Ankle biomechanics during multi-directional landings in athletes with chronic ankle instability

PLEASE CITE THE PUBLISHED VERSION

https://doi.org/10.1177/19386400231208522

PUBLISHER

SAGE Publications

VERSION

AM (Accepted Manuscript)

REPOSITORY RECORD

Sonsukong, Ainthira, Roongthiva Vathalathiti, Pongthanayos Kiratisin, Jim Richards, Daniel Fong, and Komsak Sinsurin. 2023. “Ankle Biomechanics During Multi-directional Landings in Athletes with Chronic Ankle Instability”. Loughborough University. https://hdl.handle.net/2134/24242296.v1.

Ankle biomechanics during multi-directional landings in athletes with chronic ankle instability

Ainthira Sonsukong[a], Roongthiva Vathalathiti[b], Pongthanayos Kiratisin[a], Jim Richards[c],
Daniel T.P. Fong[d], Komsak Sinsurin[a],

[a] *Biomechanics and Sports Research unit, Faculty of Physical Therapy, Mahidol University, Salaya, Thailand*
[b] *Musculoskeletal Physical Therapy Research unit, Faculty of Physical Therapy, Mahidol University, Salaya, Thailand*
[c] *Allied Health Research Unit, University of Central Lancashire, Preston, United Kingdom*
[d] *National Centre for Sport and Exercise Medicine, School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, United Kingdom*

Corresponding Author: Komsak Sinsurin, PT, Ph.D., DPT
Biomechanics and Sports Research unit, Faculty of Physical Therapy, Mahidol University, 999 Phuttamonthon 4 Road, Salaya, Nakhon Pathom 73170, Thailand.
Tel: +6624415450, Fax: +6624415454
E-mail: komsak.sin@mahidol.edu

ORCID:

Komsak Sinsurin http://orcid.org/0000-0002-4632-3230
Roongtiwa Vachalathiti https://orcid.org/0000-0002-4626-1463
Jim Richards http://orcid.org/0000-0002-4004-3115
Daniel Fong https://orcid.org/0000-0001-7314-189X

Statements and Declarations

Acknowledgments:

We would like to thank all the athletes who participated in the current study. This study was partially supported by Faculty of Physical Therapy, Mahidol University. Besides, we would like to thank all members of Biomechanics and Sports Laboratory.

Declarations:

Funding

This research project was partially supported by Mahidol University.

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

Ethics Approval

The research protocol was approved by the Mahidol University Central Institutional Review Board for Human Research (MU-CIRB 2020/315.0210). The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Consent to Participate/publish

All participants provided written informed consent for study participation and for the publication of this study prior to data collection.

Trial Registration is not applicable, because this article does not contain any clinical trials.

Data, Materials and/or Code Availability

All data from this study is available upon reasonable request to the corresponding author.

Authors’ Contribution Statements

Abstract

Background

Assessing and understanding the control of the ankle during multi-directional jump landings in athletes with chronic ankle instability (CAI) would help health professionals develop interventions to reduce the risk of recurrent injuries. The aim was to investigate the angle, angular velocity and moments of the ankle joint, and muscle activity of peroneus longus (PL), tibialis anterior (TA) and gastrocnemius (GAS) muscles during multi-directional landings in athletes with Chronic Ankle Instability (CAI).

Methods

Nineteen athletes with CAI (≤ 25 Cumberland Ankle Instability Tool -Thai Score) participated. A Vicon Nexus motion analysis system synchronously collected data with an AMTI forceplate and surface electromyography to capture kinematics, kinetics, and muscle activity, respectively. Participants were asked to perform single-leg jump-landing tests in forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions. Ankle joint kinematics, kinetics, and muscle activity of PL, TA, and GAS were analysed. Repeated measure ANOVA and Freidman tests were used to analyse the main effects of jump-landing direction.

Results

Athletes with CAI exhibited significant differences in ankle angles, angular velocities, ankle moments, and average muscle activity of GAS between directions. Greatest average EMG of GAS muscle was observed during landing in lateral direction compared with forward and 30° diagonal directions.

Conclusion

Lateral and diagonal direction movements showed the greatest risks associated with recurrent ankle sprains. Impairment of neuromuscular control in both pre-landing and landing phases were observed in athletes with CAI when considered alongside previously published data.

Keywords: multi-directions; chronic ankle instability; single-leg jump landing; ankle biomechanics; muscle activation

Level of Evidence: Laboratory-based observational study

Highlights

- Impairment of neuromuscular control in both pre-landing and landing phases were observed in athletes with CAI even though they had already returned to sports
- Increased ankle eversion and external rotation at IC phase were suggested as a compensatory movement in athletes with CAI during multi-directional landings
- To stabilize the unstable ankle during landing, athletes with CAI may attempt to increase the loading on plantarflexor muscles
- To reduce biomechanical risks, restoration of ankle control in athletes with CAI should be addressed during multi-directional jump landing.

