

Research article

Are Landing Biomechanics Altered in Elite Athletes with Chronic Ankle Instability

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Abstract

This study analyzed landing strategies used by athletes with chronic ankle instability (CAI) and copers compared to uninjured controls. Thirty participants were asked to perform a single-leg forward jump followed by a single-leg landing. Compared to uninjured controls, those with CAI athletes had significantly greater hip flexion and ankle eversion angles at initial landing, suggesting preference for using hip movements and extra ankle eversion angles to avoid ankle inversion when landing. CAI athletes were also found to have significantly decreased peroneus longus activation and higher ankle inversion velocity were both found during descending phase. And these were potential contributors to cause ankle inversion injury as there were likely many others. Based on these findings, CAI athletes may need to utilize more multi-joint or multi-muscle strategies during landing to maintain stability and prevent re-injury.

Key words: Ankle injuries, single-leg balance, ligament tear, electromyography.

Introduction

The ankle, one of the most important lower extremity joints helps maintain center of mass (COM) and body posture stability (Lee and Lin, 2007). Ankle sprains account for as many as 15%-25% of the injuries treated in medical practice and 10%-30% of all injuries in sports (Löttscher and Hintermann, 2014). In a systematic large-scale review, Fong et al showed 49.3% of ankle sprains were caused by participation in sports, with basketball (41.1%), football (9.3%), and soccer (7.9%) accounting for over half of all ankle sprains sustained during athletic activity (Fong et al., 2007; McCriskin et al., 2015; Waterman et al., 2010). About half of all athletes who sprain their ankles do not seek medical assistance after the incident, and this may have a profound adverse impact on their future in sports (McKay et al., 2001). Reluctance to receive rehabilitation and treatment after an ankle sprain causes symptoms such as long-term ankle instability and pain (Macleod et al., 2014) as well as increased likelihood of recurrent injuries (Delahunt et al., 2010; Sierra-Guzman et al., 2017). Mechanical ankle instability and functional ankle instability likely exist on a continuum, are not easy to separate, and may occur in both amateur athletes and elite athletes. Due to the complete spectrum of chronic ankle instability (CAI) often includes an overlap in presentation (Hossain and Thomas, 2015). The relapse rate for ankle sprains can reach as high as 40% and often lead to CAI (Wikstrom and Brown, 2013; Yeung et al., 1994).

Several biomechanics, neuromuscular control, and clinical studies have investigated CAI in injured patients and uninjured controls (de Noronha et al., 2006; Hopkins et al., 2009; Hubbard et al., 2007; Son et al., 2017; Willems et al., 2005; Witchalls et al., 2012). However, there remains a limited understanding of this complex pathology because many of their results based on similar measures conflict with each other (Liu et al., 2013; Needle et al., 2013; Terada et al., 2017). Consequently, there remains a need to better understand how CAI can lead to recurrent injury, exercise limitations, and participation restrictions (Hiller et al., 2011; Terada et al., 2017). Numbers of study comparing individuals with CAI to copers performing functional movement tasks have recently been published. In a CAI study in which participants were asked to perform a drop vertical jump. Doherty et al. found individuals with CAI had significant greater hip flexion during landing phase than copers group. (Doherty et al., 2016b). Hip strategy was very important for CAI during landing. Brown et al., studied the performance of a variety of landing tasks by CAI group and copers group, and found that CAI group had less plantar flexion, less sagittal plane displacement, and more frontal plane displacement at the ankle than copers group (Brown et al., 2008). Another study investigated the performance of a stop jump in CAI and copers groups (Brown et al., 2011). This study reported that compared to the copers group, the CAI had greater hip flexion at initial contact, and maximum displacement, greater hip maximum external rotation. Therefore, hip joint kinematic would be altered after ankle sprain. One study has suggested that the feedforward and feedback mechanisms of the operating muscles help to control anticipatory postures before and after landing, thereby conferring increased posture stability under dynamic conditions (Pietrosimone and Gribble, 2012). In addition, studies have identified mechanics alterations in the muscle activations and joints motions, particularly the knees and hips of athletes with CAI (Kipp and Palmieri-Smith, 2013; Pope et al., 2011; Son et al., 2017).

The effects of CAI on these elite athletes and how they land following repeated ankle sprains has not been discussed in detail. There were few studies to the best of our knowledge on altered movement strategies used by elite athletes with CAI and coper. Therefore, the purpose of this study was to investigate the biomechanical parameters in forward jump followed with hopping across an obstacle. In order to analyze the differences movement patterns and muscle activations in lower limbs among CAI, coper and uninjured controls athletes. We hypothesized that CAI athletes demonstrate altered movement strategies

and muscle activations of lower extremities during forward jump landing compared to copers and control athletes.

