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Chronic Pain Influences Lower Extremity Energetics During Landing Cutting in Patients With Chronic Ankle Instability

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Context: Chronic ankle instability (CAI) patients exhibit altered movement patterns during jump landing/cutting movements. Persistent pain is one of the residual symptoms that may affect movements. Calculating joint energetics affected by chronic pain offers a novel method to understand how chronic pain influences energetics of lower extremity joints in CAI patients.

Objective: To identify the effects of chronic pain on lower extremity energy dissipation and generation during jump landing and cutting in patients with CAI.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: Fifteen CAI patients with higher pain (6 men and 9 women; age = 22.1 ± 2.1 years, height = 1.74 ± 0.09 m, mass = 71.3 ± 10.6 kg, pain = 66.9 ± 9.4), 15 patients with CAI and lower pain (6 men and 9 women; age = 22.3 ± 2.1 years, height = 1.74 ± 0.08 m, mass = 70.1 ± 10.7 kg, pain = 89.3 ± 2.6), and 15 healthy control individuals (6 men and 9 women; age = 21.3 ± 1.7 years, height = 1.73 ± 0.08 m, mass = 70 ± 10.3 kg, pain = 100 ± 0).

Main Outcome Measure(s): Ground reaction force data were collected during 5 trials of maximal jump landing/cutting tasks. Joint power was defined as the product of angular velocity and joint moment. Energy dissipation and generation by the ankle, knee, and hip joints were calculated by integrating regions of the joint power curve.

Results: CAI patients with higher pain displayed less ankle energy dissipation ($P = .013$ and $P = .018$) and generation in the ankle ($P = .002$ and $P = .028$) than CAI patients with lower pain and healthy control individuals during the jump landing/cutting phase. CAI patients with higher pain showed more hip energy generation than CAI patients with lower pain ($P = .038$) and healthy control individuals ($P = .013$) during the cutting phase.

Conclusions: CAI patients with higher pain changed both energy dissipation and generation in the lower extremities, reducing the burden of the ankle joint during jump landing/cutting and having a hip-dominant compensatory strategy during the cutting phase. Our results suggest that chronic pain could be one of the factors that affect motor strategies in the CAI population.

Key Words: chronic ankle instability, energetics, chronic pain, motor control

Key Points

- Patients with chronic ankle instability with higher pain demonstrated altered energetics during jump landing/cutting.
- Patients with chronic ankle instability with higher pain reflected an effort to reduce the burden on the ankle joint by a hip-dominant strategy during the cutting phase.
- Patients with chronic ankle instability with lower pain showed similar energy patterns in the lower extremities as healthy control individuals.

Lateral ankle sprains (LASs) represent approximately 80% of ankle injuries related to sports.[1] About 75% of LASs occur during jump landing movements.[2] This injury leads to an average health care expense of about $12 000 per LAS, including direct medical costs and human capital costs.[3] Up to 70% of people who experience an LAS develop chronic ankle instability (CAI) with persistent symptoms, including pain, swelling, and recurrent ankle sprains.[4] There are 3 interrelated deficiencies contributing to CAI: pathomechanical, sensory-perceptual, and motor-behavioral impairments.[4] Specifically, motor-behavioral deficits are represented in altered movement patterns in CAI patients.[4] Several studies have found altered jump landing/cutting patterns in CAI patients, suggesting that examining movement patterns could provide valuable insights for preventing future LASs.[5–7]

A previous study demonstrated that CAI patients displayed altered energy dissipation and generation in the lower extremity, including ankle, knee, and hip joints, during jump landing/cutting movements.[8] Decreased joint energetics can serve as an indicator of biomechanical risk factors contributing to the onset and persistence of injuries.[8] The extent 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.[9,10] Moreover, as the magnitude of joint work (eg, energy dissipation) during drop landing affects both internal and external