Introduction

Chronic ankle instability (CAI) is the pathological condition which can develop after a lateral ankle sprain.[1] Approximately 40% of individuals who have an ankle sprain are reported to develop, and suffer from, CAI, which includes the residual symptoms of pain and swelling, ankle instability, and recurrent ankle sprains.[2] Lateral ankle sprains are mostly seen in physically active individuals[3] and athletes who perform cutting, running, and landing tasks, especially single-leg landing[4,5]. These are common movements in many sports such as basketball, volleyball, running, and soccer.[4] McKay et al reported that 45% of ankle sprains occurred during landing with another 30% occurring during turning or when changing direction.[6] with athletes with CAI reporting that this limits their capacity when performing sports activities and a reduction in their quality of life.[7] Adolescent athletes have reported a CAI prevalence of 20%[8] and a significantly lower ankle function, health-related quality of life, and physical activity.[9]

Single-leg jump landing during indoor and court sports activities shows the greatest risk of ankle sprain[10], with previous studies reporting changes in kinematics, kinetics, dynamic postural stability, and muscle activity in individuals with CAI during landing activities.[11-13] However, the majority of such studies explored unilateral landing in a forward direction which does not replicate real sport situations where athletes perform jumps and landings in multi-directions. Wikstrom et al[14] stated that conducting research with only forward jump landing does not provide sufficient predictive capability when trying to evaluate risks of lower extremity injury. More recently a study by Sinsurin et al[15] found that there were significant increases in Peroneus Longus (PL) and Tibialis Anterior (TA) muscle activity just before landing, with peak ankle evertor moments increasing when landing from forward, diagonal, and lateral directions. This study demonstrated that PL was key in the control of the ankle eversion during landing in various directions and may represent the natural control of the ankle in healthy athletes, which may in turn help to prevent excessive ankle rotation and provide a stabilising effect to the subtalar joint.

Although many athletes with CAI return to sports and competitive activities, 12% to 47% of athletes who received rehabilitation protocols still have recurrent ankle injuries.[16] This high rate of recurrent ankle injuries cannot be fully explained by current knowledge. To prevent recurrent ankle sprains and the subsequent development of CAI with the associated effects on function, a better understanding of biomechanical changes in athletes with CAI may help in the development of more effective programs of physical therapy and rehabilitation. An investigation of multi-directions of jump landing in athletes with CAI could offer new insights when compared to previous findings[15] of ankle biomechanics and muscle activity in healthy athletes performing the same test protocol. We hypothesized that risky movements of the ankle might be observed in athletes with CAI who have already returned to sports when compared to the previously published healthy cohort. Therefore, the purpose of this study was to investigate ankle movements and muscle activity of PL, TA, and medial head of Gastrocnemius (GAS) muscles during multi-directional jump landings in athletes with CAI compared with the previously published healthy cohort. This would provide a greater insight into the muscle activation and ankle biomechanics during single-leg jump landing in various directions which may help to guide future rehabilitation programs.

Materials and Methods

Participants

Collegiate basketball and volleyball athletes age between 18-25 years old who currently playing with no restriction and had a history of at least one lateral ankle sprains for more than 1 year with a score ≤ 25 on the Cumberland Ankle Instability Tool Thai version (CAIT-T)[17] participated in the current study. Exclusion criteria were; a history of serious lower extremity injuries, previous lower extremity fractures, or neurological disorders.

In the current study, the ankle sprain and CAI symptoms in all athletes were reported on the dominant leg which was identified as the leg that can performed a single-leg hop for the maximum distance.[18]

Study Procedure

Athletes presented to the motion analysis laboratory at Faculty of Physical Therapy, Mahidol University, on one occasion. They completed a demographic data (Age, weight, height, BMI, and sport type) and ankle history. All participants signed an informed consent. This study was approved by Mahidol University Central Institutional Review Board (COA No. MU-CIRB 2020/315.0210).

Kinematic and ground reaction force data from multi-directional jump-landing tests were collected using a 10 camera Vicon Nexus system (series number 1.8.4, Oxford Metric Ltd., Oxford, UK) at a sampling frequency of 200 Hz and an AMTI force plate (AMTI, Advance Mechanical Technologies Inc., USA) sampling at 1,000 Hz in the motion analysis laboratory.

Twenty-four reflective markers were attached over the bony prominences bilaterally including the; anterior superior iliac spines (ASIS), posterior superior iliac spines (PSIS), greater trochanter (GT), mid-point of iliac crest, lateral and medial femoral epicondyle, lateral and medial malleolus, distal head of the first metatarsal, distal head of the fifth metatarsal, proximal head of the fifth metatarsal, and heel. Furthermore, four rigid clusters of 4 markers were placed bilaterally on the lateral thigh and shank following the Calibrated Anatomical System Technique (CAST).[19]

Skin was shaved and cleaned and electromyography (EMG) sensors (Trigno, Delsys Inc, USA) were attached over the peroneus longus (PL), tibialis anterior (TA), and medial head of gastrocnemius (GAS) muscles following the Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations.

Single-leg jump-landing tests

The athletes with CAI were asked to perform single-leg jump-landing tests in four directions including forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions on their dominant leg with the non-tested leg in 90° of knee flexion with a neutral hip posture (Figure 1).

Athletes were asked to jump from the step height 30 cm and land on the center of the forceplate which was 70 cm far from the step with the tested leg and maintain balance after landing. In order to limit the effect of any upper limb movement, participants were instructed to place both hands on their waist. Three-completed trials of each direction were collected and analyzed. An incomplete trial was defined as landing with part of the foot off the forceplate, moving the hands off the waist, or balancing for less than 3 seconds after landing. In order to avoid any fatigue effects, at least 30 seconds rest between jump-landing trials and 5 minutes rest between the different directions was allowed.

