Introduction

Over multiple decades, lateral ankle sprains (LAS) have been reported as the most common musculoskeletal injury [11, 39, 43]. Within the United States, the annual cost to treat one LAS is approximately $1,000 [18], with total direct and indirect costs for treatment of LAS exceeding $6 billion per year [20]. Additionally, 30 to 70% of LAS patients develop a condition known as chronic ankle instability (CAI) [1, 2, 11, 27, 41]. Patients with CAI experience repetitive ankle sprains, feelings of instability following their initial LAS [24], are less physically active [30] and have a greater risk of developing post-traumatic ankle osteoarthritis [42] than individuals with no history of LAS. These long-term consequences present a significant health care burden and contribute to diminished quality of life following LAS [29].

Patients with LAS and CAI demonstrate altered biomechanics during walking [8, 37], jogging [5, 16, 40], and single-limb landing [9] when compared to healthy controls. Specifically, increased ankle inversion, prior to, at, and following ground contact, appears to be a consistent movement strategy across numerous functional tasks [8, 37, 40]. Excessive inversion of the foot and ankle puts patients closer to the mechanism of injury which may increase LAS risk and the episodes of instability patients with CAI experience [15, 25]. It remains unclear as to whether the excessive inversion during functional tasks is present prior to the initial sprain or if it is a maladaptive strategy following the sprain. Nonetheless, abnormal biomechanics may contribute to the high rates of LAS [25], making effective prevention and treatment strategies targeting injurious biomechanics of paramount importance if the rate of initial and recurrent LAS are to be reduced [28].

Comprehensive impairment-based rehabilitation programs are effective at improving self-reported function, dorsiflexion range of motion (ROM), ankle strength, and balance in patients with CAI [14, 35]. Unfortunately, rehabilitation programs have been unable to improve ankle frontal plane biomechanics during gait or other

Step-down Task Identifies Differences in Ankle Biomechanics Across Functional Activities

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Key words
biomechanics, chronic ankle instability, gait, rehabilitation

ABSTRACT

Currently, there is no clinical exam to evaluate ankle frontal plane kinematics. The purpose of this study was to determine whether individuals identified as “lateral” landing during a video-recorded step-down task have differences in ankle inversion as measured with 3-dimensional motion capture during walking, step-down, and jump-landing tasks compared to individuals identified as “non-lateral”. Fifty-seven recreationally active adults completed the descriptive laboratory study. During walking, step-down, and jump-landing tasks, participants had their ankle frontal plane kinematics measured using a 3-dimensional motion capture system. In addition, during the step-down task, participants had a posterior view video of their foot recorded using a commercial camera. Following testing, a blinded-investigator scored the step-down video of all participants by classifying them as “lateral” landing or “non-lateral” landing. Ankle frontal plane kinematics during the walking, step-down, and jump-landing tasks were compared between the two groups (lateral (N = 24) and non-lateral (N = 33)) using a binary logistic regression and time-series confidence interval analysis. During walking, stepping-down, and jump-landing, the lateral group had significantly more inversion at initial contact and during various other phases specific to each task. This study found that a clinical screening tool could identify individuals who have significantly more inversion during three tasks.
functional tasks and there is a corresponding deficit in self-reported function of up to 15% following rehabilitation [13, 36]. It has been suggested that the remaining deficit in self-reported function may be related to the persistently increased inversion during gait since other clinical measures of dorsiflexion ROM, ankle strength, and balance were restored to normal values compared to individuals without a history of ankle sprain [13, 14]. Recent evidence has supported this theory by demonstrating meaningful improvements in self-reported function in patients with CAI by simply reducing lateral loading during gait following one week of gait retraining [17]. Now that there is emerging evidence that functional pathomechanics in patients with CAI are treatable, it is imperative that we develop methods to identify patients with excessive inversion during functional tasks in clinical settings [15].