Table 1. Participants' Demographics and Self-Reported Function Outcomes

Group	Higher Pain	Lower Pain	Control	$F_{(2,42)}$ Ratio P Value
N	15	15	15	
Sex, M/F	6/9	6/9	6/9	
Unilateral/bilateral	9/6	9/6	–	
Age, year	22.1 ± 2.1	21 ± 3	22 ± 1	1.164 $P > .322$
Weight, kg	71.3 ± 10.6	74.2 ± 12.6	68.2 ± 10.2	0.069 $P > .934$
Height, m	1.74 ± 0.09	1.73 ± 0.08	1.74 ± 0.09	0.127 $P > .881$
BMI, kg/m2	22.1 ± 2.1	23.9 ± 3.6	22.3 ± 3	0.192 $P > .826$
FAAM				
ADL, %[a–c]	75.5 ± 9.8	86.2 ± 5.4	100 ± 0	50.648 $P < .001$
Sports, %[a–c]	57.0 ± 13.6	71.8 ± 9.3	100 ± 0	68.619 $P < .001$
AII[a–c]	6.6 ± 1.3	6.1 ± 0.8	0 ± 0	119.429 $P < .001$
FAOS				
Pain[a–c]	66.9 ± 9.4	91.7 ± 3.9	100 ± 0	55.914 $P < .001$

Abbreviations: ADL, activities of daily living; AII, Ankle Instability Instrument; BMI, body mass index; FAAM, Foot and Ankle Ability Measure; FAOS, Foot and Ankle Outcome Score; F, female; M, male.
[a] The higher pain group showed lower scores and more *yes* answers than the control group ($P < .01$, $P < .01$, $P < .01$, and $P < .01$).
[b] The lower pain group showed lower scores and more *yes* answers than the control group ($P < .01$, $P < .01$, $P < .01$, and $P < .01$).
[c] The higher pain group showed lower scores and more *yes* answers than the lower pain group ($P < .01$, $P < .01$, $P = .03$, and $P = .01$).

forces on a joint, altered joint energetics of the lower extremity may contribute to further injuries by increasing stress on each joint.[9,10]

However, previous studies have reported conflicting results of energy dissipation in the ankle joint in CAI patients during functional movements.[8,11] One possible explanation is that researchers have not considered various subfactors that vary patient to patient. One of these subfactors is chronic ankle pain (one of the residual symptoms) lasting longer than 3 months during daily or physical activity.[12] Chronic pain, considered a hallmark of most chronic musculoskeletal injuries, not only results in changes in the central nervous system but also leads to altered motor outcomes, thereby causing modifications in neural mechanisms.[13–16] For instance, people who have anterior knee pain have been found to develop neuromuscular impairments, which can lead to further weakness and inhibition of the muscles surrounding the knee joint (ie, arthrogenic muscle inhibition) and changes in movement patterns, including proximal and distal joints.[16,17] Because alterations in distal joints affect proximal joints through the kinetic chain during movement tasks, it is essential to investigate the energetics of the distal joints.[16] Despite the known negative effects of chronic pain on movement patterns, there has been a paucity of research exploring the specific impact of chronic pain on altered neuromechanics in CAI patients.

Therefore, understanding how chronic pain influences both energy dissipation and generation during demanding multiplanar movements may provide better insights into those factors contributing to CAI during sports activities. The purpose of this study was to investigate the effects of chronic pain on joint energetics during jump landing/cutting movements in CAI patients. We hypothesized that patients with higher pain would show reduced energy dissipation and generation in the ankle compared with CAI patients with lower pain and healthy control individuals. We also hypothesized that patients with higher pain would display increased energy dissipation and generation in proximal joints (eg, knee and hip) compared with CAI patients with lower pain and healthy control individuals.

METHODS

Design

This research was a cross-sectional and controlled laboratory study. Data were collected in a biomechanics laboratory. Participants completed a single laboratory session. The independent variable was group (CAI patients with higher pain, CAI patients with lower pain, and healthy control individuals). The dependent variables were contributions to energy dissipation and generation by the ankle, knee, and hip joints during maximal jump landing/cutting.