Data acquisition and analysis

The marker trajectories and ground reaction force data were filtered with fourth-order zero-lag of Butterworth digital filters at cut-off frequencies of 6 Hz and 45 Hz which were determined using the residual analysis technique.[20] Three-dimensional lower extremity joint kinematics and kinetics were calculated using Visual3D (C-Motion, Rockville, MD, USA). Angle, angular velocity, and net joint moment (NJM) of the ankle joint were extracted and reported at initial contact and at peak vertical ground reaction force (vGRF) which were averaged from 3 trials.

The EMG data were filtered using a second-order bandpass Butterworth filter (30 - 350 Hz) and full-wave rectified.[15] Average EMG data of the 100 ms before (pre-landing phase) and 300 ms after initial contact (landing phase) were calculated and normalized to the maximum observed EMG amplitude of the forward jump landing (%max), and the average EMG data from the 3 trials was calculated for the different jump directions.

Statistical analysis

The sample size was calculated by using the partial η^2 at 0.16 of PL muscle from the study of Delahunt et al in 2006.[21] The effects size was 0.4364358. The p-value was set at 0.05 and power 80%. At least number of participants with 20% dropout was 11 participants which was estimated with the G*Power 3.1.9.4 program. Shapiro-Wilk tests were used to determine the distribution of data. For normally distributed data Repeated Measures ANOVA tests were used to compare the different jump directions, and Post-hoc pairwise comparisons with Bonferroni correction were used when a significant main effect was seen. For any non-normally distributed data Friedman tests were used to compare the effect of jump direction, and where a significant effect was seen post-hoc Wilcoxon tests were used. The level of statistical significance was set at p-value less than 0.05 and all analysis was performed using SPSS version 18.

Results

Nineteen athletes with CAI were recruited and their characteristics are shown in Table 1. Athletes with CAI exhibited significant differences of ankle angles, ankle angular velocities, ankle NJM (Table 2, Figure 2), and average 300 ms EMG of GAS between directions of jump landing (Table 3). Interestingly, multi-directional jump landing did not influence evertor NJM or muscle activation of PL and TA.

Table 1 Subject Characteristics (n = 19)

Athletes' characteristics	**Mean ± SD**
Age (years)	20.0 ± 1.3
Weight (kg)	66.0 ± 5.3
Height (cm)	176.6 ± 6.3
BMI (kg/m^2)	21.1 ± 1.2
CAIT-T Score	19.8 ± 3.4

Table 2 Ankle angles and angular velocities at initial contact and peak vGRF and ankle NJM at peak vGRF during jump landing in forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions.

Dependent variables	**Jump-landing directions**								***p*-Values**
	Forward (0°)		**30° diagonal**		**60° diagonal**		**Lateral (90°)**		
	mean ± SD	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	
At initial contact									
Ankle angle (°)									
Dorsiflexion (+)/ Plantarflexion (-)	-20.5 ± 6.1	-23.5, -17.6	-21.7 ± 4.7	-23.9, -19.4	-19.5 ± 6.7	-22.7, -16.3	-20.5 ± 5.0	-23.0, -18.1	0.262
Inversion (+)/ Eversion (-)	-3.5 ± 4.8	-5.8, -1.2	-3.5 ± 4.9	-5.8, -1.1	-4.7 ± 6.0	-7.6, -1.8	-6.2 ± 5.9[a,b,c]	-9.0, -3.3	**0.001***
Internal (+)/ External (-) rotation	-8.6 ± 5.2	-11.1, -6.1	-12.6 ± 4.7[a]	-12.6, -8.1	-10.9 ± 4.7[a]	-13.1, -8.6	-12.2 ± 5.7[a,b,c]	-15.0, -9.5	**< 0.001***
Ankle velocity (°/s)									
Sagittal plane	-316.5 ± 86.8	-358.3, -274.6	-395.0 ± 68.2[a]	--427.8, -362.1	-412.1 ± 106.2[a]	-463.3, -360.9	-435.9 ± 52.7[a,b]	-461.2, -410.4	**< 0.001***
Frontal plane	16.6 ± 226.4	-92.6, 125.7	24.6 ± 121.0	-33.7, 83.0	22.7 ± 101.7	-26.3, 71.7	-14.9 ± 155.6	-89.9, 60.0	0.633
Horizontal plane	-106.9 ± 39.6	-125.9, -87.8	-73.9 ± 30.8[a]	-88.7, -59.1	-60.2 ± 38.0[a]	-78.5, -41.8	-45.4 ± 32.4[a,b]	-61.0, -29.7	**< 0.001***
At peak vGRF									
Ankle angle (°)									
Dorsiflexion (+)/ Plantarflexion (-)	-1.1 ± 3.5	-2.8, 0.6	0.9 ± 3.7[a]	-0.9, 2.7	3.9 ± 3.9[a,b]	2.0, 5.8	11.0 ± 4.5[a,b,c]	8.8, 13.2	**< 0.001***

