Ankle

Lower Extremity Biomechanics During a Drop-Vertical Jump in Participants With or Without Chronic Ankle Instability

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Context: Chronic ankle instability (CAI) is a condition characterized by range-of-motion, neuromuscular, and postural-control deficits and subjective disability, reinjury, and post-traumatic osteoarthritis. Differences have been reported in kinematics, kinetics, surface electromyography (EMG), and ground reaction forces during functional tasks performed by those with CAI. These measures are often collected independently, and the research on collecting measures simultaneously during a movement task is limited.

Objective: To assess the kinematics and kinetics of the lower extremity, vertical ground reaction force (vGRF), and EMG of 4 shank muscles during a drop-vertical-jump (DVJ) task.

Design: Controlled laboratory study.

Setting: Motion-capture laboratory.

Patients or Other Participants: Forty-seven young, active adults in either the CAI (n = 24) or control (n = 23) group.

Intervention(s): Three-dimensional motion capture was performed using an electromagnetic motion-capture system. Lower extremity kinematics, frontal- and sagittal-plane kinetics, vGRF, and EMG of the shank musculature were collected while participants performed 10 DVJs.

Main Outcome Measure(s): Means and 90% confidence intervals were calculated for all measures from 100 milliseconds before to 200 milliseconds after force-plate contact.

Results: Patients with CAI had greater inversion from 107 to 200 milliseconds postcontact (difference = $4.01^{\circ} \pm 2.55^{\circ}$), smaller plantar-flexion kinematics from 11 to 71 milliseconds postcontact (difference = $5.33^{\circ} \pm 2.02^{\circ}$), greater ankle sagittal-plane kinetics from 11 to 77 milliseconds postcontact (difference = 0.17 ± 0.09 Nm/kg) and from 107 to 200 milliseconds postcontact (difference = 0.23 ± 0.03 Nm/kg), and smaller knee sagittal-plane kinematics from 95 to 200 milliseconds postcontact (difference = $8.23^{\circ} \pm 0.97^{\circ}$) than control participants after landing. The patients with CAI had greater vGRF from 94 to 98 milliseconds postcontact (difference = 0.83 ± 0.03 N/kg) and peroneal activity from 17 to 128 milliseconds postcontact (difference = 10.56 ± 4.52 N/kg) than the control participants.

Conclusions: Patients with CAI presented with differences in their landing strategies that may be related to continued instability. Kinematic and kinetic changes after ground contact and greater vGRF may be related to a faulty landing strategy. The DVJ task should be considered for rehabilitation protocols in these individuals.

Key Words: motion analysis, ankle sprains, kinematics, kinetics

Key Points

- Potentially harmful changes occurred during a drop-vertical-jump (DVJ) task in physically active patients with chronic ankle instability (CAI).
- Kinematic, kinetic, and peroneus longus electromyography amplitude changes in the ankle during a DVJ may indicate neuromuscular changes in patients with CAI.
- The unique challenges presented by the DVJ task versus gait for patients with CAI should be addressed during rehabilitation.

hronic ankle instability (CAI) has been associated with changes in subjective instability and disability in active individuals and during sport.^{1,2} Compared with healthy individuals, patients with CAI have changes in strength,³ neuromuscular function,^{4,5} balance and postural control,⁶ ground reaction force,^{7,8} and gait.^{9–13} Researchers^{2,14} have hypothesized that the differences play a role in continued instability, "giving way," and long-term joint dysfunction. Ankle sprains have been reported to occur often in sports such as basketball, football, and soccer, which involve both gait and jumping and landing tasks.^{15,16} Few authors have assessed the biomechanics of bilateral jump-landing tasks, such as the drop–vertical-jump (DVJ), in patients with CAI. For the DVJ, an individual performs a bilateral jump from a 30-cm box a distance of one-half the

Table. Participant Demographics

Characteristic	Group	
	Chronic Ankle Instability	Healthy Control
No. of participants	24	23
Involved limb	12 right, 12 left	13 right, 10 left
	Mean \pm SD	
Age, y	21.4 ± 3.1	21.7 ± 2.9
Height, cm	169.0 ± 8.8	165.4 ± 12.6
Mass, kg	70.7 ± 3.9	63.3 ± 13.3
No. of sprains	4.6 ± 4.2	0.0 ± 0.0
Time since first sprain, y	6.8 ± 4.5	0.0 ± 0.0
Godin Leisure-Time		
Exercise Questionnaire score	69.2 ± 26.9	82.9 ± 24.4
Identification of Functional		
Ankle Instability		
Questionnaire score	23.1 ± 3.8	0.0 ± 0.0
Foot and Ankle Ability		
Measure-Activities of		
Daily Living subscale, %	86.7 ± 7.5	100.0 ± 0.0
Foot and Ankle Ability		
Measure-Sport subscale, %	66.5 ± 15.7	100.0 ± 0.0

person's height to a target, lands on both feet, and executes a maximal vertical jump.

