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Lower Extremity Energy Dissipation and Generation During Jump Landing and Cutting in Patients With Chronic Ankle Instability

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Context: Participants with chronic ankle instability (CAI) frequently display altered movement patterns during functional movements. However, it remains unclear how these altered joint kinematics during jump landing negatively affect ankle joint health in the CAI population. Calculating joint energetics may offer an important method to estimate the magnitude of lower extremity joint loading during functional movements in participants with CAI.

Objective: To determine differences in energy dissipation and generation by the lower extremity during maximal jump landing and cutting among groups with CAI, copers, and controls.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Forty-four participants with CAI, 44 copers, and 44 controls.

Main Outcome Measures(s): Kinematics and kinetics of the lower extremity and ground reaction force data were collected during a maximal jump-landing and cutting task. The product of angular velocity in the sagittal plane and joint moment data represented joint power. Energy dissipation and generation by the ankle, knee, and hip joints were calculated by integrating regions of the joint power curve.

Results: Participants with CAI displayed reduced ankle energy dissipation (35.9% ± 10.1%) and generation (31.6% ± 12.8%; $P < .01$) compared with copers (dissipation = 43.6% ± 11.1%; generation = 40.4% ± 12.0%) and controls (dissipation = 41.3% ± 11.1%; generation = 39.6% ± 12.0%) during maximal jump landing and cutting. Participants with CAI also displayed greater energy dissipation at the knee (45.1% ± 9.1%) than copers (39.7% ± 9.5%) during the loading phase and greater energy generation at the hip than controls (36.6% ± 16.8% versus 28.3% ± 12.8%) during the cutting phase. However, copers displayed no differences in joint energetics compared with controls.

Conclusions: Participants with CAI displayed differences in both energy dissipation and generation by the lower extremity during maximal jump landing and cutting. However, copers did not show altered joint energetics, which may represent a coping mechanism to avoid further injuries.

Key Words: ankle sprain, joint energetics, functional movement

Key Points

- Participants with chronic ankle instability displayed altered joint energetics (ie, energy dissipation and generation) in the lower extremity during jump landing and cutting.
- Copers showed similar energy dissipation and generation by the ankle, knee, and hip joints compared with controls, which can explain the lack of further injuries in this group.

Ankle injuries account for 10% of all sports-related injuries, with up to 80% of ankle injuries being lateral ankle sprains (LASs).[1] Although LASs are frequently considered innocuous injuries, approximately 70% of patients with an LAS experience residual symptoms, such as swelling, pain, recurrent sprains, perceived ankle instability, recurrent giving way episodes, or all of the above, which can persist for 6 to 18 months after the initial LAS.[1] Chronic ankle instability (CAI) has been characterized by residual symptoms often in conjunction with self-reported disability.[2] Furthermore, about 70% of participants with CAI often develop degenerative changes in the ankle joint.[3] On the other hand, some patients with an LAS can return to preinjury levels of function and activity without any persistent symptoms and perceived ankle instability and are referred to as *copers*.[4]

Hertel and Corbett[2] suggested that 3 interrelated deficits—pathomechanical, sensory-perceptual, and motor-behavioral—are contributing factors to CAI. Specifically, authors of previous studies have reported altered motor-behavioral functions in participants with CAI, including delayed reaction time of the peroneal muscles to inversion perturbation[5] and reduced lower extremity muscle strength[6] relative to uninjured controls. Moreover, authors of several studies reported that these alterations of motor-behavioral functions may result in recurrent LASs.[7] Furthermore, these alterations in participants with CAI may result in decreased physical activity[8] and diminished health-related quality of life.[9]

Although altered movement patterns in participants with CAI may provide important insights into how to prevent further LASs, conflicting results have been reported in the jump-landing literature.[7,10] For example, participants with CAI have shown (1) more ankle inversion and reduced ankle dorsiflexion angles,[11] (2) reduced ankle plantar flexion and knee extension moments as well as ankle and knee joint stiffness,[12] and (3) reduced movement variability at the knee and hip joints[13] during single-leg landing. However, they also had (1) less ankle inversion and plantarflexion angles,[14] (2) increased knee flexion angle,[14] and (3) increased ankle eversion angle.[15] Furthermore, some researchers found no differences in functional movement patterns in the ankle joint between individuals with CAI and controls.[13] These discrepancies across the literature hinder clinicians in developing appropriate rehabilitation programs for the CAI population.