Inversion (+)/ Eversion (-)	-13.5 ± 4.0	-15.5, -11.6	-10.2 ± 4.5[a]	-12.3, -8.0	-9.6 ± 5.0[a]	-12.0, -7.2	-10.3 ± 4.8[a]	-12.6, -8.0	**< 0.001***
Internal (+)/ External (-) rotation	-4.1 ± 4.9	-6.5, -1.8	-10.4 ± 3.8[a]	-12.3, -8.6	-13.6 ± 4.0[a,b]	-15.5, -11.7	-16.5 ± 4.4[a,b,c]	-18.6, -14.4	**< 0.001***
Ankle velocity (°/s)									
Sagittal plane	-369.8 ± 71.9	-404.5, -335.1	-401.8 ± 48.8	-425.3, -378.2	-337.0 ± 66.6	-409.1, -344.9	-347.9 ± 60.0[b]	-376.8, -319.0	**0.02**
Frontal plane	6.3 ± 180.6	-80.8, 93.4	25.8 ± 154.1	-48.5, 100.1	17.2 ± 124.5	-42.8, 77.3	20.2 ± 128.4	-41.4, 82.1	0.963
Horizontal plane	-187.9 ± 33.7	-204.1, -171.6	-116.1 ± 32.9[a]	-132.0, -100.3	-81.5 ± 34.9[a,b]	-98.4, -64.7	-54.5 ± 27.3[a,b,c]	-67.7, -41.4	**< 0.001***
Ankle NJM (Nm/kg)									
Plantarflexor (+)/ Dorsiflexor (-)	2.04 ± 0.33	1.77, 2.32	2.13 ± 0.42	1.93, 2.33	2.54 ± 1.35	1.89, 3.19	2.60 ± 0.50[a,b]	2.36, 2.84	**< 0.001***
Invertor (+)/ Evertor (-)	0.15 ± 0.67	-0.18, 0.47	-0.23 ± 0.82	-0.62, 0.18	-0.22 ± 1.56	-0.96, 0.53	-0.37 ± 1.67	-1.12, 0.44	0.443
Internal (+)/ External (-) rotator	0.05 ± 0.10	0.01, 0.10	-0.23 ± 0.10	-0.28, -0.18	-0.36 ± 0.13[a,b]	-0.42, -0.30	-0.52 ± 0.23[a,b]	-0.63, -0.42	**< 0.001***

*Statistical significance $p < 0.05$ of repeated ANOVA

[a] Statistically significant difference compared with forward (0°) direction ($p < 0.05$).

[b] Statistically significant difference compared with 30° diagonal direction ($p < 0.05$).

[c] Statistically significant difference compared with 60° diagonal direction ($p < 0.05$).

Table 3 Average EMG of the Peroneus longus (PL), Tibialis anterior (TA), and medial head of Gastrocnemius (GAS) muscles before and after jump landing in forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions (mean ± SD).

Dependent variables	**Jump-landing directions**								***p*-Values**
	Forward (0°)		**30° diagonal**		**60° diagonal**		**Lateral (90°)**		
	mean ± SD	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	**mean ± SD**	**95% CI (lower, upper)**	
Average EMG 100 ms before landing (% max)									
PL	16.40 ± 10.55	11.31, 21.48	20.17 ± 13.91	13.46, 26.87	22.40 ± 20.11	12.71, 32.09	26.48 ± 22.27	15.75, 37.22	0.562
TA	9.51 ± 6.59	6.34, 12.69	10.24 ± 10.54	5.16, 15.32	13.21 ± 12.48	7.19, 19.22	13.42 ± 12.94	7.19, 19.66	0.562
GAS	22.32 ± 12.62	16.24, 28.41	23.91 ± 16.05	16.17, 31.64	24.75 ± 17.86	16.14, 33.36	21.28 ± 14.67	14.21, 28.35	0.345
Average EMG 300 ms after landing (% max)									
PL	41.50 ± 8.13	37.58, 45.41	44.75 ± 16.24	36.93, 52.58	49.51 ± 17.62	41.01, 58.00	52.79 ± 34.64	36.10, 69.48	0.222
TA	42.05 ± 8.74	37.84, 46.26	41.95 ± 13.07	35.65, 48.25	47.22 ± 11.84	41.51, 52.92	49.43 ± 14.53	42.43, 56.43	0.195
GAS	35.91 ± 6.56	32.77, 39.09	36.16 ± 8.89	31.87, 40.45	40.36 ± 11.75	34.70, 46.03	45.40 ± 13.33[a,b,c]	38.98, 51.83	**0.004***

*Statistical significance ($p < 0.05$) of Friedman's test
*CI = Confidence Interval
*SD = Standard Deviation

[a] Statistically significant difference compared with forward (0°) direction ($p < 0.05$).

[b] Statistically significant difference compared with 30° diagonal direction ($p < 0.05$).

[c] Statistically significant difference compared with 60° diagonal direction ($p < 0.05$).

Discussion

The aim of the current study was to investigate ankle movements and muscle activity of peroneus longus, tibialis anterior and medial head of Gastrocnemius muscles during jump landings in multi-directions in athletes with CAI who had already returned to sports or competition. Our findings showed that athletes with CAI exhibited significant differences in ankle angles, ankle angular velocities, ankle NJM (Table 2), and average 300 ms EMG of GAS between the directions of jump landing (Table 3). Interestingly, multi-directional jump landing did not influence evertor NJM or the muscle activity of PL and TA.

The patterns of average angular displacement and velocity in the sagittal plane were similar while the frontal and horizontal planes exhibited a variation between the jump landing directions (Figure 2). During landing, joint displacement and velocity of ankle dorsiflexion were the highest during the jump landing in the lateral direction. Interestingly, gradual increases in the ankle eversion displacement and velocity were observed after initial contact during diagonal and lateral jump landings compared with the forward direction.