Participants

There was a total of 45 physically active volunteers, including 15 CAI patients with higher pain (higher pain), 15 CAI patients with lower pain (lower pain), and 15 healthy control individuals (control), with an age range of 18 to 35 years (Table 1). We followed the International Ankle Consortium's position statement to define CAI inclusion criteria.[18] We also used the pain subsection of the Foot and Ankle Outcome Scores to quantify chronic pain for group inclusion.[19] For CAI criteria, we used the following self-reported function questionnaires to determine potential CAI participants: Foot and Ankle Ability Measure (FAAM) activities of daily living (FAAM-ADL), FAAM-Sports, and the Ankle Instability Instrument (AII).[20,21] The position statement of the International Ankle Consortium recommends the FAAM questionnaire if self-reported ankle disability is important. Specific inclusion criteria for the higher pain, lower pain, and control groups can be seen in Table 2. For CAI patients who reported a history of bilateral LASs, the limb with worse self-reported function on the AII was designated as the involved limb for the testing. For chronic pain levels, we measured before movement tasks and followed a previously published study,[22] which defined the higher pain group as having scores of 75% or less,[18] whereas the lower pain group was defined as having scores of 85% or more. The reason we set 85% for the lower

Table 2. Specific Inclusion and Exclusion Criteria for Each Group

CAI		Control
1) 2 or more acute LASs requiring immobilization and/or non-weightbearing for ≥3 d or external supports for ≥7 d or both		1) No history of previous LAS
2) History of at least 2 "giving way" episodes within the past 6 months		2) FAAM-ADL = 100%
3) FAAM-ADL < 90%		3) FAAM-Sports = 100%
4) FAAM-Sports < 80%		4) No *yes* answer on the AII
5) ≥5 *yes* answers on the AII		5) Physical activity ≥3 d/wk for 90 min within the past 3 mo
6) No lower extremity surgery and/or fracture		
7) Physical activity ≥3 d/wk for 90 min within the past 3 mo		
CAI with higher pain	CAI with lower pain	
FAOS pain scores ≤ 75	FAOS pain scores ≥ 85	

Abbreviations: ADL, activities of daily living; AII, Ankle Instability Instrument; CAI, chronic ankle instability; FAAM, Foot and Ankle Ability Measure; FAOS, Foot and Ankle Outcome Score; LAS, lateral ankle sprain.

pain group is that a difference of approximately 10% in self-reported function scores may reflect differences in ankle functional outcomes and biomechanical factors.[23–26] Therefore, during recruitment, we excluded CAI participants who scored between 75% and 85%. Participant exclusion criteria were (1) a history of lower extremity surgery, (2) a history of bone fracture in the lower extremity, (3) a history of neurologic disorders, including concussion and nausea, and (4) acute musculoskeletal structure injuries of lower extremity joints in the past 3 months. Before enrollment, all participants provided written informed consent, as approved by the Brigham Young University's Institutional Review Board (IRB2022-153).

Procedures

The investigators explained the overall procedures before participation. Participants read and signed their informed consent forms. Participants were provided with spandex clothing and athletic shoes (T-Lite XI, Nike) by the investigators. Anthropometric data, including weight, height, and age, were recorded for each participant. A total of 44 reflective markers were placed bilaterally on participants' bony landmarks, including the anterior- and posterior-superior iliac spines, greater trochanters, medial and lateral femoral condyles and malleoli, posterior heels, dorsal midfoot, middle forefoot, and medial and lateral forefoot. Additionally, 4 rigid, square-shaped clusters, each consisting of 4 markers, were placed over the lateral mid-thigh and mid-shank bilaterally. Data were collected using 12 high-speed cameras (250 Hz, Qualisys) and an in-ground force plate (1000 Hz, AMTI) to capture 3-dimensional (3D) kinematics and kinetics during the testing. Marker placement procedures have been previously described.[5,8]

Each participant performed 2 practice and 5 successful maximal forward jump landing/cutting tasks, as described in previous research.[8] These tasks involved a maximal vertical forward jump with both feet from a normalized distance (ie, 50% of participant's height) to the center of a force plate. We used 3 out of the 5 highest maximum jumps to normalize the vertical height based on the posterior superior iliac spine. Participants then landed on the involved leg only and immediately executed a 90° side-cut to the contralateral side at a normalized distance (ie, 65% ± 5% of participant's height).

To ensure task consistency, 3 target points (start, landing on the force plate, and 90° side-cutting) were provided. An investigator asked participants to "jump as high as you can," "land on the force plate with your involved leg only," and "quick contralateral 90° side-cut immediately after landing" using maximal effort while facing forward during the task.