Participants with CAI showed altered movement patterns with reduced ankle joint displacement during jump landing.[14] Since adequate ankle range of motion (ROM) plays an essential role in reaching a stable ankle joint position during functional movements,[16] limited ROM in the ankle joint during functional movements may negatively affect ankle joint health in the CAI population. One feasible way to estimate lower extremity joint loading during functional movements can be through calculating joint energetics.[17] Joint energetics use both kinetic (ie, joint moments) and kinematic (ie, joint angular velocity) data to estimate the contributions to both energy dissipation and generation by the lower extremity (ie, ankle, knee, and hip joints) during functional tasks.[18] The magnitude of joint-specific energy contributions can be affected by changing kinematic characteristics (eg, joint angles at initial contact and angular displacement) or by the mechanical demands of tasks.[19] Moreover, the magnitude of joint work (eg, energy dissipation) during drop landing affects both internal and external forces on a joint.[19]

Previous researchers have demonstrated the effects of CAI on joint energetics in the lower extremity. Particularly, participants with CAI displayed reduced ankle energy dissipation and increased hip energy dissipation during single-leg landing.[20] However, this research was limited in that they focused mainly on uniplanar movements, which may be simplified compared with movements of actual sports activities. Furthermore, authors of most studies have calculated energy dissipation only during landing, even though cutting movements also require explosive forces, which may affect joint health in the lower extremity. Thus, investigating contributions to both energy dissipation and generation during demanding and multiplanar movements (eg, jump landing and cutting) may provide better insights into those factors contributing to degenerative changes in the ankle joint in the CAI population.

The purpose of this study was to determine differences in both energy dissipation and generation by the lower extremity during maximal jump landing and cutting among groups with CAI, copers, and controls. We hypothesized that participants with CAI would have alterations in both energy dissipation and generation by the ankle, knee, and hip joints during maximal jump landing and cutting. We also hypothesized that copers would have similar energy dissipation and generation by the ankle, knee, and hip joints when compared with controls.

METHODS

Design

This research was a controlled laboratory trial. Data were collected in the biomechanics laboratory at the university, and participants completed a single data-collection session. The independent variable was group (ie, CAI, copers, and controls). The dependent variables were contributions to energy dissipation and generation by the ankle, knee, and hip joints during maximal jump landing and cutting.

Participants

A total of 132 physically active individuals, including 44 participants with CAI, 44 copers, and 44 controls, volunteered (Figure 1). We followed the participant selection criteria of the International Ankle Consortium's position statement for CAI[21] and a recommendation for copers.[4] We used the following self-reported function questionnaires to determine potential participants: the Foot and Ankle Ability Measure Activities of Daily Living (FAAM-ADL), FAAM-Sports, and the Ankle Instability Instrument (AII). Specific inclusion criteria for the CAI, coper, and uninjured control groups can be seen in Table 1. For participants with CAI who reported a history of bilateral LASs, the limb with the worst self-reported function on the AII was designated as the involved limb for testing. Participants' exclusion criteria were (1) a history of surgery; (2) a history of fracture in the lower extremity; (3) a history of neurologic disorders, including concussion and nausea; and (4) acute injury to musculoskeletal structures of lower extremity joints in the past 3 months. All participants provided written informed consent, as approved by the university's institutional review board, before participation.

