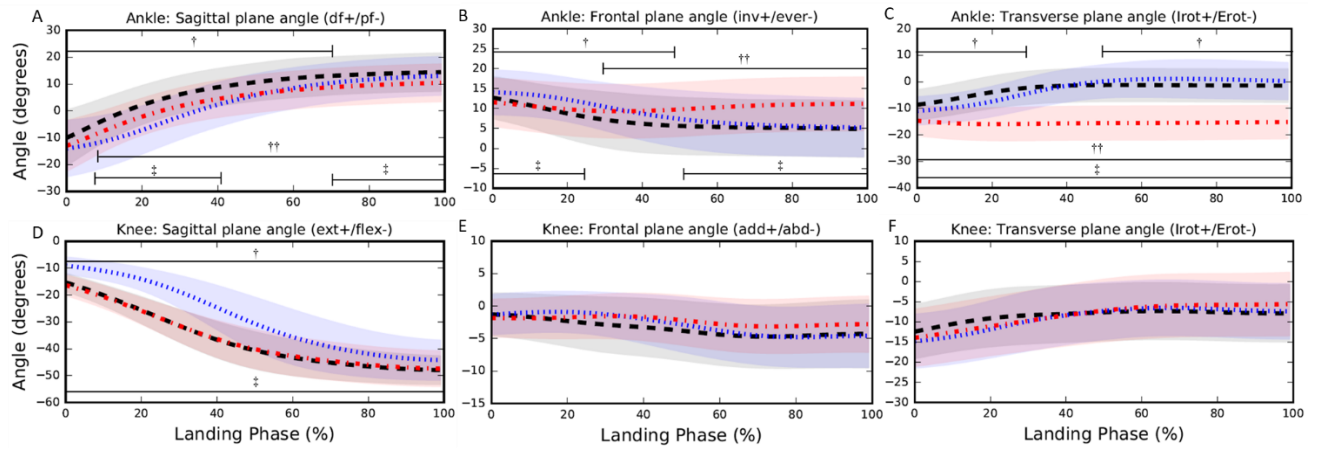
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<b>Variables</b>	<b>Mean (SD)</b>
<b>Gender ratio (M/F)</b>	6/16
<b>Age (years)</b>	24.9 (4.9)
<b>Mass (Kg)</b>	70.6 (11.4)
<b>Height (m)</b>	1.68 (0.08)
<b>Number of sustained sprains</b>	3.5 (2.0)
<b>Ankle giving way (episodes/month)</b>	5.9 (2.8)
<b>Time from first ankle sprain (year)</b>	5.8 (3.8)
<b>Time since last sprain (year)</b>	1.8 (1.9)
<b>Foot Posture Index</b>	4.1 (3.0)
<b>FAAM-ADL (%)</b>	84.2 (5.5)
<b>FAAM-S (%)</b>	62.8 (7.9)
<b>IPAQ (MET-min/week)</b>	4210 (3354)