At initial contact (IC) phase

The foot is the first body segment that contacts the ground and plays an important role in order to be the shock absorber during jump-landing tasks.[22] Significant differences were seen in ankle eversion and external rotation (Table 2). Ankle eversion and external rotation showed an increasing trend from forward to lateral directions of jump landing, respectively. This may be the movement strategy of athletes with CAI in order to avoid risks of recurrent ankle sprain including avoiding ankle inversion and internal rotation postures at IC.[23] The ankle movements in the athletes with CAI in the current study showed differences compared to Sinsurin[24], who studied healthy athletes using the same protocol as the current study. During jump landing in forward, 30° diagonal, 60° diagonal and lateral direction, the healthy athletes showed ankle rotations of 1.2°, 1.0°, -0.8°, and -4.9° with much less movement into eversion while both external rotation and eversion were showing an increasing trend in the current study. A previous study[25] exhibited a 4.0° greater ankle eversion in elite athletes with CAI compared with coper and healthy groups during a single-leg jump-landing task in forward direction. They preferred using greater angles in both eversion and external rotation angles for responding various directions of jump landing. A similar angle of plantarflexion was noted between jump-landing directions. Plantarflexion angles at the IC phase in healthy athletes were -20.7°, -20.8°, -20.8°, and -19.3°.[24] This seems that ankle control in sagittal plane between healthy athletes and athletes with CAI responds similarly during landing in various directions.

During lateral landing, the athletes with CAI contacted the ground with slower ankle external rotation velocity and faster plantar flexion velocity compared to diagonal and forward directions, respectively. Although athletes with CAI seem to have a strategy to control the ankle angular velocity in the transverse plane, the highest ankle plantarflexion velocity was found in the lateral direction. Co-contraction impairment of ankle muscles might be the reason and the association with the pre-landing phase would be important for positioning the foot before initial contact.[26]

At peak vertical ground reaction force (vGRF) phase

Ground reaction force can be controlled by adjusting the flexion movement of lower extremity joint.[27,28] Impact force and energy distribution during landing has a strong relationship to the sagittal motion of ankle and knee joints.[29] The findings of the current study found that jump-landing direction significantly influenced ankle angles in three planes.

Highest ankle dorsiflexion and external rotation, and lowest eversion were observed in the lateral landing. Significantly lower velocity of ankle external rotation was noted in lateral jump landing compared with forward and diagonal directions (Table 2). This finding may indicate that, to respond in various direction of jump landing, athletes with CAI control energy dissipation by adjusting ankle dorsiflexion, eversion, and external rotation. In 2017, Sinsurin et al[24] showed a similar pattern of ankle dorsiflexion with significantly increasing trend (1.2°, 2.7°, 6.6°, and 14.3°) from forward to lateral direction, respectively. However, ankle eversion (1.5° - 1.8°) and external rotation (11.8° - 13.3°) showed no significant change. It appears that when landing with a directional challenge, healthy athletes prefer adjusting ankle movement in the sagittal plane while frontal and rotational motions remain stable. On the other hand, athletes with CAI prefer adjusting three planes of ankle movement which might indicate less stabilizing during landing.

Multi-directional jump landing significantly influenced ankle NJMs in the sagittal and horizontal planes. Greater mechanical demand of plantarflexor and external rotator muscles was observed in lateral, diagonal, and forward directions, respectively (Table 2). Athletes with CAI might attempt to stabilize by using the plantarflexor muscles as evidenced by the greater ankle plantarflexor moment during landing in various directions. On the other hand, in healthy athletes, high plantarflexor NJM was noted in the forward direction while internal rotator NJM showed an increasing trend from forward, diagonal, and lateral directions.[24] The current finding may indicate that athletes with CAI used different strategies of muscle contraction in order to control the ankle during jumping in multi-directions. However, a previous study demonstrated that an increase in plantarflexor moment may decrease the energy transition to proximal joints causing a false position of the knee and is associated with knee injury.[29] Fleming et al, in 2001, suggested that high ankle plantar flexor contraction could lead to more knee flexion during the landing, which would cause greater stress force in the knee joint and risk ACL injury.[8] Future studies should observe knee and hip moments in athletes with CAI during jump landing in various directions.

Average EMG 100 ms before and 300 ms after initial contact

The neuromuscular system is the key of movement control and can help to prevent injury by increasing the dynamic stability during landing.[30] In the pre-landing phase, there was no significant difference in average EMG between jump-landing directions (Table 3A). The PL muscle plays an important role in order to counteract the ankle inversion stress and control the ankle during landing.[31] Similar pattern and average activity of PL muscle were observed between the current study and the previous study. However, TA muscle activation had quite a different pattern (Figure 3). Healthy athletes exhibited a similar amplitude of TA muscle activation in all directions[15] while the current study was showed an increasing trend from forward, 30° diagonal, 60° diagonal, and lateral directions, respectively. Moreover, average TA muscle activities in athletes with CAI were greater than data of healthy athletes[15] in all directions. This finding demonstrates that adaptive control of the ankle in athletes with CAI is noted with increased TA muscle activity during jump landing from forward to lateral directions. This may be a risky factor of recurrent ankle sprain from ankle inversion that is the result of high activity of TA muscle in pre-landing phase.

In the landing phase, a trending increase of GAS muscle activation was significantly observed in all directions. This corresponds to an increasing trend of plantarflexor NJM at peak vGRF. Interestingly, GAS muscle activation in the current study showed different magnitude and pattern compared with the previous study.[15] In healthy athletes, the magnitude of GAS activation was similar in all directions of jump landing. Moreover, the magnitudes of EMG in athletes with CAI was higher than healthy athletes by 7.56 % – 18.07 % max which assumes a higher loading at the ankle joint as well (Figure 3B).