Procedures

Before participation, the primary investigator went over experimental procedures, and participants read and signed their informed consent. Anthropometric data, including height, mass, age, and gender, were recorded for each participant before marker placement. Each participant completed 5 successful maximal forward jump-landing and cutting trials, as described by previous researchers.[14] Briefly, jump-landing and cutting tasks consisted of a maximal vertical forward jump from a normalized distance (ie, 50% of the participant's height) to the center of a force plate, a landing on the involved limb, and an immediate 90° side cut to the contralateral side at a normalized distance (ie, 65% ± 5% of the participant's height). Three target locations (starting, landing on the force plate, and side-cutting locations) were provided to ensure consistency during the tasks. Participants were asked to "jump as high as you can," "land on the force plate with your involved leg only," and "side cut at 90° to the contralateral side as quickly as possible" using maximal effort while facing forward during the task. Controls performed the task with their dominant leg, which was assessed by asking individuals to self-report their dominant limb for activities such as kicking a soccer ball. Up to 5 practice trials of jump landing and cutting were allowed for each participant to reduce learning effects before actual data collection. After practice trials, each participant performed 10 trials

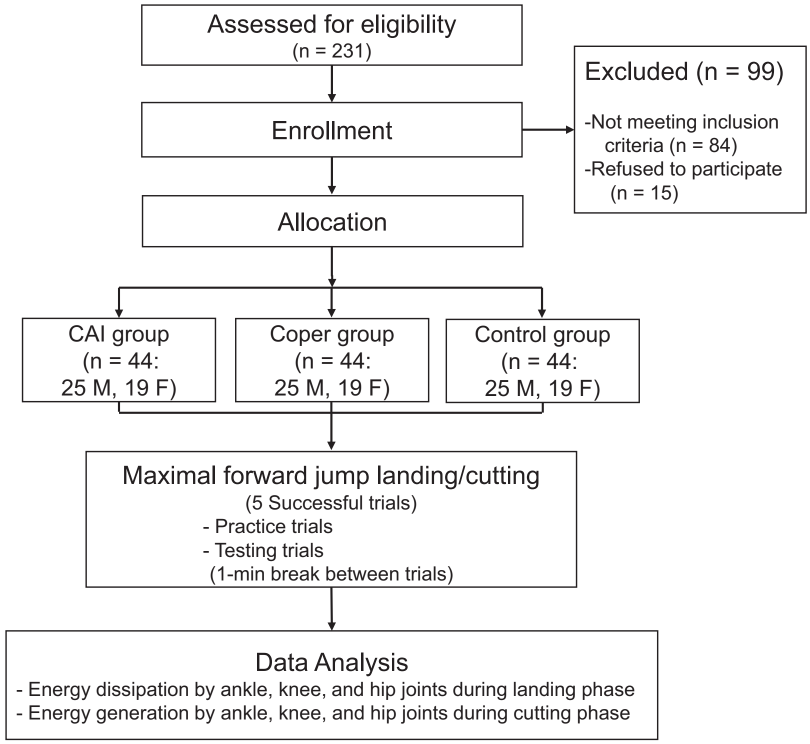

Figure 1. Flow chart of experimental procedures.

of jump landing and cutting. The mean of the first 5 trials was used to estimate a range of maximal vertical jump height by adding ±5%, the average maximal vertical jump height. The next 5 successful trials were used for data analysis. A trial was discarded and repeated when a participant missed any of the target locations or the maximal vertical jump height was outside the range of the maximal vertical jump height determined in the first 5 trials. A 1-minute rest period between each trial was provided to minimize fatigue effects.