Data Processing

Qualisys Track Manager software (Qualisys) was used to process the 3D trajectories for each reflective marker and the ground reaction force data, followed by exportation to Visual3D software (C-Motion). Both ground reaction force and trajectory data were smoothed with a fourth-order, low-pass Butterworth filter using a 10-Hz cutoff frequency.[8] As described previously, a rigid link model comprising the foot, shank, thigh, and pelvis segments was created.[5] Three-dimensional 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 each participant's height and weight. The product of angular velocity and joint moment data represented joint power.[8]

Contributions to energy dissipation and generation by the ankle, knee, and hip were determined by integrating the negative (dissipation) or positive (generation) regions of the joint power curve.[8] Specifically, 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/cutting. Because both the peak ankle inversion and plantarflexion angles occurred during the first 150 milliseconds of impact, the loading phase defined the time from initial contact with the force plate (vertical ground reaction force > 15 N) to 150 milliseconds afterward.[8] Energy generation by the ankle, knee, and hip joints was calculated by integrating the positive area of the power curve graph during the cutting phase of the maximal jump landing/cutting.[8] Because the high impact forces during maximal deceleration were attenuated and generated during the 150 milliseconds of the event, the cutting phase was designated the period from maximal knee flexion to 150 milliseconds following it.[8] The contribution to energy dissipation and generation by the lower extremity was calculated as a percentage of the total energy dissipation and generation.

Statistical Analysis

All data analyses were conducted using JMP Pro 16 (SAS Institute) and assessed for normality using the Shapiro-Wilk test. Participants' demographics were analyzed using 1-way analysis of variance. Energy dissipation and generation data by the ankle, knee, and hip joints violated the Shapiro-Wilk test, so energetics data were analyzed using the Kruskal-Wallis

Table 3. Lower Extremity Energy Dissipation of Higher Pain, Lower Pain, and Control Groups

	Higher Pain	Lower Pain	Control	ES (r) High Pain Versus Low Pain	ES (r) High Pain Versus Control	ES (r) Low Pain Versus Control	z	P Value
Ankle	33.47 (3.35)[a,b]	42.37 (8.13)	46.48 (2.87)	0.64	0.61	0.30	8.64	.01
Knee	42.84 (9.79)	38.78 (8.83)	36.03 (6.65)	0.18	0.45	0.27	3.23	.20
Hip	23.68 (12.72)	18.86 (7.99)	17.28 (9.06)	0.31	0.37	0.05	2.51	.29

Abbreviation: ES, effect size.

[a] The higher pain group showed less energy dissipation in the ankle during the loading phase than the lower pain group ($z = 2.49$, $P < .013$).

[b] The higher pain group showed less energy dissipation in the ankle during the loading phase than the control group ($z = 2.36$, $P = .018$).

test and Wilcoxon paired comparison to evaluate between-group differences. The significance level for all analyses was set at $P < .05$. In addition, Wilcoxon effect size (r), calculated as the z statistic divided by the square root of the sample size, was used to estimate the magnitude of difference in dependent variables between groups, as our data are not normally distributed. Wilcoxon effect size (r) was commonly classified as *small* (0.10–0.3), *moderate* (0.30–0.5), and *large* ($\geq$0.5).

RESULTS

Self-reported function outcomes are shown in Table 1. The higher and lower pain groups showed lower self-reported ankle function, including the FAAM-ADL ($P < .01$ and $P < .01$) and FAAM-Sport ($P < .01$ and $P < .01$), than the control group. The higher pain group showed a lower FAAM-ADL ($P = .01$) and FAAM-Sport ($P = .01$) score than the lower pain group. The higher pain and lower pain groups displayed more *yes* answers in AII ($P < .01$ and $P < .01$) than the control group. The higher pain group displayed more *yes* answers in AII ($P = .03$) than the lower pain group.