The ability to identify patients with excessive inversion during gait and other functional tasks may improve prevention and intervention programs by allowing clinicians to apply targeted interventions to just the patients who may be at a greater risk of sustaining a LAS [15]. Due to the complexity of foot and ankle biomechanics and the speed at which subtle motions occur during walking [22] and other functional tasks, kinematic assessment for excessive inversion has relied on 3-dimensional motion capture, which has minimal clinical utility. However, it was recently demonstrated that the extent of inversion is conserved within patients across various weight bearing tasks [12]. Specifically, the amount of ankle inversion during a simple step-down task is strongly correlated to the amount of inversion during walking and jump-landing [12]. These results suggest that it may be possible to screen for increased ankle inversion across three functional movements by evaluating a simple step-down task [12]. Furthermore, frontal plane position of the foot during flight phases is indicative of frontal plane position at and following initial contact, suggesting that clinicians may only need to evaluate the step-down task during one phase, simplifying the assessment as a clinical screening tool [12]. Therefore, the purpose of this study was to first determine whether a relationship between a clinical classification during a step-down task using simple dichotomous (lateral or non-lateral) scoring and 3-dimensional (3D) laboratory measures of ankle inversion at initial contact during 3 separate tasks (walking, step-down, and jump-landing) exists. Next, our purpose was to determine whether recreationally active individuals scored “lateral” during initial contact of the step-down task have significant differences in ankle frontal plane motion as measured by a 3D motion capture system during walking, step-down, and jump-landing tasks when compared to individuals who were scored as ‘non-lateral’. Based upon our prior results [12] that demonstrated strong relationships between the extent of inversion across these three tasks, we hypothesize that our clinical scoring system during the step down task will be predictive and will identify differences in frontal plane motion during all three tasks.

Materials & Methods

Study design

We completed a descriptive laboratory study to compare ankle frontal plane kinematics during three tasks (walking, step-down, jump-landing) in young adults that were scored as either ‘lateral’ or ‘non-lateral’ during a simple step-down screening task. The study was approved by the University’s Institutional Review Board and participants had their rights protected. Prior to participation, all participants completed the informed consent process. This study met the ethical standards of the International Journal of Sports Medicine [21].

Participants

Fifty-seven individuals (gender = M:27; F:30, age = 21.2 ± 3.1y, height = 171.7 ± 8.5 cm, mass = 76.1 ± 15.7 kg) who participate in moderate to vigorous physical activity at least 3 times per week for 30 min completed this study. Physical activity was measured using the Godin Leisure-Time Activity questionnaire [19]. All participants were free from injury or illness that prevented them from being able to complete the functional tasks.

Instrumentation and participant set-up

All functional tasks were completed using standard athletic shoes (ASICS Gel-Contend 2, ASICS America INC., Irvine, CA). Three-dimensional kinematics during the 3 tasks were measured by an electromagnetic system (TrackSTAR, Ascension Technologies Inc., Burlington, VT) with a sampling rate of 144 Hz and collected/analyzed using motion capture software (MotionMonitor, Version 8, Inovative Sports Training, Inc., Chicago, IL). Initial contact during each task was determined by a non-conductive embedded force plate with a sampling rate of 1440 Hz (Bertec Corporation, Columbus, OH) and synchronized with the electromagnetic system using the motion capture software. Three sensors were used to calculate ankle frontal plane kinematics and were placed on the dorsal aspect of the 1st metatarsal, posterior calcaneus, and lateral mid-shank. Holes were cut in the posterior aspect of the shoe to allow for sensor placement directly on the skin [13]. All sensors were attached to the limb by using double-sided tape, Leukotape®, and an elastic wrap. Sensors were only placed on one limb, which was determined randomly via coin-flip; however, in the event the participant reported a previous ankle sprain, the affected limb was used. We utilized the affected limb to be inclusive of a wide range of frontal plane motion across all subjects but since we did not include or exclude subjects based upon ankle sprain or instability status, this was not utilized in any part of our analysis. A second elastic wrap was placed on the contralateral limb to mimic the compression of the elastic wrap on the tested limb. Following set-up, ankle joint digitization was completed using a 4th moveable sensor used to local proximal and distal joint landmarks (medial/lateral knee joint line, medial/lateral malleolus, and distal tip of the 2nd phalanx). All instrumentation and participant set-up procedures have been previously reported [3, 13].