To facilitate motion analysis during landing and cutting, the participant dressed in spandex clothing and athletic shoes (model T-Lite XI; Nike) provided by the investigators. A total of 44 reflective markers were placed bilaterally on participants' bony landmarks including the anterior- and posterior-superior iliac spine, greater trochanter, medial and lateral femoral condyle and malleoli, posterior heels, dorsal midfoot, middle forefoot, medial forefoot, and lateral forefoot. Four rigid clusters with 4 markers were also placed over the lateral midthigh and midshank. Twelve high-speed cameras (250 Hz; Qualisys) and an in-ground force plate (1000 Hz; AMTI) were used to collect the 3-dimensional (3D) kinematics and kinetics during testing. Marker placement procedures were described in a previous article.[14]

Data Processing

The 3D trajectories for each reflective marker and the ground reaction force (GRF) data were identified using

Table 1. Specific Inclusion Criteria for Each Group

CAI	Coper	Control
≥2 acute LASs required immobilization, nonweight bearing, or both for ≥3 d or external supports for ≥7 d or both.	≥1 acute LASs required immobilization, nonweight bearing, or both for ≥3 d or external supports for ≥7 d or both.	No history of previous LAS.
History of at least 2 giving way episodes within past 6 mo.	Return to moderate levels of weight-bearing physical activity without repeated ankle injury within past 12 mo.	FAAM-ADL = 100%.
FAAM-ADL < 90%.	FAAM-ADL = 100%.	FAAM-Sports = 100%.
FAAM-Sports < 80%.	FAAM-Sports =100%.	No *yes* answers on the AII.
≥5 *yes* answers on the AII.	No *yes* answers on the AII.	Physical activity ≥ 3 d/wk for 90 min within the past 3 mo.
No LE surgery or fracture.	No previous testing ankle rehabilitation.	
Physical activity ≥ 3 d/wk for 90 min within the past 3 mo.	Physical activity ≥ 3 d/wk for 90 min within the past 3 mo.	

Abbreviations: ADL, activities of daily living; AII, ankle instability instrument; CAI, chronic ankle instability; FAAM, Foot and Ankle Ability Measure; LAS, lateral ankle sprain; LE, lower extremity.

QTM software (Qualisys) and exported to Visual 3D software (C-Motion). The GRF and trajectory data were smoothed using a fourth-order, low-pass Butterworth filter with a 10 Hz cutoff frequency. As described previously,[14] a rigid link model (foot, shank, thigh, and pelvis segments) was created, and 3D joint kinematics in the ankle, knee, and hip joints were calculated using a Cardan rotation sequence. Internal joint moments of the ankle, knee, and hip were calculated using an inverse dynamics method and normalized by the height and weight of each participant. The product of angular velocity and joint moment data represented joint power.[17]

Contributions to energy dissipation and generation by the ankle, knee, and hip were calculated by integrating the negative (energy dissipation) or positive (energy generation) regions of the joint power curve (Figure 2). First, the energy dissipation by the ankle, knee, and hip joints was calculated by integrating the negative area of the power curve during the loading phase of the maximal jump landing and cutting. Since the peak ankle inversion and plantarflexion angles during jump landing or cutting occurred during the first 150 milliseconds of impact,[22,23] the loading phase was decided as the period from initial contact with the force plate (vertical GRF $>$ 15 N) to 150 milliseconds after initial contact. Next, the energy generation by the ankle, knee, and hip joints was calculated by integrating the positive area of the power curve during the cutting phase of the maximal jump landing and cutting. Because the high-impact forces during maximal deceleration were attenuated and generated during the first 150 milliseconds of the event,[24] the cutting phase is the period from maximal knee flexion to 150 milliseconds after maximal knee flexion. The contribution to energy dissipation and generation by the lower extremity was calculated relative to the total energy dissipation and generation and reported as a percentage.

Statistical Analysis

All data analyses were performed using JMP Pro 16 (SAS Institute). Participant demographic data were analyzed using 1-way analyses of variance to evaluate the between-groups differences. Tukey HSD post hoc tests were used to further analyze significant findings. Self-reported function questionnaires and energy dissipation and generation by the ankle, knee, and hip joints were analyzed using Kruskal-Wallis tests to evaluate the between-groups differences. The significance level for all analyses was set at $P \leq .05$. In addition, Cohen d effect sizes (calculated by dividing mean differences by the pooled SDs) and 95% CIs were calculated to estimate the magnitude of difference in dependent variables between groups.