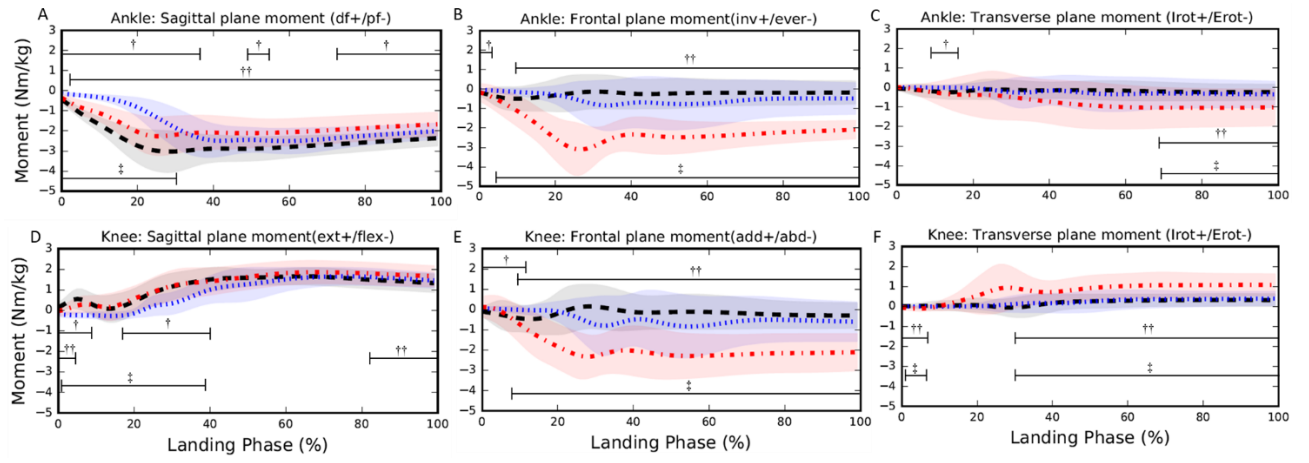
**Table 1. Demographic data. Captions : FAAM-ADL: Foot and Ankle Ability Measures-Activity of Daily Living-Activity of daily living, FAAM-Sports: Foot and Ankle Ability Measures-Activity of Daily Living-Sports, IPAQ: International Physical Activity Questionnaire**

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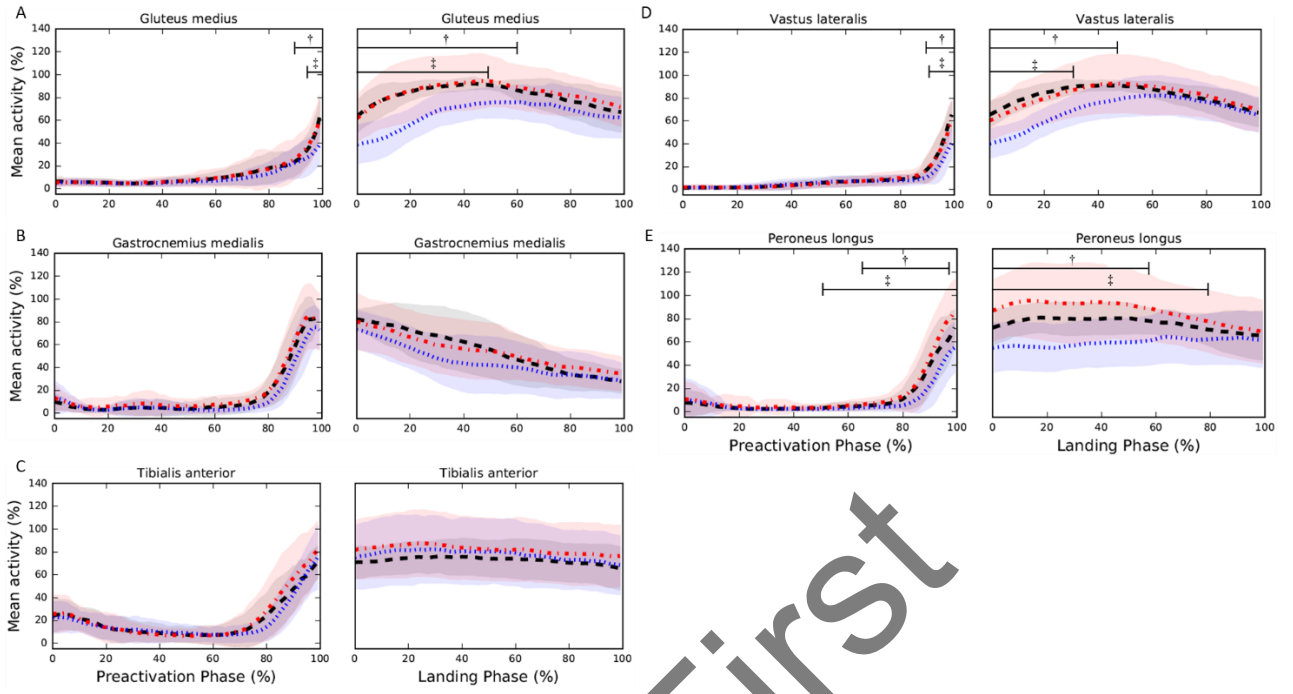