A trending increase of PL and TA muscle activation was observed in the landing phase of forward to lateral directions (Figure 3B). In healthy athletes[15], PL muscle activation exhibited a significant increase from the forward to lateral directions while TA muscle activation exhibited a decrease. This may represent how healthy athletes stabilize the ankle joint during landing with directional challenge. TA and PL have demonstrated good co-activation in order to stabilize the subtalar joint during landing in various directions.[32] In contrast, athletes with CAI preferred an increase of PL, TA, and GAS muscle activation to stabilize the ankle joint in the critical phase of landing which may not be efficient for stabilizing the ankle joint and distributing impact loading through lower extremity joints.

The current study demonstrates that a direction of jump-landing affects the ankle biomechanics and muscle activation. Single-leg jump landings in lateral and diagonal directions show greater risks of recurrent ankle sprain than forward directions. Even though athletes with CAI had already returned to sport, they still showed some biomechanical risks for recurrent ankle sprain during jump landing with multi-directional challenges. Therefore, this is a challenge that rehabilitation programs need to consider to create more effective programs to prevent recurrent ankle injury. Restoration of cortical excitability and PL muscle performance is suggested for rehabilitation programs of athletes with CAI.[26,33] A testing protocol of multi-directional challenge during single-leg jump landing could guide clinicians for designing a test of evaluation as a part of return-to-sport consideration.

Athletes in the current study were basketball and volleyball players who were members of the university team. Applying the results in other sport players and tasks should be interpreted carefully. For future study, joint biomechanics of the hip and the knee, and proximal muscle activation would be interesting in order to better understand lower limb control and compensation after return-to-sports in athletes with CAI.

Conclusion

Multi-directional single-leg jump landing significantly influenced the ankle biomechanics and GAS muscle activation in athletes with CAI who had returned to sport.

Single-leg jump landings in lateral and diagonal directions showed greater possible risks for recurrent ankle sprain than the forward direction. Therefore, rehabilitation programs need to create a more effective program in order to possibly prevent recurrent ankle injury.

Declaration of interest statement

No conflict of interest

References

1. Hiller CE, Nightingale EJ, Raymond J, et al. Prevalence and impact of chronic musculoskeletal ankle disorders in the community. *Arch Phys Med Rehabil*. 2012;93:1801-1807.
2. Gerber JP, Williams GN, Scoville CR, et al. Persistent disability associated with ankle sprains: a prospective examination of an athletic population. *Foot Ankle Int*. 1998;19:653-660.
3. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train.* 2007;42:311.
4. Fong DT-P, Hong Y, Chan L-K, et al. A systematic review on ankle injury and ankle sprain in sports. *Sports Med Open*. 2007;37:73-94.
5. Kipp K, Palmieri-Smith RM. Differences in kinematic control of ankle joint motions in people with chronic ankle instability. *Clin Biomech*. 2013;28:562-567.
6. McKay GD, Goldie P, Payne WR, et al. Ankle injuries in basketball: injury rate and risk factors. *Br J Sports Med*. 2001;35:103-108.
7. Arnold BL, Wright CJ, Ross SE. Functional ankle instability and health-related quality of life. *J Athl Train*. 2011; 634-641.
8. Fleming BC, Renstrom PA, Ohlen G, et al. The gastrocnemius muscle is an antagonist of the anterior cruciate ligament. *J Orthop Res Ther*. 2001;19:1178-1184.

9. Donovan L, Hetzel S, Laufenberg CR, et al. Prevalence and impact of chronic ankle instability in adolescent athletes. *J Orthop Sports Med*. 2020;8:962.

10. Doherty C, Delahunt E, Caulfield B, et al. The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. *Sports Med Open*. 2014;44:123-140.

11. Kim H, Son SJ, Seeley MK, et al. Altered movement strategies during jump landing/cutting in patients with chronic ankle instability. *Scand J Med Sci Sports*. 2019;29:1130-1140.

12. Moisan G, Mainville C, Descarreaux M, et al. Unilateral jump landing neuromechanics of individuals with chronic ankle instability. *J Sci Med Sport*. 2020;23:430-436.

13. Moisan G, Mainville C, Descarreaux M, et al. Lower limb biomechanics during drop jump landing in individuals with chronic ankle instability. *J Athl Train*. 2022;57:1039-1047.

14. Wikstrom EA, Tillman MD, Schenker SM, et al. Jump-landing direction influences dynamic postural stability scores. *J Sci Med Sport*. 2008;11:106-111.

15. Sinsurin K, Vachalathiti R. Jalayondeja W, et al. How to control ankle joint in various directions of one leg jump-landing: frontal plane moment and EMG study. ISBS-Conference Proceedings Archive; 2013.

16. Herzog MM, Kerr ZY, Marshall SW, et al. Epidemiology of ankle sprains and chronic ankle instability. *J Athl Train*. 2019;54:603-610.

17. Yingyongsaksri S, Hiller C, Tharawadeepimuk K, et al. Reliability and validation of the Thai version of the Cumberland Ankle Instability Tool (CAIT-THA). *Disabil Rehabil*. 2022;1-6

18. Van der Harst J, Gokeler A, Hof A. Leg kinematics and kinetics in landing from a single-leg hop for distance. A comparison between dominant and non-dominant leg. Clin Biomech. 2007;22:674-680.19.

19. Cappozzo A, Catani F, Della U, et al. Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin Biomech. 1995;10, 171-178.