RESULTS

Participant demographic results are presented in Table 2. No significant differences in age, mass, and height among the 3 groups were present. Participants with CAI displayed lower self-reported function on the FAAM-ADL, FAAM-Sports, and AII than copers and controls. No differences were observed between copers and controls on self-reported function.

Table 3 shows the percentage of total energy dissipation by each joint (ie, ankle, knee, and hip). A significant difference between groups was found in energy dissipation by ankle and knee joints during the loading phase. Participants with CAI displayed less ankle energy dissipation than copers and controls ($P < .01$). In addition, participants with CAI displayed greater energy dissipation at the knee than copers ($P = .02$). The effect sizes for ankle and knee energy dissipation during the loading phase were moderate, with 95% CIs that did not cross zero. However, no differences were apparent in the percentage of total energy dissipation for each joint between copers and controls.

Table 4 shows the energy generation contribution for each joint. Another significant group difference was found regarding ankle and hip energy generation contributions during the cutting phase. Participants with CAI displayed less energy dissipation contribution in the ankle joint than copers and controls ($P < .01$). In addition, participants with CAI displayed more hip energy generation contribution than controls ($P < .01$). The effect sizes for ankle and hip energy generation contributions during the cutting phase were moderate, with 95% CIs that did not cross zero. However, no differences were found in the percentage of total energy generation for each joint between copers and controls.

DISCUSSION

The purpose of this study was to determine differences in both energy dissipation and generation by the lower extremity during maximal jump landing and cutting among groups of CAI, copers, and controls. The primary finding was that only participants with CAI displayed altered energy dissipation and generation by the lower extremity, such as (1) less ankle energy dissipation and generation than copers and controls, (2) more knee energy dissipation than copers, and (3) more hip energy generation than controls during maximal jump landing and cutting. The secondary finding was that, in contrast to the CAI group, copers displayed no differences in either energy dissipation or generation compared with controls, which may represent a potential coping mechanism allowing copers to avoid further LASs. Thus, calculating joint energetics can be an effective method to evaluate biomechanical deficits between individuals with and those without CAI.

To our knowledge, we are the first to comprehensively determine differences in both energy dissipation and generation among CAI, copers, and control participants during jump landing and cutting. Although previous researchers have shown that participants with CAI display altered patterns of energy dissipation during single-leg landing,[20] we cannot determine altered patterns of energy dissipation in participants with CAI during potentially injurious situations, which include multiplanar movements. Moreover, authors of most studies have not assessed patterns of energy generation—doing so could have led to a better understanding of how participants with CAI transfer from the impact of landing to generating energy during cutting.

Our data were partially consistent with a previous study[20,25] in which participants with CAI displayed less energy dissipation at the ankle than did copers. Specifically, participants with CAI demonstrated lower energy