Methods

Participants

In this study, the participants standard inclusion and exclusion criteria endorsed by the International Ankle Consortium (power analysis: the statistical power is 80% and Cohen's *d* (effect size) is 26) (Gribble et al., 2013). We distributed the self-administered Cumberland Ankle Instability Tool (CAIT) (intraclass correlation coefficient, ICC = 0.96) (Hiller et al., 2006) to one hundred fifty college athletes separately at different times over a two-month period at one university, National Taiwan Normal University, located in Taipei, Taiwan. About the definition of elite athletes which likely includes athletes capable of national-level competition. Immediately following the questionnaire, a trained interviewer categorized the participants (all participants), as uninjured controls, copers, and CAI, based on the CAIT score. An athlete was defined as having CAI if he or she had a CAIT score ≤ 24 (Gribble et al., 2013). This designation was further confirmed in an athlete by the interviewer if the participant had a history of traumatic ankle sprains requiring two or more medical consultations, complained of repetitive lateral ankle sprains for at least six months or often feared his or her ankle might malfunction (Gribble et al., 2013). All participants were further evaluated by an experienced physical therapist to confirm the severity of ankle functional instability. The physical therapist would perform anterior drawer test and talar tilt test to evaluate ATFL and CFL ligaments (Lynch, 2002). Copers was defined as individuals with a history of previous initial sprain but no complaints of instability (Wikstrom and Brown 2013). These participants also had to have had (1) no complaints of ankle instability or repeated episodes of giving way, (2) resumed all pre-injury activities without limitation for at least 12 months before testing, and (3) no episodes of re-injury. (4) All their CAIT scores had to range between 25 and 28. Uninjured control participants had to have CAIT scores >29 and no history of ankle sprain. We excluded all participants from the copers and uninjured controls groups if they had sustained an ankle injury within one year of the study period (Gribble et al., 2013). Finally, athletes in these three groups were matched by age, gender, height, weight, and leg dominance (age, height, weight, and forward jump distance of the participants were limited within 10%). All participants were found to have right leg dominance, and affected leg was found to be on right side of the participant (van Melick et al., 2017). Finally, thirty of these collegiate Division I athletes were participate in this study (Table 1). This study recruited basketball, volleyball and badminton athletes as ex-

perimental participants. All participants read and signed informed consent forms. The study was approved by the Taipei Medical University Ethics Committee (TMU-JIRB201403009). The characteristics of the participants are summarized in Table 1 and flow diagram of participant recruitment is given in Figure 1.

Instruments

The thirty participants were asked to perform a jumping and landing task. Kinematics data were collected by ten infrared cameras at 200 Hz (Vicon MX 13+, Oxford, UK). Kinetics data were collected by one force platform at 1000 Hz (Kistler 9287, Winterthur, Swiss). EMG data were collected by eight wireless electrodes at 1000 Hz (Delsys Wireless EMG, Natick, MA, USA). Vicon Nexus 2.8 software was used to synchronize and acquire the lower extremity 3D kinematics, kinetics, and muscle activation profiles during single leg forward jump-landings. The sixteen reflective markers based on the Helen Hayes marker set were placed bilaterally on the participant's bony prominences (Sinsurin et al., 2013). Wireless EMG sensors were placed on the belly of the following lower limb muscles during all the tests. Surface electrodes were oriented parallel to the muscle fiber orientation over the midline of the muscle belly, as determined by manual palpation during a voluntary contraction. EMG activity was recorded from the gluteus medius (GM), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), tibialis anterior (TA), peroneus longus (PL), medial gastrocnemius (MG), and soleus (S) of the affected leg only (Feger et al., 2015).

The wireless EMG electrodes were placed on the center of muscle belly and parallel to the direction of the muscle fibers (Hermens et al., 2000).

Testing procedures

Before the performance of the task and collection of data, participants have 15 minutes warmed up exercise and running on a treadmill at a self-selected speed for approximately 5 minutes. For the experimental task, participants were asked to perform a single-leg forward jump over a 15 cm high hurdle finishing with a single-leg landing (affected leg only) on a force plate (Liu et al., 2013). All tasks were performed barefooted. The forward jump distance was standardized to 100% of individual's leg length (greater trochanter to lateral malleolus) (Figure 2). Hands were free during the flight phase but had to be placed on the hip immediately upon landing. The participants were requested to maintain their balance for five seconds following landing. If participants could not maintain their balance or if they cm high hurdle finishing with a single-leg landing (affected leg only) on a force plate (Liu et al., 2013). All tasks were performed barefooted. The forward jump distance was standardized to 100% of individual's leg length (greater

Table 1. Group (n = 30) characteristics expressed as means (standard deviations).

Groups	Healthy (8M; 2F)	Coper (8M; 2F)	CAI (8M; 2F)
Age (year)	20.1 (2.0)	19.6 (1.6)	20.1 (1.2)
Height (m)	1.76 (.08)	1.77 (.09)	1.76 (.08)
Body mass (kg)	67.2 (9.9)	71.3 (9.2)	67.8 (7.4)
CAIT (score)	29.4 (.8)	26.8 (1.1)	19.3 (1.9) *
Ankle sprains (number of times)	0.0 (.0)	1.0 (.0)	3.6 (.9) *
Forward jump (cm)	36.2 (3.4)	35.4 (2.2)	36.0 (2.1)

* p < .0001 compared with Healthy and Coper.