20. Winter DA. Biomechanics and Motor Control of Human Movement: John Wiley & Sons; 2009.

21. Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in subjects with functional instability of the ankle joint. Scand J Med Sci Sports. 2007;17:641-648.

22. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23:617-621.

23. Kristianslund E, Bahr R, Krosshaug T. Kinematics and kinetics of an accidental lateral ankle sprain. *J Biomech*. 2011;44:2576-2578.

24. Sinsurin K, Srisangboriboon S, Vachalathiti R. Side-to-side differences in lower extremity biomechanics during multi-directional jump landing in volleyball athletes. *Eur J Sport Sci*. 2017;17:699-709.

25. Lin J-Z, Lin Y-A, Lee H-J. Are landing biomechanics altered in elite athletes with chronic ankle instability. *J Sports Sci Med*. 2019;18:653.

26. Tretriluxana J, Nanbancha A, Sinsurin K, et al. Neuromuscular control of the ankle during pre-landing in athletes with chronic ankle instability: Insights from statistical parametric mapping and muscle co-contraction analysis. *Phys Ther Sport*. 2021;47:46-52.

27. Lee J, Song Y, Shin CS. Effect of the sagittal ankle angle at initial contact on energy dissipation in the lower extremity joints during a single-leg landing. *Gait Posture*. 2018;62:99-104.

28. McNitt-Gray J, Hester D, Mathiyakom W, et al. Mechanical demand and multijoint control during landing depend on orientation of the body segments relative to the reaction force. *J Biomech*. 2001;34:1471-1482.

29. Norcross MF, Blackburn JT, Goerger BM, et al. The association between lower extremity energy absorption and biomechanical factors related to anterior cruciate ligament injury. *Clin Biomech*. 2010;25:1031-1036.

30. Williams GN, Chmielewski T, Rudolph KS, et al. Dynamic knee stability: current theory and implications for clinicians and scientists. *J Orthop Sports Phys Ther*. 2001;31:546-566.

31. Li H-Y, Zheng J-J, Zhang J, et al. The effect of lateral ankle ligament repair in muscle reaction time in patients with mechanical ankle instability. *Int J Sports Med*. 2015;36:1027-1032.

32. Neptune RR, Wright IC, Van Den Bogert AJ. Muscle coordination and function during cutting movements. *Med Sci Sports Exerc*. 1999;31:294-302.

33. Wakabayashi H, Kaneda K, Sato D, et al. Effect of non-uniform skin temperature on thermoregulatory response during water immersion. *Eur J Appl Physiol*. 2008;104:175-181.

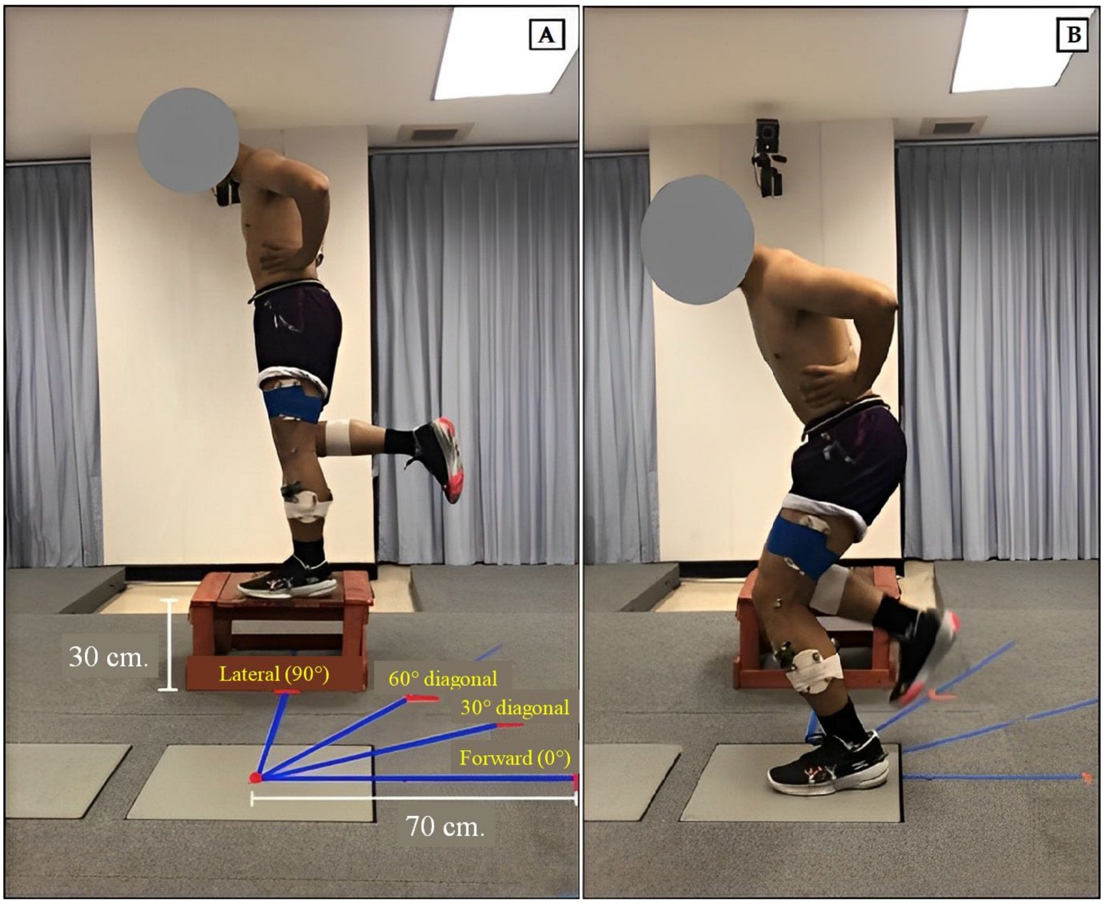

Figure 1. Single-leg jump-landing tests in multi-directions (A; starting position, B; landing on the forceplate)