During gait, patients with CAI display greater inversion^{9,12} and changes in sagittal-plane ankle motion,^{9,17} which may place them in a position that increases the risk of an inversion-mechanism injury. Neuromuscular changes have been reported during assessments of strength³ and balance¹⁸ and during gait.⁴ Changes in neuromuscular function may represent a faulty control mechanism for protecting the joint when in a deleterious position during gait. Given that gait primarily occurs in the sagittal plane, it may not challenge individuals in a way that is similar to that in sport. Jump-landing tasks are more challenging for individuals with CAI.

Electromyography (EMG) has been used to assess the muscles surrounding the ankle in patients with CAI, as it may show faulty kinematic positions and associated neuromuscular changes. Activation of the anterior tibialis, peroneus longus, lateral gastrocnemius, rectus femoris, biceps femoris, and gluteus medius muscles occurred sooner relative to initial contact during gait in patients with CAI.⁴ The peroneus longus had a longer duration of activation in patients with CAI than in healthy control participants during walking gait.4 During functional exercises, patients with CAI demonstrated less EMG amplitude in the peroneus longus, anterior tibialis, and lateral gastrocnemius, with moderate to large effect sizes indicating moderate to large decreases in muscle activity compared with healthy control participants.⁴ Changes in muscle activity during gait and functional exercises require unique coordination of the entire lower extremity.

The DVJ is commonly used as an evaluation tool that simulates the mechanisms of landing and propulsion during athletic participation.^{19,20} The task has been helpful for assessing patients with pathologic knee conditions, including after anterior cruciate ligament injury and reconstruction.²⁰ The task requires coordination throughout the entire lower extremity to land, control the eccentric forces of the drop landing, and generate a propulsive force to perform

the vertical jump. The ability to position the foot and lower extremity during landing and takeoff is of interest in patients with CAI, as differences in this population may result in additional lateral ankle sprains. Hoch et al²¹ found decreases in total sagittal-plane motion of the hip, knee, and ankle during walking gait that may reflect alterations of force absorption during landing. Researchers have reported that, during both cutting tasks⁸ and single-limb landing, patients with ankle instability displayed alterations in vertical ground reaction force (vGRF) and vGRF timing.⁷ Dayakidis and Boudolos⁸ noted that, during a single-limb landing task, the onset of peak vGRF was too fast for effecting a motor response.

To our knowledge, no investigators have assessed lower extremity kinematics and kinetics during a DVJ in patients with CAI; however, differences in single-limb drop jumps have been found between patients with ankle instability and healthy control participants. Delahunt et al²² observed altered peroneus longus activity and increased ankle inversion in patients with functional instability compared with healthy control participants. Brown et al²³ showed that patients with mechanical instability had less dorsiflexion than ankle-sprain copers and had greater eversion and less sagittal-plane displacement than patients with functional instability and copers during a single-limb drop landing. These findings may indicate that jumping represents a unique task that places the patient at risk for sprain.

Therefore, the purpose of our study was to assess the ankle, knee, and hip frontal- and sagittal-plane kinematics and internal joint moments and surface EMG amplitude of the peroneus longus, peroneus brevis, anterior tibialis, and medial gastrocnemius from 100 milliseconds before to 200 milliseconds after landing from a DVJ. We hypothesized that patients with CAI would have greater inversion, more plantar flexion, and less knee and hip flexion. We also hypothesized that their kinetics would not be different but their peroneal amplitude would be higher before landing on a force plate.

METHODS

We completed a laboratory study with 1 independent variable of group (CAI, healthy control). The dependent variables of the frontal- and sagittal-plane kinematics and kinetics of the ankle, knee, and hip and the EMG amplitude of 4 lower extremity muscles (peroneus longus, peroneus brevis, anterior tibialis, and medial gastrocnemius) were assessed during a DVJ from 100 milliseconds before to 200 milliseconds after initial contact. We normalized vGRF to each participant's body mass and analyzed the 200 milliseconds after initial contact.