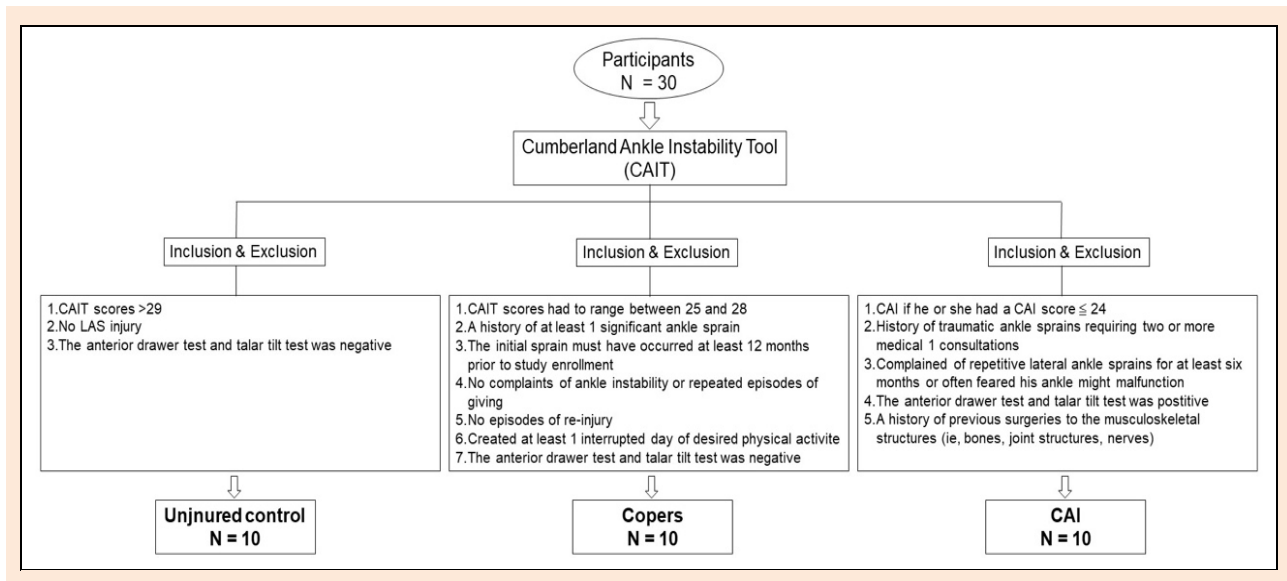


Figure 1. Flow diagram of participant recruitment.

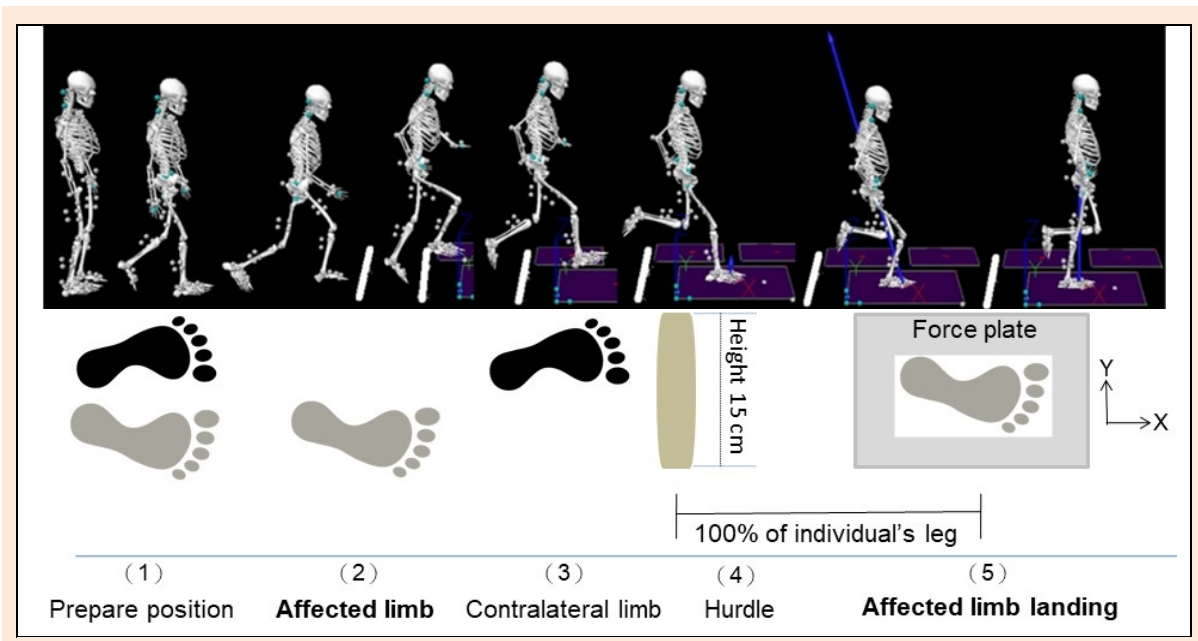


Figure 2. Forward jump testing protocol.

trochanter to lateral malleolus) (Figure 2). Hands were free during the flight phase but had to be placed on the hip immediately upon landing. The participants were requested to maintain their balance for five seconds following landing. If participants could not maintain their balance or if they made an extra movement during single-leg landing, that trial was considered a failure. The experiment continued until a total of three successful trials were collected, with three-minute intervals between each trial.

Data processing

Kinematics and kinetics data were processed using Visual 3D software (C-motion, Rockville, MD, USA). The 3D marker trajectories and GRF data were filtered by a fourth-order zero-lag Butterworth digital filter at cut-off frequencies at 8 Hz and 40 Hz, respectively (Sinsurin et al., 2013).