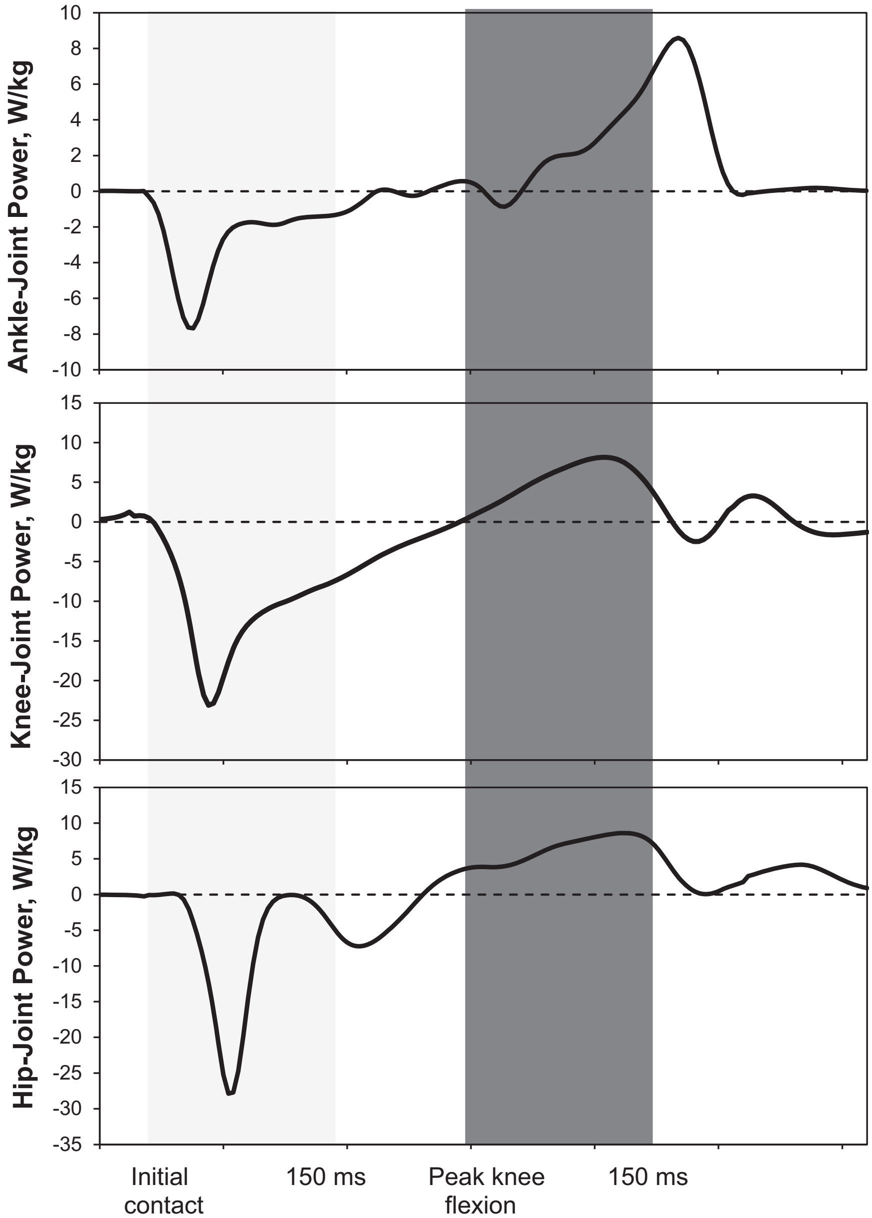

Figure 2. Example of data processing to calculate energy dissipation and generation in the lower extremity. The bright shaded area (left side) represents the energy dissipation phase, and the dark shaded area (right side) represents the energy generation phase during maximal jump landing or cutting.

dissipation of the ankle than copers and controls ($P < .01$) and greater energy dissipation of the knee than copers ($P = .02$) during the loading phase. Previously, participants with CAI had altered movement patterns with reduced ankle joint displacement during maximal jump landing and cutting.[14] Thus, limited displacement in the ankle joint may result in reduced energy dissipation by the ankle joint during the loading phase, which may reflect an effort to reduce the burden on the ankle joint during demanding movements. Moreover, increased energy dissipation by the knee joint may result from proximal adaptation of the knee to compensate for deficits in the ankle joint.[10] As the knee joint plays an important role in attenuating impact force during landing,[19] participants with CAI may try to unload their ankle joint and use more of the knee joint due to high elasticity of the knee extensor muscles.[26]

Table 2. Participants Demographics (Mean ± SD)