Participants

Forty-seven young, physically active adults (age range = 18-40 years; CAI n = 24, control n = 23) were recruited to participate in the study (Table). We defined *physically active* as participating in at least 20 minutes of physical activity 3 or more times per week. Inclusion criteria for the CAI group were a history of 1 or more lateral ankle sprains at least 12 months before the study and continued instability. The CAI group scored less than 85% on the Foot and Ankle Ability Measure-Sport (FAAM-S) subscale and greater than 10 on the Identification of Functional



Figure 1. Frontal-plane kinematic results for the A, ankle, B, knee, and C, hip, and kinetic results for the D, ankle, E, knee, and F, hip. Means \pm 90% confidence intervals presented throughout the task. The significant period is boxed. ^a Mean difference = 4.01 \pm 2.55; effect size = 0.65 (95% confidence interval = 0.29, 1.29).

Ankle Instability (IdFAI) Questionnaire. The FAAM-S is a measure of self-reported function during sport-related activity and is valid for assessing ankle instability.²⁰ The IdFAI is a valid assessment of the presence of CAI and is accurate across age groups.^{21,22} The healthy control group had no history of lower extremity injury and scored 100% on the FAAM-S and zero on the IdFAI. No participant had a history of lower extremity fracture or surgery or reported pathologic conditions other than CAI that would alter balance or function. These criteria were based on current recommendations for research involving patients with CAI.²

All participants provided written informed consent, and the study was approved by the University of Virginia Institutional Review Board (#17170).

Instruments

Kinematic and kinetic data were collected using the trakSTAR (Ascension Technology Corporation, Shelburne,

VT) electromagnetic motion-analysis system and The MotionMonitor software (version 8; Innovative Sports Training Inc, Chicago, IL) at a sampling rate of 1440 Hz. A force plate (Bertec Corp, Columbus, OH) was used to assess the initial-contact timing of all DVJs. We performed the EMG measures using surface electrodes (Delsys, Inc, Natick, MA) placed on the muscles of interest. All EMG signals were amplified with a gain of 1000 and digitized using a 4-channel acquisition system (Bagnoli Desktop EMG system; Delsys, Inc). All patients wore standardized footwear (Brooks Sports, Inc, Seattle, WA). The shoes had a region of the heel cup removed to allow sensor placement directly on the foot. The shoe manufacturer was consulted to ensure that the structure of the shoe would not be affected by removing this portion.⁷

Procedures

All patients completed the questionnaires: Foot and Ankle Ability Measure, FAAM-S, IdFAI, and Godin



Figure 2. Sagittal-plane kinematic results for the A, ankle, B, knee, and C, hip, and kinetic results for the D, ankle, E, knee, and F, hip. Means \pm 90% confidence intervals (CIs) presented throughout the task. The significant periods are boxed. ^a Mean difference = 5.33 \pm 2.02; effect size = 0.73 (95% CI = 0.32, 1.33). ^b Mean difference = 8.23 \pm 0.97; effect size = 1.01 (95% CI = 0.44, 1.46). ^c Mean difference = 0.17 \pm 0.09; effect size = 0.87 (95% CI = 0.47, 1.50). ^d Mean difference = 0.23 \pm 0.89; effect size = 0.89 (95% CI = 0.34, 1.35).

Leisure-Time Exercise Questionnaire. Fifteen DVJ trials were captured using 10 electromagnetic sensors (bilateral midthigh, midshank, posterior calcaneus, and base of the second metatarsal and T12 and C7 spinous processes). Next, digital markers were generated at the head, anteriorsuperior iliac spine, posterior-superior iliac spine, kneejoint line, and ankle-joint line to assess the joint centers of the ankle, knee, and hip.

We placed 4 surface EMG electrodes on the midmuscle bellies of the peroneus longus, peroneus brevis, anterior tibialis, and medial gastrocnemius. Manual muscle testing was performed to identify all muscles, and EMG readings were used to ensure accurate electrode placement and minimal crosstalk between muscles. Before the DVJ trials, all patients stood with both feet on the force plate for 10 seconds to enable us to collect measures of muscle activation during quiet standing.