The position and orientation data were synchronised with the GRF data. The joint angles were calculated as previously reported by Wu et al. (2002). Euler rotations (X-Y-Z, representing respectively dorsi / plantar flexion, eversion / inversion, ab / adduction) were used to calculate motion between the defined segments in the different planes (Wu et al., 2002). Kinematics and kinetics data used to calculate all the 3 planes lower extremity joint angle, velocity, moment, and muscle activities during forward jump-landing. Acqknowledge software (version 4.2; Biopac Systems) was used to process EMG signal data. A 10 to 500 Hz bandpass filter and calculated using a 20-sample moving average root mean square (RMS) algorithm (Grindstaff et al., 2015). The values of maximum voluntary isometric contraction (MVIC) were obtained to normalize some of the studied variables (Burden et al., 2003). MVICs of the

ankle, knee and hip muscle groups were performed using a BIODEX 900-800 dynamometer (Biodex Systems, Inc., Shirley, New York). At least 3 min elapsed between each set of three MVICs and at least 5 min between each MVIC group to minimize the effects of fatigue. During each MVIC, participants were encouraged to observe the development of the torque-time trace on the BIODEX PC monitor (Burden et al., 2003).

The jump-landing movement was further divided into two phases: pre-landing and descending. The pre-landing phase was defined 100 ms prior to initial contact. The landing was defined as initial foot contact with the force plate. The initial foot contact from single leg jump-landing was determined based on a 10 N vertical ground reaction force threshold. The descending phase was defined from initial contact to the maximum knee flexion angle. The Kinematics and kinetics data were normalized to 100% from initial contact to the maximum knee flexion angle. In order to compute co-activation for the descending phase of the forward jump-landing, the following equation was applied (Marquez et al., 2013):

$$\text{Muscle co-activation (\%)} = (\text{RMS EMG}_{\text{antagonist}} / \text{RMS EMG}_{\text{agonist}}) \times 100.$$

Statistical analysis

First, the homogeneity of variance test was conducted when comparing three independent groups on a continuous outcome with ANOVA. Second, one-way ANOVA was conducted to compare the differences of lower extremity joint kinematics and muscle activations during jump-landing among the uninjured controls, copers, and CAI groups. Post hoc comparisons were performed using the Scheffe's test, if statistical significance was found among the groups. P value $< .05$ was considered significant. All statistical operations were performed using SPSS Version 22.0 (SPSS, Chicago, IL).

Results

Movement pattern

Participants' characteristics are summarized in Table 1. Except for CAIT score and number of ankle sprains, there were no significant differences between groups. All participants were able to complete the forward jump test. At the initial single leg jump-landing, compared to the CAI group, the uninjured controls group had a significantly smaller hip flexion angle ($F = 4.83$, $p = 0.017$, $\eta^2 = 0.279$, power = 0.748) (Table 2), ankle eversion angle ($F = 7.74$, $p = 0.003$, $\eta^2 = 0.392$, power = 0.921) (Figure 3), and ankle inversion angular velocity in the early stage of landing ($F = 11.91$, $p = 0.001$, $\eta^2 = 0.509$, power = 0.988) (Figure 4). The CAI had a significant greater hip flexion angle ($F = 7.17$, $p = 0.004$, $\eta^2 =$

0.374, power = 0.899) (Table 2) and hip adduction angle ($F = 3.77$, $P = 0.037$, $\eta^2 = 0.232$, power = 0.633) (Figure 5), but had smaller ankle inversion angle ($F = 4.97$, $p = 0.016$, $\eta^2 = 0.293$, power = 0.758) (Figure 5) during descending phase. At the peak moment of descending phase, the CAI group had a significantly greater ankle eversion moment compared to the uninjured controls and copers groups ($F = 10.36$, $p = 0.002$, $\eta^2 = 0.614$, power = 0.959) (Figure 6).

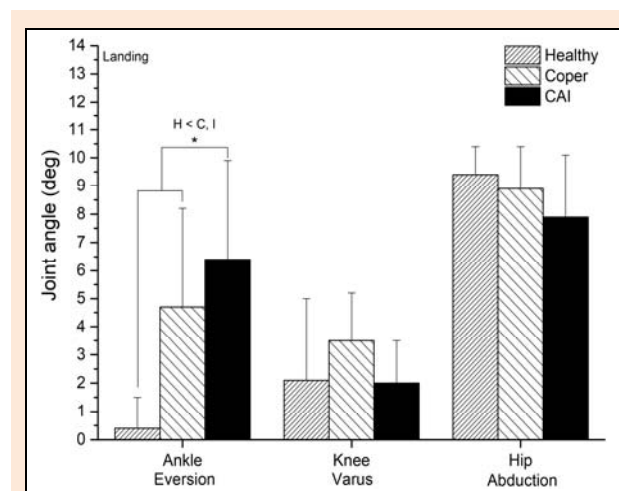


Figure 3. The lower extremity joint angle at the initial contact with the ground. H = Uninjured control group; C = Copers group; I = CAI group; + values indicate ankle eversion, knee valgus, hip abduction. * $p < 0.05$.