During the step-down task, 2D video of the posterior ankle was recorded using an off the shelf camera (GoPro Hero 4 Black, GoPro Inc., San Mateo, CA) recording with a resolution of 1080p and at 60 frames-per-second. The camera was placed directly on the ground with the middle portion of the lens approximately 7.5 cm high and 300 cm behind the middle portion of the force plate. The camera was controlled using a wireless remote.

Procedures

Following set-up, participants completed 15 trials of walking, step-down, and jump-landing [12]. For the walking task, we used previ-
ously reported methods [13] where participants were instructed to look forward at an eye-level target at the end of a 7.3 m raised walkway and walk forward at their normal walking pace to the end of the walkway. The investigator altered the participant’s starting point to ensure the participant’s natural walking stride caused the entire foot of the involved limb to strike the forceplate. Once the participant felt that they were walking normally and consistently striking the forceplate, 15 trials were recorded. Participants were able to take multiple steps before striking the forceplate and multiple steps after striking the forceplate. After walking trials, participants completed the step-down task by stepping off a 30 cm step on to the forceplate with their involved limb [32]. While completing the task, participants were instructed to look forward at an eye-level target, step off the step, and continue their forward momentum by walking forward. The step was placed directly behind the forceplate for step-down trials. In addition to the 3D recording, using the off the shelf video camera, a posterior view of landing was recorded for each trial. Finally, following the step-down task, participants completed 15 jump-landing trials using commonly reported procedures [38]. Participants were instructed to jump forward with both limbs off a 30 cm box that was placed half their height away from the forceplate and land with their involved foot completely inside the forceplate and their uninvolved foot completely outside. Upon landing, participants completed a maximum vertical jump.

Data reduction

3D kinematics analysis

Using a cut-off frequency of 14.5 Hz, kinematic data for the 3 tasks were filtered with a low-pass 4th-order Butterworth filter [13]. Ankle inversion was calculated using the Euler rotation method (Y,X,Z) within the motion capture software [13]. For the walking tasks, one stride cycle from each of the middle 5 trials were subjected to analysis [5]. The stride cycle was defined as initial contact of the involved limb until the frame before the 2nd initial contact of the same limb (terminal swing). Initial contact was identified by using the embedded forceplate and defined as the instance a vertical ground limb (terminal swing). Initial contact was identified by using the foot was identified by using an algorithm of velocity within the motion capture software [31]. Within the motion capture software, the 5 stride cycles were re-sampled to 100 frames where each frame represented 1% of the landing-cycle. Between groups did not overlap for at least 3 consecutive data points were considered statistically significant [13]. Analysis was completed using Microsoft Excel (Version 2016, Microsoft Corp., Redman, WA).

Results

The blinded-investigator scored 24 participants as “lateral” (gender = M:8; F:16; age = 21.7 ± 4 y, height = 173.5 ± 8.3 cm, mass = 79.7 ± 16.3 kg) and 33 participants as “non-lateral” (gender = M:22; F:11, age = 20.8 ± 2.3 y, height = 170.4 ± 8.6 cm, mass = 73.5 ± 14.9 kg). All results for our CI analysis are reported as: (mean difference ± 90 % CI; % of cycle at which the differences occurred).

Binary logistic regression

For all three binary logistic models, the amount of inversion at initial contact was a significant predictor of the assigned group membership that was based upon our clinical score of participants as lateral or non-lateral. The independent variables were the amount of inversion at initial contact as measured by 3D motion capture and the dependent variable was group (Lateral and Non-lateral) based upon our clinical screening tool. Data was analyzed using Statistical Package for Social Sciences (SPSS) Version 20.0 (SPSS, Inc, Chicago, IL).