All participants completed 15 DVJs. A 30-cm box was placed at half the patient's height from the center of the embedded force plate. We directed patients to drop off the box with both feet leaving the box and landing at the same time, but with only the limb of interest striking the force plate, and then to jump up toward a mark on the ceiling directly above the force plate. For patients with CAI, the limb of interest was recorded as the involved limb or, in the case of bilateral CAI, the limb perceived as "worse." For healthy participants, the limb was matched based on sex, height, and mass. All patients were allowed 3 practice trials to ensure they understood the task. Researchers monitored the 15 trials to ensure consistency, and participants repeated trials when they missed the force plate.

Processing

Frontal- and sagittal-plane joint angles, moments, and EMG amplitudes were extracted for the ankle, knee, and hip. Trials were filtered and normalized to 100 points representing 100 milliseconds before initial contact on the force plate to 200 milliseconds postcontact. The 300-millisecond window was converted to 100 percentage points for analysis. For all trials, 33% represented initial contact. Surface EMG amplitudes were root mean square



Figure 3. Normalized vertical ground reaction force results. The significant period is boxed. ^a Mean difference = 0.83 ± 0.03 ; effect size = 0.71 (95% confidence interval = 0.21, 1.21).

rectified and then normalized to the mean quiet-standing trials.⁴ The EMG results represented additional activity above the activation of quiet standing. All analyses were performed using The MotionMonitor software. For presentation of all results, normalized data were returned to the time domain of the jumping trial based on contact with the force plate.

Statistical Analysis

For all of the dependent variables, we generated group means, standard deviations, and 90% confidence intervals (CIs) through the entire DVJ trial. Regions where the group CIs did not overlap were considered different. From these regions, group mean differences and Cohen d effect sizes were calculated. We processed the data using MATLAB (version R2015a; The MathWorks, Inc, Natick, MA) and Excel (version 2013; Microsoft Corp, Redmond, WA). Using the CI technique, we set the α level at .10 to generate the 90% CI.

RESULTS

The CAI group had greater ankle inversion from 107 to 200 milliseconds postcontact (difference = $4.01^{\circ} \pm 2.55^{\circ}$; Cohen d = 0.65 [90% CI = 0.29, 1.29]; Figure 1) and was in less plantar flexion from 11 to 71 milliseconds postcontact (difference = $5.33^{\circ} \pm 2.02^{\circ}$; Cohen d = 0.73 [90% CI = 0.32, 1.33]; Figure 2) than the healthy group. The CAI group also exhibited greater plantar-flexion moment from 11 to 77 milliseconds postcontact (difference = 0.17 ± 0.09 Nm/kg; Cohen d = 0.87 [90% CI = 0.47, 1.50]) and from 107 to 200 milliseconds postcontact (difference = 0.23 ± 0.03 Nm/kg; Cohen d = 0.89 [90% CI = 0.34, 1.35]; Figure 2). No differences were found in ankle frontal-plane moments (Figure 1).

We observed less knee flexion in the CAI group from 95 to 200 milliseconds postcontact (difference = $8.23^{\circ} \pm 0.97^{\circ}$; Cohen d = 1.01 [90% CI = 0.44, 1.46]; Figure 2). No group differences were noted in knee frontal-plane motion or frontal-plane or sagittal-plane joint moments (Figures 1 and 2). The groups did not differ in hip kinematics or kinetics (Figures 1 and 2).

The CAI group had higher vGRF from 94 to 98 milliseconds postcontact (difference = 0.83 ± 0.03 N/kg; Cohen d = 0.71 [90% CI = 0.21, 1.21]; Figure 3). The CAI group had greater peroneus longus amplitude from 17 to 128 milliseconds postcontact (difference = 10.56 ± 4.52 above quiet-standing activity; Cohen d = 1.13 [90% CI = 0.38, 1.40]; Figure 4). No group differences were observed in peroneus brevis, anterior tibialis, or medial gastrocnemius EMG activity (Figure 4).

DISCUSSION

The CAI group had greater ankle inversion postcontact with the force plate (107-200 milliseconds postcontact). Delahunt et al²² reported that, during a single-legged drop landing, patients with ankle instability had more inversion from 200 to 95 milliseconds before initial contact. No researchers have demonstrated differences after initial contact during single-limb jump landing. In our study, the CAI and healthy groups began to move into eversion after contact with the force plate; however, the healthy group continued into greater eversion than the CAI group. During this point of the DVJ, patients with CAI should be absorbing the energy of the landing. Less eversion during this period may reflect an inability to manage the forces of the landing, which may be related to higher vGRF in the CAI group. These landing mechanics may indicate a centrally mediated process to control and stabilize the ankle during this landing task. A more inverted position may also place the ankle in a deleterious position, requiring



Figure 4. Surface electromyography results for the A, peroneus brevis, B, peroneus longus, C, anterior tibialis, and D, medial gastrocnemius. The significant period is boxed. ^a Mean difference = 10.56 ± 4.52 ; effect size = 1.13 (95% confidence interval = 0.38, 1.40).

greater activation by the peroneal muscles to pull the foot out of this position or prevent an inversion mechanism. The DVJ task appears to be associated with different landing strategies than a single-limb landing. Greater inversion after landing during the DVJ may change the forces on the lower extremity and the landing strategies.