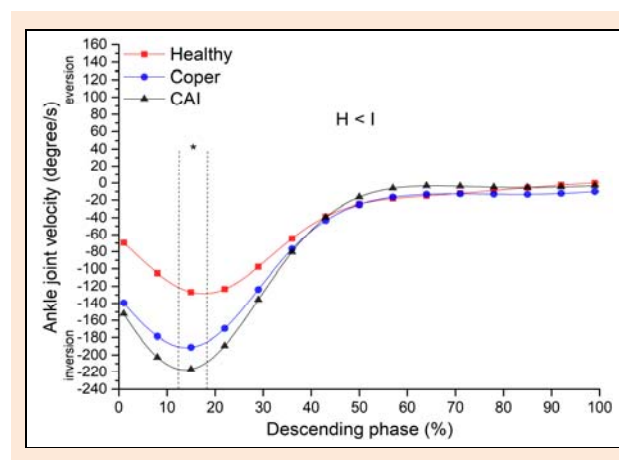


Figure 4. Ankle joint velocity of frontal plane during the descending phase. Descending phase: Initial contact to maximum knee flexion; H = Uninjured control group; C = Copers group; I = CAI group; 0% indicates initial landing; 100% indicates max squat; 0% indicates initial landing; 100% indicates max squat; 0% indicates initial landing; 100% indicates max squat; + values indicate ankle eversion; - values indicate ankle inversion. * $p < 0.05$.

Table 2. Kinematic variables (n = 30) of sagittal plane for joint angle and one-way ANOVA significant.

		Healthy	Coper	CAI	p	Post hoc
Landing (deg)	Hip	27.3 (4.9)	32.9 (3.6)	34.7 (6.3)	.017*	H < I
	Knee	15.1 (3.2)	16.6 (3.5)	15.3 (5.3)	.689	
	Ankle	-24.0 (4.4)	-22.0 (4.9)	-23.1 (3.6)	.612	
Max squat (deg)	Hip	33.4 (2.5)	39.3 (2.6)	43.6 (8.2)	.004*	H < I
	Knee	54.1 (7.2)	51.8 (4.3)	52.3 (7.9)	.741	
	Ankle	14.4 (4.0)	14.9 (3.3)	13.8 (4.6)	.843	
Range of motion (deg)	Hip	6.4 (1.6)	8.8 (3.4)	9.4 (2.0)	.042*	H < I
	Knee	38.8 (4.2)	35.2 (2.9)	37.0 (6.0)	.274	
	Ankle	38.5 (5.9)	36.9 (4.3)	36.9 (4.4)	.747	

Positive value: ankle dorsiflexion; Negative value: ankle plantar flexion; *indicates statistical significance $p < .05$; range of motion was defined from initial contact to the maximum knee flexion angle; H = Uninjured control group; C = Copers group; I = CAI group.

Table 3. Different phase EMG activity and one-way ANOVA significant.

Phases	Muscle	F	p	η^2	power	Post hoc
Pre-landing	TA	4.77	.018*	.293	.737	H > C, I
	PL	6.09	.008*	.367	.836	H > C, I
Landing	MG	5.68	.013*	.401	.793	H, C < I
	Soleus	4.00	.033*	.267	.653	H, C < I
Descending	PL	4.82	.017*	.287	.745	H > C, I
	TA	3.98	.035*	.285	.645	H > C, I
	Soleus/TA	4.34	.026*	.283	.692	H < I
	MG/TA	3.58	.047*	.264	.596	H < I

H = Uninjured control group; C = Copers group; I = CAI group; GM = gluteus medius; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; TA = tibialis anterior; PL = peroneus longus; MG = medial gastrocnemius; S = soleus; Pre-landing phase: 100 ms prior to initial contact; Landing: Initial contact with ground; Descending phase: Initial contact to maximum knee flexion.

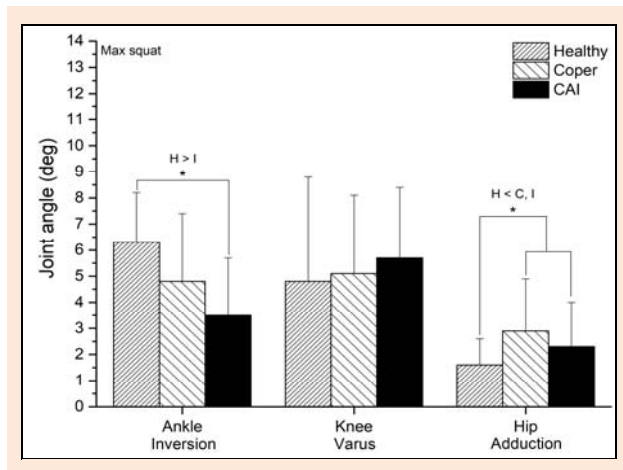


Figure 5. The lower extremity joint angle at the maximum knee flexion. H = Uninjured control group; C = Copers group; I = CAI group; + values indicate ankle inversion, knee valgus, hip adduction. * $p < 0.05$.

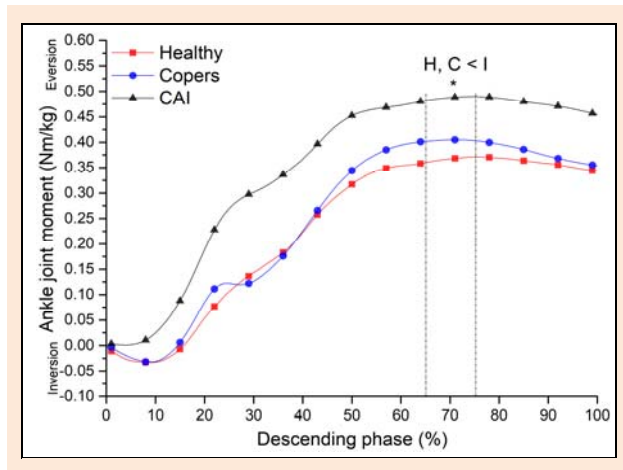


Figure 6. Ankle joint moment of frontal plane during the descending phase. H = Uninjured control group; C = Copers group; I = CAI group; 0% indicates initial landing; 100% indicates max squat; 0+ values indicate ankle eversion; - values indicate ankle inversion. * $p < 0.05$.