The higher pain group showed less energy dissipation in the ankle during the landing phase than the lower pain ($z = 2.49$, $P < .013$, $r = 0.64$) and control groups ($z = 2.36$, $P = .018$, $r = 0.61$; Table 3). The higher pain group showed less energy generation in the ankle during the cutting phase than the lower pain ($z = 2.19$, $P = .002$, $r = 0.57$) and control groups ($z = 3.11$, $P = .028$, $r = 0.80$) groups. The higher pain group exhibited more energy generation in the hip during the cutting phase than the lower pain ($z = 2.07$, $P = .038$, $r = 0.53$) and control groups ($z = 2.49$, $P = .013$, $r = 0.64$; Table 4). All significant differences have a large effect size (r), which implies that a significant proportion of the variance in the outcome can be attributed to the effect being studied.

DISCUSSION

The purpose of this study was to identify the effect of chronic pain on energy dissipation and generation by ankle, knee, and hip joints during jump landing/cutting in CAI patients. The primary finding is that the higher pain group displayed less energy dissipation and generation in the ankle joint during the loading and cutting phase than the lower pain and control groups, which supports our first hypothesis. The secondary finding is that the higher pain group showed greater energy generation in the hip joint during the cutting phase than the lower pain and control groups, partially supporting our second hypothesis. Thus, combining both kinetic and kinematic data for joint energetics calculations offers an effective method to assess neuromechanical deficits in CAI patients experiencing chronic pain.

Interestingly, the higher pain group showed reduced contribution to energy dissipation in the ankle joint during the loading phase compared with the lower pain and control groups. This finding suggests that chronic pain may affect ankle joint movement in an attempt to reduce the burden of the ankle joint during jump landing/cutting. Previous studies have reported that CAI patients had altered joint energetics in the ankle joint during functional movements.[8,11] However, these studies have not considered chronic pain levels as being one of the residual symptoms in CAI patients. The current study's findings show that chronic ankle pain had a negative impact on and reduced contribution to the biomechanical energetics in the ankle joint in CAI patients. Therefore, the higher perceived chronic ankle pain in CAI patients results in reduced energy dissipation in the ankle joint.

Reduced ankle joint energetics in the higher pain group may result from limited dorsiflexion range of motion. Arthrokinematic and/or osteokinematic restrictions have been shown in CAI patients following LAS, adversely impacting ankle range of motion.[4,27] The decreased dorsiflexion range of motion makes it hard for them to fully achieve the normal maximal

Table 4. Lower Extremity Energy Generation of Higher Pain, Lower Pain, and Control Groups

	High Pain	Low Pain	Control	ES (r) High Pain Versus Low Pain	ES (r) High Pain Versus Control	ES (r) Low Pain Versus Control	z	P Value
Ankle	24.91 (11.53)[a,b]	34.18 (10.53)	40.32 (11.91)	0.57	0.80	0.38	11.39	.03
Knee	27.58 (7.24)	29.17 (7.45)	26.11 (9.24)	0.06	0.04	0.06	0.10	.95
Hip	47.51 (14.20)[c,d]	36.64 (12.21)	33.56 (13.52)	0.53	0.64	0.15	7.44	.02

Abbreviation: ES, effect size.

[a] The higher pain group showed less energy generation in the ankle during the cutting phase than the lower pain group ($z = 2.19$, $P = .002$).

[b] The higher pain group showed less energy generation in the ankle during the cutting phase than the control group ($z = 3.11$, $P = .028$).

[c] The higher pain group exhibited more energy generation in the hip during the cutting phase than the lower pain group ($z = –2.07$, $P = .038$).

[d] The higher pain group exhibited more energy generation in the hip during the cutting phase than the control group ($z = –2.49$, $P = .013$).

range of ankle motion of a healthy population, which, in turn, leads to reduced energy dissipation during tasks.[8] Given that mechanical restrictions are associated with chronic pain, decreased dorsiflexion range of motion may be an effort to reduce chronic pain in the ankle joint during landing and may potentially alleviate additional stress on the ankle joint in CAI patients.[28,29] However, because we did not measure mechanical factors in this study, the relationship between mechanical restriction and chronic pain level in CAI is unclear. Future research is warranted to examine the relationship between the limited dorsiflexion range of motion and energy dissipation patterns in the lower extremities in CAI patients commensurate with different levels of chronic pain.