We also analyzed group differences using a time-series confidence interval (CI) analysis. Ankle frontal plane kinematics were compared between groups: (Lateral and Non-lateral) for each task: (walking, step-down, and jump-landing). Group means and associated 90 % CIs were calculated across the 100 data points of the gait cycle for the walking task, and across the 100 data points of the landing-cycle for the step-down and jump-landing tasks [13]. Using a time-series CI analysis, kinematics were compared across the entire cycle between groups for each task [13]. Areas where CIs between groups did not overlap for at least 3 consecutive data points were considered statistically significant [13]. Analysis was completed using Microsoft Excel (Version 2016, Microsoft Corp., Redman, WA).
bership that was based upon our clinical score of subjects as lateral or non-lateral (walking, \( p < 0.001 \); step-down, \( p < 0.001 \); jump-landing, \( p = 0.008 \)). The odds ratios were 1.888 (95% CI: 1.366 – 2.611) for walking, 1.318 (95% CI: 1.134 – 1.533) for step-down, and 1.121 (95% CI: 1.030 – 1.221) for jump-landing indicating that for every 1 degree increase in inversion at initial contact subjects were 1.888, 1.318, or 1.121 times as likely to get classified as lateral, respectively.

**Walking task**

During the walking task, the group identified as lateral had significantly more inversion during initial contact phase (3.6 ± 0.9°; 1–6%) and mid-stage through terminal swing phases (3.7 ± 1.0°; 22–100%) than the non-lateral group (▶ Fig. 1). The largest group differences in ankle inversion were observed at initial contact (5.0°), toe-off (6.1°), and terminal swing (5.2°).

**Step-down task**

The lateral group had significantly more inversion than the non-lateral group throughout the entire step-down task (3.9 ± 1.1°; 1–100%), ▶ Fig. 2). The largest group differences in ankle inversion during the step-down task occurred during terminal flight (6.4°), initial contact (6.2°), and toe-off (6.0°).

**Jump-landing task**

With regards to the jump-landing task, the lateral group had significantly more inversion during the flight through initial contact phases (4.9 ± 0.7°; 1–21%), ▶ Fig. 3), where the largest group difference in ankle inversion occurred during the initial contact phase (5.5°).

**Discussion**

We were able to confirm that a relationship exists between 3D ankle frontal plane kinematics during 3 separate tasks and our clinical classification of lateral or non-lateral. Furthermore, we identified that individuals who visibly make first contact with the outer 1/3rd of their shoe during a simple step-down screening task have significantly more ankle inversion as measured by 3 dimensional motion analysis during walking, stepping-down, and jump-landing when compared to individuals whose first point contact occurred more medially. To our knowledge, this is the first study that has identified differences in ankle frontal plane kinematics in individuals grouped by a visual biomechanic ankle assessment tool. Our results suggest that analyzing a single step-down task with a commercial camera may be sufficient to screen for increased inversion across multiple tasks.

Biomechanic differences between individuals with a history of LAS and healthy controls has been well established in the laboratory setting [3–10, 16, 22, 23, 37]. A reduction in ankle dorsiflexion [3–5, 16, 23] and an increase in ankle inversion [4, 6–9, 23, 37] are two of the most commonly reported biomechanic differences observed during functional tasks following LAS and with CAI. Both of these alterations, whether in isolation or in combination, are theorized to contribute to recurrent LAS and may increase the risk of first time ankle sprains [6, 7, 16, 23, 37]. Furthermore, a prospective study has identified individuals with a laterally shifted center of pressure during gait at initial contact are at a greater risk of sustaining a LAS, regardless of sprain history [44]. Considering the relationship between gait and LAS, ankle biomechanic assessment should be included in patient screening programs regardless of sprain history. However, it is important to note that not all patients...
with LAS and CAI will develop the aforementioned pathomechanics during functional tasks, and this underscores the importance of effective screening tools so that an ‘assess-treat-reassess’ paradigm can be followed in clinical practice [15].