EMG activity

During the pre-landing phase, compared the CAI and copers group, the uninjured controls group had significantly greater muscle activation of TA and PL (Table 3) (Figure 7). At the initial landing, compared to the CAI group, the copers and uninjured controls groups had significantly smaller muscle activation of MG and Soleus (Table 3) (Figure 8). During the descending

phase, compared to the CAI and copers groups, the uninjured controls group had significantly greater muscle activation of the PL and TA (Table 3) (Figure 9). However, during the descending phase, compared to the CAI group, the uninjured controls group had significantly smaller co-activation the Soleus/TA and MG/TA (Table 3) (Figure 10).

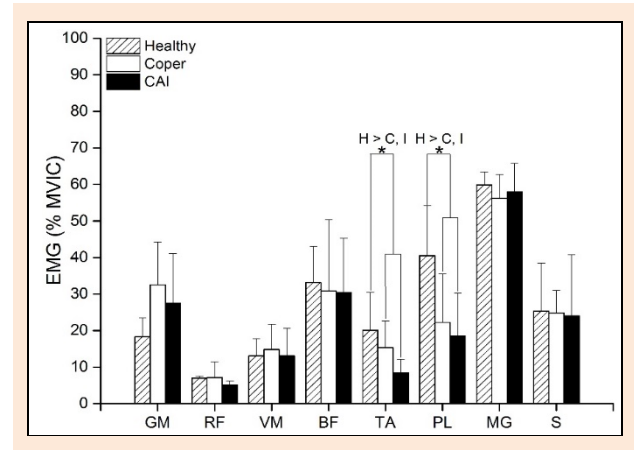


Figure 7. The lower extremity muscle activities during the pre-landing phase. Pre-landing phase: 100 ms prior to initial contact; H = Uninjured control group; C = Copers group; I = CAI group; GM = gluteus medius; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; TA = tibialis anterior; PL = peroneus longus; MG = medial gastrocnemius; S = soleus. * $p < 0.05$.

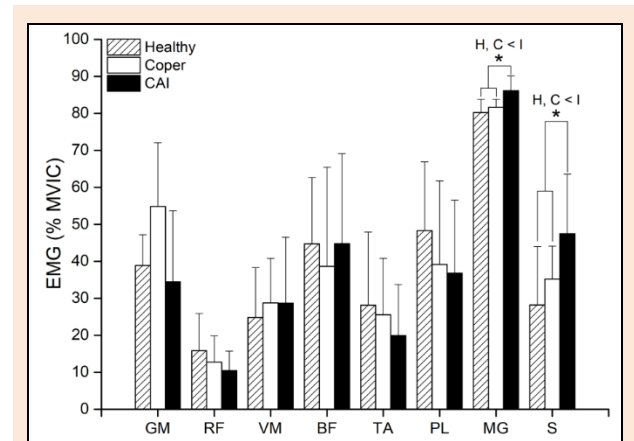


Figure 8. The lower extremity muscle activities at the initial contact with the ground.Initial landing: Initial contact with ground; H = Uninjured control group; C = Copers group; I = CAI group; GM = gluteus medius; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; TA = tibialis anterior; PL = peroneus longus; MG = medial gastrocnemius; S = soleus. * $p < 0.05$.

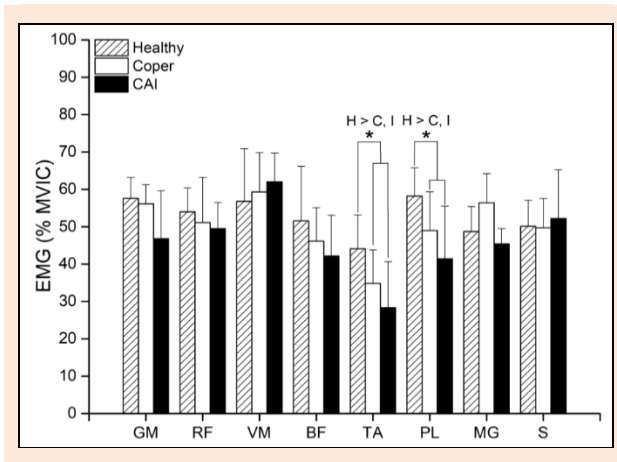


Figure 9. The lower extremity muscle activities during the descending phase. Descending phase: Initial contact to maximum knee flexion; H = Uninjured control group; C = Copers group; I = CAI group; GM = gluteus medius; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; TA = tibialis anterior; PL = peroneus longus; MG = medial gastrocnemius; S = soleus. * $p < 0.05$.

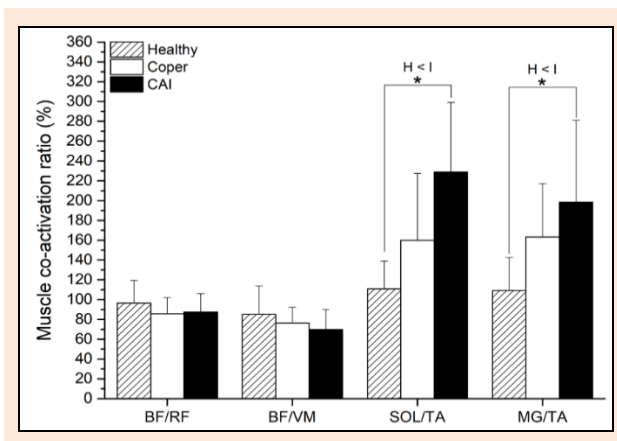


Figure 10. The lower extremity muscle co-activation during the descending phase. Descending phase: Initial contact to maximum knee flexion; H = Uninjured control group; C = Copers group; I = CAI group; GM = gluteus medius; RF = rectus femoris; VM = vastus medialis; BF = biceps femoris; TA = tibialis anterior; PL = peroneus longus; MG = medial gastrocnemius; S = soleus. * $p < 0.05$.