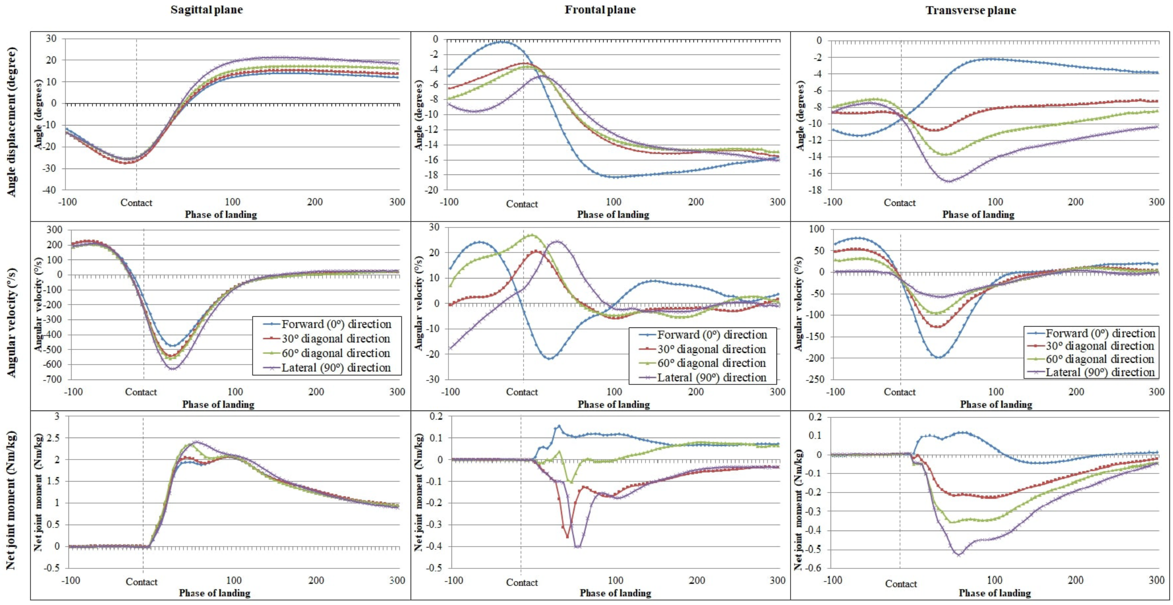

Figure 2. Average ankle angle displacement, angular velocity, and net joint moment (NJM) during landing. In Y-axis represents angular displacement, velocity, and NJM. In X-axis showed phase of landing between 100 ms before foot contact the ground to 300 ms after foot contact the ground

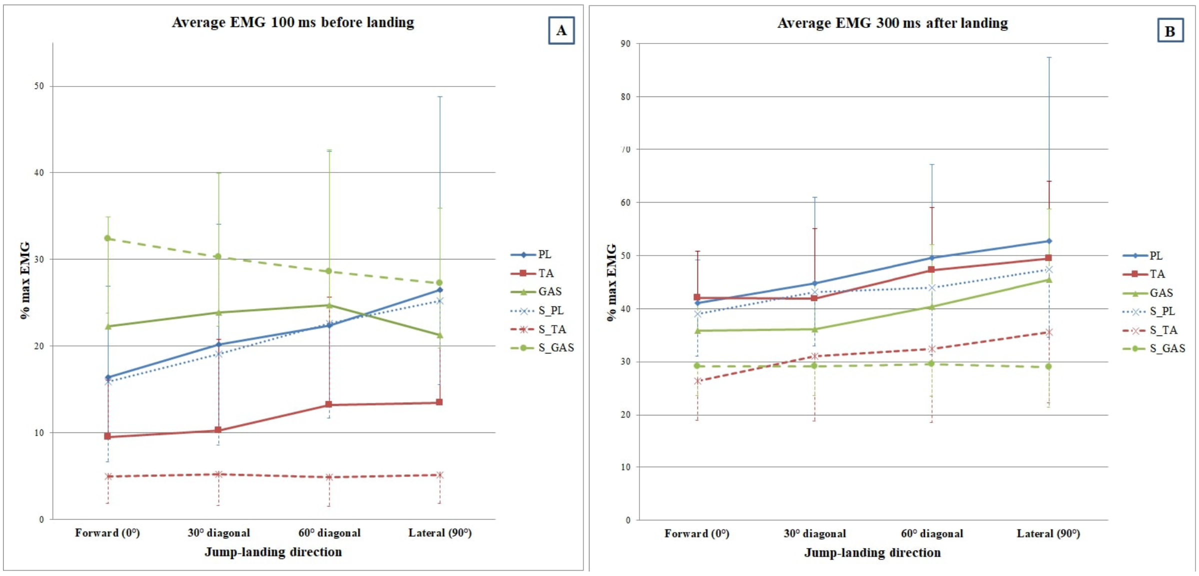

Figure 3. Average EMG of PL, TA, and GAS muscles in pre-landing phase (A) and in landing phase (B). S_PL or TA or GAS; result of average EMG from the previous study [15]