Our purpose was to assess whether differences in ankle frontal plane kinematics existed between two groups that we created by using a step-down task with a simple yes/no-scoring criteria with the goal of developing an evidence-based biomechanic ankle assessment tool. The intent of this investigation was not to create a clinical tool that can quantify ankle frontal plane kinematics during a given functional task, but rather identify individuals who are most likely to exhibit excessive inversion during these tasks. Based on the results stemming from the binary logistic regression analysis and given the significant relationship between the clinical step-down task and the laboratory measures of ankle inversion across all three tasks, we have determined that clinicians can classify participants as either “lateral” or “non-lateral” with some confidence. Clinicians can determine that individuals who land on the lateral aspect of their foot during a step-down task are much more likely to display increased inversion during walking, stepping-down, and jump-landing. The individuals scored as “lateral” had anywhere between a 5–6.4° difference in peak inversion across all three tasks when compared to ‘non-lateral’ individuals. This is similar in magnitude to the differences between patients with LAS and CAI during walking [6, 36], single-limb landing [9], and jump-landing [23] when compared to healthy controls suggesting the discriminative ability is clinically relevant.

With the understanding that the majority of ankle sprains occur during loading [24], it is important to note that the lateral and non-lateral group consistently demonstrated some of the largest group differences during the flight to ground contact transition. Any task with a loading response that follows an aerial phase will have the trajectory of the loading response partially dictated by the preceding flight phase [12, 25]. In other words, if an individual is in an inverted position just prior to initial contact, the loading response will also begin in an inverted position. This is particularly problematic if a subtle inversion perturbation is superimposed upon an already inverted landing. The “lateral” group in this investigation was inverted prior to initial contact, they experienced maximal inversion at initial contact and continued an inverted loading response during all three tasks. If this same kinematic profile occurred during sporting activity in patients with LAS and CAI with an altered somatosensory system [33, 34], the mal-alignment and lateral foot trajectory could theoretically explain episodes of instability and recurrent ankle sprain.

Aside from identifying large differences in ankle inversion during functional tasks, this study recapitulates that a simple step-down task may be sufficient when screening for increased inversion. Previous research established that the magnitude of ankle frontal plane kinematics are conserved across walking, step-down, and jump-landing [12], and this study indicates dichotomous scoring can separate more inverted patients during screening from patients with less or normal amounts of inversion. This is also important from a rehabilitation perspective as it could theoretically suggest that improving kinematics during one task may translate to improved kinematics in other tasks, although this hypothesis needs to be studied further. For example, if a patient lands on the outer 1/3 of their foot during the step-down assessment but is not currently able to complete jump-landing exercises, implementing gait re-training may positively impact the individual’s jump-landing mechanics during a functional rehabilitation progression. Additionally, gait training has been shown to improve frontal plane kinematics during...
ics in patients with CAI [17], whereas, there are no evidence based recommendations for improving jump-landing biomechanics. Therefore, implementing gait-retraining [17] may be one approach to improve landing kinematics, but this theory will need to be investigated further.

Limitations
An important limitation is that this biomechanic ankle assessment tool has not been prospectively tested and therefore, an individual who is scored as being lateral may not be at a greater risk of sustaining a lateral ankle sprain. Furthermore, this tool is not intended to identify individuals with CAI, but is intended to be utilized in future investigations in patients that meet criteria for CAI with the goal of identifying the subset of patients with CAI with excessive inversion during walking, stepping-down, and jump-landing who may benefit from targeted interventions. For this reason, the inclusion criteria for the current investigation were broadly defined as individuals who were recreationally active. Finally, clinicians must recognize that other lower extremity biomechanic changes (other than inversion) may also contribute to lateral ankle sprains and that not all individuals with a history of lateral ankle sprains exhibit altered biomechanics. Future studies are needed to determine this biomechanic ankle assessment tool’s sensitivity, specificity and reliability.

Conclusion
This study found that using simple yes/no-scoring criteria during posterior visual inspection of a step-down task to identify individuals who contact the ground more medially. Clinicians should appreciate the utility of screening for excessive inversion and the potential benefit of treating this conserved movement strategy with gait retraining.

Acknowledgements
Acknowledgements: This study was funded by the University of Toledo’s DeArce-Koch Memorial Endowment Fund in Support of Medical Research and Development #205260.

Conflict of Interest
The authors declare no conflict of interest.

References