	CAI	Coper	Control
N	25 M, 19 F	25 M, 19 F	25 M, 19 F
Age, y	23.1 ± 2.2	22.6 ± 2.3	22.6 ± 2.5
Height, m	1.75 ± 0.1	1.74 ± 0.1	1.74 ± 0.1
Mass, kg	72.6 ± 11.2	71.2 ± 12.9	69.9 ± 10.6
FAAM-ADL, %	84.3 ± 5.2	100 ± 0.0	100 ± 0.0
FAAM-Sports, %	67.6 ± 9.4	100 ± 0.0	100 ± 0.0
AII, No. yes	6.4 ± 1.1	0.0 ± 0.0	0.0 ± 0.0

Abbreviations: ADL, activities of daily living; AII, ankle instability instrument; CAI, chronic ankle instability; FAAM, Foot and Ankle Ability Measure.

On the other hand, arthrokinematic or osteokinematic restrictions or both after ankle injuries in participants with CAI may negatively affect energy dissipation at the ankle during the loading phase. Less energy dissipation in the

Table 3. **Lower Extremity Energy Dissipation of CAI, Coper, and Control Groups**[a]

	CAI	Coper	Control	ES CAI Versus Coper	ES CAI Versus Control	ES Coper Versus Control	$F_{2,131}$	P Value
Ankle	35.9 (10.1)[b,c]	43.6 (11.1)	41.3 (9.1)	**0.73 (0.3, 1.16)**	**0.56 (0.14, 0.99)**	0.23 (−0.19, 0.65)	6.27	<.01
Knee	45.1 (9.1)[b]	39.7 (9.5)	42.0 (8.1)	**0.58 (0.15, 1.01)**	0.36 (−0.06, 0.78)	0.26 (−0.16, 0.68)	4.16	.02
Hip	18.9 (8.9)	16.7 (9.0)	16.7 (7.9)	0.25 (−0.17, 0.67)	0.26 (−0.16, 0.68)	0.00 (−0.42, 0.42)	2.01	.38

Abbreviations: CAI, chronic ankle instability; ES, effect size.
[a] Significant differences in values between groups are highlighted in bold for clarity.
[b] Statistically significant difference between CAI and coper groups.
[c] Statistically significant difference between CAI and control groups.

ankle joint in participants with CAI may help reduce ankle joint loading during maximal jump landing. However, reduced energy dissipation at the ankle due to arthrokinematics or osteokinematic restrictions or both in participants with CAI possibly offsets their efforts to reduce the joint loading in the ankle and prevent further injuries. In addition, repetitive joint loading with pathomechanical impairments (eg, limited range of dorsiflexion) in the CAI population may negatively affect ankle joint health. Thus, future researchers should examine the relationship between the limited range of dorsiflexion and the patterns of energy dissipation in the lower extremity in participants with CAI.

It is noteworthy that participants with CAI also had the lowest energy generation by the ankle joint relative to copers and controls ($P < .01$, both) and more energy generation by the hip joint than controls ($P < .01$) during the cutting phase. Hertel and Corbet[2] found that participants with CAI displayed reduced concentric plantarflexion strength. They may try to reduce ankle joint loading to avoid further injuries during cutting movements. Moreover, greater energy generation by the hip joint in participants with CAI supports the idea that CAI participants have adopted hip-dominant strategies to compensate for reduced energy generation by the ankle joint.[10] Because of the mechanical advantages of the hip joint, such as greater muscle volume and strength,[19] participants with CAI tend to rely on the hip joint more than controls to generate propulsive force during the task. However, an inefficient proximal-distal joint power transfer onto the ground to accelerate their center of mass during the cutting phase may limit effective functional movements. Thus, clinicians should consider incorporating hip muscle strengthening programs so that participants with CAI may effectively absorb and generate greater force during athletic performance.