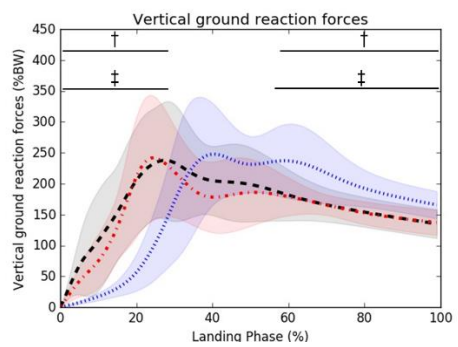
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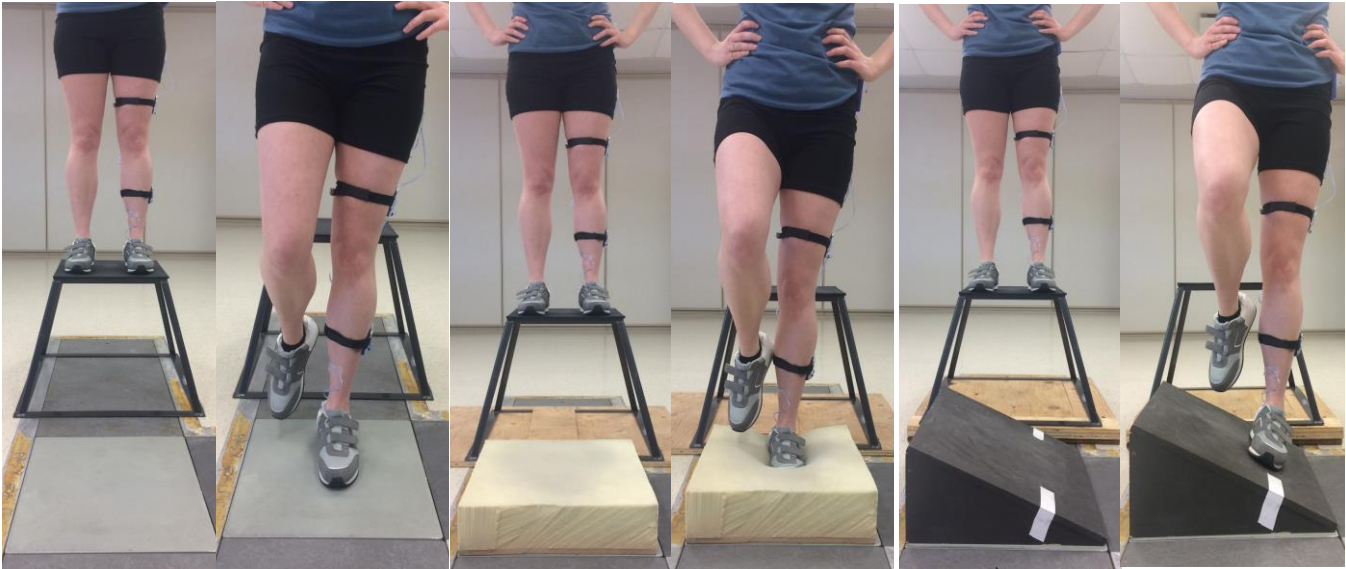
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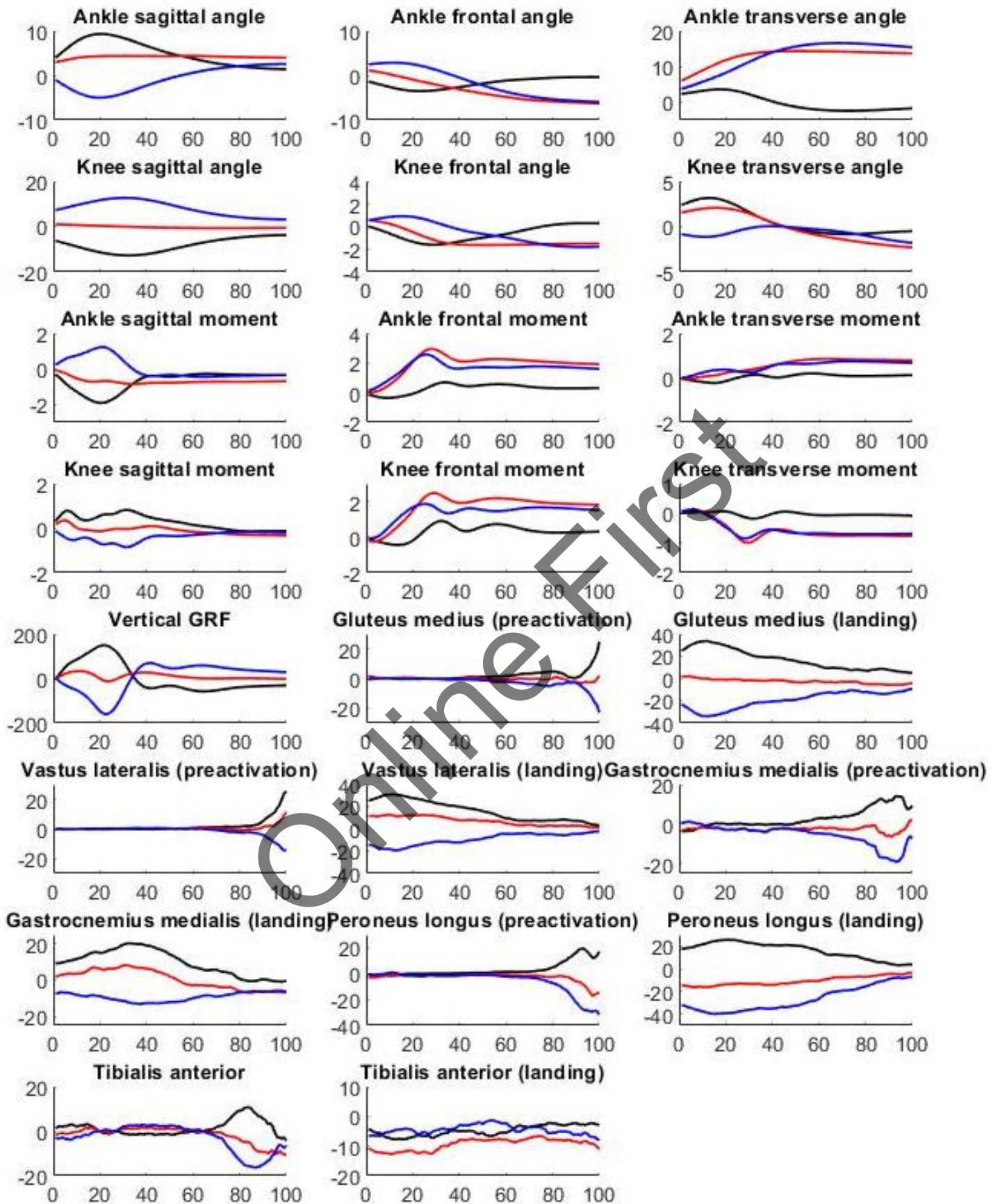


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Supplementary material 1 : Execution of DROP (left), FOAM (middle) and WEDGE (Right) tasks

Online First



**Supplementary material 2:** Mean between-task differences

**Captions:** Red line: Differences between DROP and WEDGE (+ if DROP is greater); Black line: Differences between DROP and FOAM (+ if DROP is greater); Blue line: Differences between FOAM and WEDGE(+ if FOAM is greater).