Discussion

The main objective of this study was to analyze single-leg jump-landing patterns in CAI, copers, and uninjured control athletes and to determine whether CAI athletes would use different movement pattern combined with different lower extremity muscles activation strategy. The major findings were that copers athletes have similar landing pattern which showed in CAI athletes, suggesting that ankle sprain sequelae increase the risk of recurrent injuries. Second, CAI athletes and copers athletes had significantly lower ankle muscle activations than uninjured control athletes. This finding would be associated with decreased neuromuscular control of ankle and caused increased inversion angular velocity which was possibly a key contributor to the recurrent injuries. CAI and copers athletes also frequently used ankle eversion as their major alteration movements at the initial landing to reduce the effect of ankle over-inversion. In addition, both groups used more hip flexion and adduction to control trunk movement in order

to compensate possibly ankle inversion. Further, CAI athletes tended to co-contract muscles around ankle joint to help them achieve a better joint stability. In this study, we found that CAI athletes and copers athletes had significantly less activation of the PL muscle suggested that altered neuromuscular control of ankle stability in the frontal plane which might result in a higher angular velocity during ankle inversion (Figure 7 and 9). According to Steib et al., ankle sprains cause changes in proprioception, muscle strength, and balance (Steib et al., 2013). The PL muscle has been found to be the first muscle to contract in response to sudden ankle inversion stress and is important for controlling the dynamic stability of the ankle joint (Li et al., 2015). The TA muscle, dorsiflexor and invertor, also plays an important role for ankle stability. Therefore, it is possible that the PL and TA muscles are impaired in CAI athletes. This impairment may lead to insufficient repression of ankle inversion at initial landing, thereby producing a higher angular velocity of inversion in the following descending phase (Konradsen and Voigt, 2002). This landing behaviors may be risky or have negative consequences. In the initial of descending phase (~10-20%), we found that CAI demonstrated a smaller ankle eversion moment and less PL activation than uninjured control athletes (Figure 6 and 9), which resulted in -220 deg/sec of inversion angular velocity in CAI (Figure 4). CAI were not able to efficiently control inversion angular velocity in the descending phase of landing. This would make them prone to recurrent ankle sprains. Similar results have been reported by other studies (Gehring et al., 2014).

The current study also found that both CAI and copers athletes had greater eversion at initial contact and less inversion during descent period (Figure 3 and 5). They tried to avoid a risky landing position by limiting ankle inversion angles. Those alteration movements as their major landing strategy to reduce the possibility of ankle over-inversion during jump-landing. From our results, CAI athletes demonstrated a greater ankle eversion as a protective mechanism. However, the protective mechanism only occurs at initial landing (0~5 %). CAI athletes showed insufficient activation of PL muscle and small ankle eversion moment with higher ankle inversion velocity during 10-20 % of descending phase (Figure 6, 7 and 9). Although the CAI athletes involved in this study were at increased potential risk of experiencing recurrent ankle sprains, they employed special motion pattern to cope with impact during the landing phase. A study by Doherty et al. on the drop-landing of CAI patients showed that they had ankle eversions in the early stage of landing, which then turned into inversions upon initial contact; furthermore, the angular of ankle inversions of all CAI patients was lower than control group (Doherty et al., 2015). This motion pattern was also found in our study. Gehring et al. suggest that ankle sprains might result in functional impairment of the calcaneofibular ligament and PL muscle. It's could cause increased ankle inversion motion (Doherty et al., 2015; Gehring et al., 2014; Stormont et al., 1985), creating larger ranges of motion in the frontal plane during landing which could lead to a higher risk of sprain. Thus, we found that CAI and copers athletes used greater eversion motion to avoid over-inversion and thereby lowered risk of ankle inversion sprain.

Doherty et al. suggested that an athlete's ability to control the joint is compromised after ankle injury and suggested alterations mechanism might be adopted to readjust joint coordination in a manner that improves ankle stability in CAI and coper athletes (Doherty et al., 2015).

In this study, we found that CAI athletes utilized more hip flexion and adduction to maintain stability (Table 2, Figure 5). Hertel et al. have also suggested that CAI patients tend to use hip joint strategies for balance and stability in the landing phase (Hertel et al., 2002), and that CAI might be able to gain sufficient balance to effectively stabilize themselves in the sagittal plane by applying more hip flexion motion to buffer the impact of GRF. Doherty et al., studying how people with acute ankle sprains execute drop-landings, found that hip flexion was the motion most often used before landing (Doherty et al., 2015). The GRF and lower extremity stiffness encountered during landing has been correlated with the degree of stretch of the lower limb joints before landing (Doherty et al., 2015; Farley and Morgenroth, 1999); therefore, an increase of the hip flexion could effectively reduce hip joint stiffness, reducing the impact of the GRF. Hip abductions and adductions are the primary hip motions in the frontal plane. Tashman et al. suggested that frontal plane stability of the lower extremities critically influence the landing phase of a jump (Tashman et al., 2004). This influence was a result of the pre-stretch of the gluteus medius muscles at the earlier stage, which helped the hip joints execute abduction in the landing phase, offsetting effects such as shock and instability caused by the use of a single-leg to support the body (Dalton et al., 2011).