Importantly, our results suggest that participants with CAI may have a reduced ability to generate explosive power from the ankle joint during athletic movements. Because the ankle joint plays an important role in the explosive transition of muscle contraction (ie, eccentric contraction to concentric contraction) during cutting,[27] reduced energy generation by the ankle joint may hinder athletic performance in the CAI population. In addition, as participants with CAI consistently displayed strength deficits around the ankle joint,[2] combining less energy generation at the ankle joint with muscle weakness in participants with CAI may negatively affect their functional performance, such as side hopping and figure-of-8 hopping.[28] Therefore, more studies are needed to better understand diminished movement control and athletic performance in participants with CAI.

Another interesting finding of the current study was that copers displayed no differences in both energy dissipation and generation relative to controls, which is consistent with a previous study.[25] One plausible explanation for no changes being found in lower extremity joint energetics is that copers may have an ability to coordinate their various compensatory strategies to stabilize the lower extremity during tasks.[4] Thus, it might be presumed that various compensatory strategies in copers may offset their neuromechanical deficits to prevent further injuries. Another possible explanation may be related to spinal reflex excitability. Since copers restored the ability to reflexively excite plantarflexors via alpha motor neurons,[29] they may have an adequate neuromuscular response of the ankle joint during jump landing and cutting. Thus, the ability to coordinate improved motor control variability[4] and retention of usual supraspinal motor control[29] may lead copers to develop compensatory energy dissipation and generation of the lower extremity to prevent recurrent injuries. Further research is needed to better understand the relationship between neuromuscular control and joint energetics in the lower extremity during demanding movements.

Limitations of the Study

Several limitations to the current study exist. First, we focused on physically active and young adults, but they did not essentially participate in athletic performances requiring explosive movements. Therefore, our findings cannot be

Table 4. **Lower Extremity Energy Generation of CAI, Coper, and Control Groups**

	CAI	Coper	Control	ES CAI Versus Coper	ES CAI Versus Control	ES Coper Versus Control	$F_{2,131}$	P Value
Ankle	31.6 (12.8)[a,b]	40.4 (12.0)	39.6 (12.0)	0.71 (0.28, 1.14)	0.64 (0.22, 1.07)	0.07 (−0.35, 0.48)	6.92	<.01
Knee	31.8 (10.2)	29.6 (9.5)	32.1 (8.23)	0.22 (−0.20, 0.64)	0.03 (−0.45, 0.39)	0.28 (−0.14, 0.70)	0.97	.38
Hip	36.6 (16.8)[a,b]	30.0 (12.5)	28.3 (12.8)	0.45 (0.02, 0.87)	0.56 (0.13, 0.98)	0.13 (−0.28, 0.55)	6.75	<.01

Abbreviations: CAI, chronic ankle instability; ES, effect size.
[a] Statistically significant difference between CAI and coper groups.
[b] Statistically significant difference between CAI and control groups.

generalized to athletic populations with CAI who frequently perform these high-velocity types of movements. Second, because this study was a cross-sectional design, it is unclear whether participants with CAI and copers had preexisting altered joint energetics in the lower extremity or whether these alterations were caused by LASs. Third, calculating joint energetics still requires complex data (ie, joint kinematic and kinetic data), which may be out of reach for many clinical settings. Future research is needed to investigate differences in joint energetics between individuals with and those without CAI using wearable technology, such as an inertial measurement unit and wireless load sensing insoles, to overcome this obstacle.

CONCLUSIONS

We are the first to determine differences in both energy dissipation and generation of the lower extremity during maximal jump landing and cutting among groups of CAI, copers, and controls. Participants with CAI showed reduced ankle energy dissipation and generation compared with copers and controls during loading and cutting phases. Altered knee energy dissipation during the loading phase and hip energy generation during the cutting phase may represent efforts to compensate for deficits in the ankle joint. In contrast, relative to controls, copers demonstrated no changes in either energy dissipation or generation, which may explain the lack of further injuries in this group. Therefore, clinicians need to develop rehabilitation programs incorporating proximal muscle strengthening exercises so that participants with CAI may efficiently absorb and generate greater force during athletic performance.

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