Notably, in the current study, the higher pain group exhibited lower energy generation in the ankle joint during the cutting phase than the lower pain and control groups. This finding indicates an altered ability to generate explosive power from the ankle joint during the cutting phase in CAI patients with higher chronic pain. A previous study demonstrated that CAI patients had less energy generation in the ankle joint during the cutting phase than healthy control individuals, consistent with our result.[8] Therefore, chronic pain may be one of several factors affecting the ability to generate explosive power from the ankle joint during multiplanar movements in CAI patients.

CAI patients have consistently demonstrated muscle inhibition and strength deficits around the ankle joint.[4,30] Additionally, chronic pain, independent of other injury factors, has been shown to cause muscle inhibition and weakness.[16,17,31] Previous studies have demonstrated that foot pain is strongly associated with foot muscle weakness, and knee pain severity is one of the factors affecting deficits in quadriceps muscle strength.[16,17,31] The relationship between less ankle energy generation and muscle weakness around the ankle would lead to decreased levels of functional movements in CAI patients with high chronic pain.[32] Moreover, the ankle joint plays an important role in the explosive transition of muscle contraction (ie, eccentric contraction to concentric contraction) during the cutting phase.[21] Reduced energy generation by the ankle joint may hinder athletic performance in the CAI population, and, perhaps more importantly, reduced energy generation may limit dynamic stabilization of the ankle during demanding movement. Therefore, because previous studies have not considered the effects of chronic pain on muscle inhibition and strength in the CAI population, future studies should investigate the effects of chronic pain on muscle inhibition and strength in these patients for better understanding.[4,30,33]

Another interesting finding of this study is that the higher pain group showed more energy generation in the hip joint during the cutting phase than the lower pain and control groups. This finding may indicate that the higher pain group showed a hip-dominant strategy to compensate for the attenuated ability of the ankle joint during the cutting phase. The higher pain group, either voluntarily or involuntarily, may reduce ankle joint burden to avoid pain during cutting movements. The reduced ability of the ankle joint due to chronic pain is compensated for by using the relatively large amount of muscle mass and strength, along with structural advantages conferred by the hip joint.[10,17] However, given that CAI patients have consistently shown muscle weakness around the ankle and hip joints, the increased reliance on the hip joint may potentially signify an excessive generation of force during cutting movements.[4,34] This continued use of excessive generation of force at the hip joint may lead to additional hip-related musculoskeletal injuries. Consequently, clinicians should consider the importance of rehabilitation programs that address chronic pain control and also aim to restore hip muscle strength and joint stability to mitigate the risk of further damage.

The lower pain group showed similar energy dissipation and generation in the ankle, knee, and hip joints as the control group. These findings indicate that the lower pain group had a similar ability as the control group, suggesting that reducing chronic pain levels may help restore lower extremity energetics in CAI patients during jump landing/cutting. Therefore, chronic pain could be a significant limiting factor in lower extremity movement in CAI patients. Given that these current findings appear according to the degree of chronic pain level, previous conflicting results in CAI may be attributed to varying chronic pain levels.[8,11] Clinicians should prioritize chronic pain control to help CAI patients restore lower extremity function similar to that of healthy control individuals during rehabilitation. Further, we recommend that future studies investigate how chronic pain control treatment may enable recovering ankle and hip joint function in CAI patients during jump landing/cutting movements.

Limitations

This study has several limitations. First, although Likert scales are generally reliable measures, assessing the levels of chronic pain relies on the subjective opinions of the participants. Second, calculating joint energetics requires joint kinematic and kinetic data, which are not easily accessible and may be inaccessible for many clinical settings. Therefore, future studies could investigate the differences in joint energetics in CAI patients using portable force plates and OpenCap software (Stanford University) using smartphones to facilitate and increase the accessibility of joint energy calculation.

CONCLUSIONS

In conclusion, CAI patients with higher pain demonstrated both altered energy dissipation and generation by the ankle joint, reducing the burden of the ankle joint during the jump landing/cutting phase, and CAI patients with higher pain may use a hip-dominant strategy to compensate for reduced energy generation in the ankle joint during the cutting phase. In addition, CAI patients with lower pain as well as healthy control individuals showed similar energy patterns by lower extremities. Therefore, chronic pain level is one of the factors that may affect motor outcomes of the lower extremity.

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DECLARATION OF INTERESTS

We declare that we have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.

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