From 17 to 128 milliseconds postcontact, the peroneus longus had greater amplitude in the CAI than in the healthy group. During this period, the CAI group had a foot position near neutral, whereas the healthy group was moving into eversion. Frontal-plane joint moments were not different during this period; however, we observed a trend toward the CAI group having a greater eversion moment (difference = 0.09 ± 0.02 Nm/kg; Cohen d = 0.37). This discrepancy may indicate that higher amplitude in the EMG signal does not reflect an increase in force generation due to a potential neuromuscular change within the individual. Researchers have found greater peroneus

longus amplitude during walking gait⁴ and less eversion strength^{3,24} in patients with CAI. The relationship between force and EMG signal is not well understood.²⁵ Investigators^{25,26} have reported that EMG increased nonlinearly with increasing force of muscle contraction; however, surface EMG signals may be limited by a variety of factors, including crosstalk within the signal, variations in electrode placement, and synergistic muscle-force production. When evaluating medial patellofemoral ligament reconstructions, Tompkins et al²⁷ demonstrated a side-by-side difference in knee-extension strength with no statistical change in quadriceps surface EMG. They hypothesized that this difference was due to the surgical intervention or an underlying deficit related to the pathologic condition. Further study is needed to assess this relationship during dynamic tasks.

After contact, the CAI group was in less plantar flexion than the healthy group. Drewes et al¹⁷ reported that, during

gait, patients with CAI had less dorsiflexion during stance and more plantar flexion during the swing phase. From 11 to 71 milliseconds postcontact, the ankle should be moving into maximal dorsiflexion as force is absorbed. Researchers have suggested that changes in the sagittal-plane motion of the ankle are due to mechanical instability of the joint²³ or sensorimotor dysfunction and joint-position-sense deficits.^{2,28} Patients with CAI have less dorsiflexion, which may explain their increased knee flexion 95 to 200 milliseconds postcontact to improve energy absorption.¹⁷ After contact, the CAI group also presented with greater ankle plantar-flexion moments (107-200 milliseconds versus 11-77 milliseconds postcontact). From 95 to 200 milliseconds postcontact, this group had less knee flexion, which may reflect less absorption capability and may require greater ankle plantar flexion to manage the forces at the distal ankle joint.

No differences were found in surface EMG amplitudes of the peroneus brevis, anterior tibialis, or medial gastrocnemius throughout the DVJ trial. Delahunt et al^{11,22} similarly noted no differences in the soleus, rectus femoris, and anterior tibialis during a single-legged drop-jump task and walking gait. Examination of other muscles of the lower extremity and their role in dynamic stability of the ankle joint has been limited.

Jump landing is a common cause of lateral ankle sprain, and the ankle is the most commonly injured joint in many sports involving jump landing.¹⁵ We selected the DVJ task based on its similarity to the landing tasks experienced during sport; however, the retrospective nature of our study may have limited the validity of these results. Future researchers should determine the relationship between our findings and causality of CAI. We analyzed a narrow window of the DVJ task because the period of landing may be important; energy absorption must occur before energy production. Investigators should expand this window to capture the movement strategies used during the DVJ task and determine appropriate interventions to improve movement strategies in this population.

Our findings reflect the importance of force management in the population with CAI. This includes the results at the knee, which plays a role in absorbing the energy of the landing task. An impairment-based rehabilitation program that includes the knee and ankle should be used to treat patients with CAI.²⁹ Research into retraining landing mechanics and focusing on both the ankle and knee may improve outcomes in this population.

CONCLUSIONS

Our findings indicated potentially deleterious changes during a DVJ task in physically active patients with CAI. The results in the ankle, including kinematics, kinetics, and peroneus longus EMG amplitude, agree with those previous authors observed during walking gait and may indicate neuromuscular changes within this population during a landing task. Compared with gait, the DVJ task presents unique challenges to the patient with CAI and should be addressed during rehabilitation.

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