Additionally, CAI athletes in this study tended to co-contract muscles around the ankle joint to achieve a higher level of activation, which help them achieve better joint control and stability. One study has reported both excessive inversion and ankle plantarflexion to be major mechanisms underlying ankle sprains (Gehring et al., 2014). If so, ankle stability in the sagittal plane was as important as in the frontal plane in order to avoid ankle re-injury. Several investigators reported that lower extremity joint stability was given by muscle co-activation (Klein et al., 1993; Ruan and Li, 2010). Our results showed that the CAI athletes had greater MG/TA co-activation than the uninjured control athletes (Fig 10). The medial gastrocnemius (MG) muscle was a two-joint muscle and works as both ankle plantar flexor and knee flexor. Scholars revealed that MG contributed to the stability of both ankle and knee (Nashner, 1977; Shultz et al., 2000). Studies have also shown that a reduction in TA muscle activation may put the lateral ankle joints of athletes with CAI at greater risk of stress (Rosen et al., 2013; Wilkerson et al., 1997). During jump-landing, TA muscle insufficiently contraction may be ineffective in stabilizing the talonavicular joint, which could cause increased foot pronation (Rosen et al., 2013). Besides, foot pronation also increased lateral joint stress which was identified as a source of pain in CAI (Caulfield et al., 2004; Ferkel et al., 1991; Rosen et al., 2013). Although CAI athletes have insufficient frontal plane muscle activation and impaired proprioception due to repeated ankle sprains, they still could utilize different

muscles to compensate for the insufficient activation of ankle joint. The CAI athletes in our study tended to achieve greater co-activation of MG/TA, which helped them maintain ankle stability while performing single leg forward jump-landing. Whether muscle co-contraction was also helpful for ankle stability in the frontal plane, further investigation was needed in the future.

In this study, we found that coper athletes utilized a similar jump-landing pattern to CAI athletes. Studies have reported that first-time ankle sprain (coper) patients were able to maintain similar ankle motion patterns as uninjured controls, while other studies report that coper athletes use alternated motion mechanisms to maintain ankle stability and that those mechanisms cause their motion patterns to be reminiscent of those of CAI athletes (Liu et al., 2016; Macleod et al., 2014). Post-ankle sprain sequelae including pain, swelling, ROM limitation, decreased performance, joint instability, and giving way. Ankle sprain could damage ligaments and peripheral tissues may contribute to the similarity in coper and CAI athletes movement patterns (Park and Singh, 2014). According to Doherty in a time analysis of the gait cycle in CAI and copers athletes, found the two groups have similar gait cycles and similar biomechanical characters (Doherty et al., 2016a), suggesting the two groups moved alike. Coper athletes spent 12+ months successfully avoiding ankle sprain, mainly because the lower extremity neuromuscular system exists a self-defend mechanism which helps copers to avoid recurrent injuries (Denyer et al., 2013; Konradsen et al., 1997). In the current study, EMG data revealed that CAI and coper athletes had less TA and PL muscle activations, and greater ankle inversion velocity during descending phase (Fig 4, 9). These results showed that coper athletes still have higher risk than healthy control to suffer a recurrent ankle sprain. Furthermore, biomechanical characters of copers at the jump-landing were found just between healthy controls and CAI athletes. Overall, from the CAIT questionnaires, copers might have similar scores to healthy controls. However, when conducting single leg jump-landing task, copers did demonstrate some alternated mechanisms from healthy control and were more similar to CAI athletes. These alternated mechanisms of copers could be a risk factor turning into concurrent ankle injuries.

A limitation of this study is that the results were obtained from most of male participants. There were only 2 female participants in each exam group. Therefore, the results of alteration mechanism of ankle in CAI and copers may not be applicable to all female CAI and copers cases. Future prospective investigation with an expanded sample size and sex is needed to confirm the information presented in the current study.

Conclusion

In conclusion, this study showed CAI athletes demonstrated different jump-landing kinetics and kinematics from healthy controls. During forward jump, those particular landing behaviors may be risky or have negative consequences. The external biomechanical mechanism of both CAIs and copers mainly involved eversion of ankle joint as

well as hip flexion. Their internal alteration mechanism mainly involved greater muscle co-contraction in MG and TA of the ankle joint. Together, these individual kinematics and kinetics helped them maintain stability in dynamic conditions and prevent recurrent injuries. Whether alteration mechanisms indirectly affect future sport performance requires further study.

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The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare.

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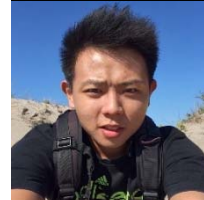
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Key points

- CAI athletes utilize more multi-joint or multi-muscle strategies during landing to maintain stability and prevent re-injury.
- CAI weaker control of ankle stability increases higher angular velocity during ankle inversion, possibly a key contributor to the recurrence of injuries.
- CAI athletes and coper athletes had significantly lower peripheral ankle muscle activation than healthy athletes.

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