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Research article

Impact of Fatiguing Exercises on Movement Strategies in Chronic Ankle Instability, Lateral Ankle Sprain Copers, and Controls

Hyung Gyu Jeon [1], Inje Lee [2], Hyunsoo Kim [3], Heeseong Jeong [4], Sunghe Ha [2], Byong Hun Kim [5] and Sae Yong Lee [1]🖂

[1] Department of Physical Education, Yonsei University, Seoul, Republic of Korea; [2] Department of Sports Rehabilitation Medicine, Kyungil University, Gyeongsan, Republic of Korea; [3] Department of Kinesiology, West Chester University, West Chester, Pennsylvania; [4] Department of Sports and Health Management, Mokwon University, Daejeon, Republic of Korea; [5] Department of Sports Science, Dongguk University, Gyeongju, Republic of Korea

Abstract

While research exists to induce fatigue using isokinetic dynamometers or simple repetition tasks in patients with chronic ankle instability (CAI), there is a lack of research examining landing movement strategies using fatigue protocols that mimic actual sports. Therefore, we aimed to investigate the effects of CAI and fatiguing exercises on the lower-extremity kinematics and kinetics during single-leg drop landings among patients with CAI, lateral ankle sprain (LAS) copers and controls. A cross-sectional study recruited 20 patients with CAI, 20 LAS copers, and 20 controls in a biomechanics laboratory. All participants performed single-leg drop landings before and after the fatiguing exercises. The fatiguing exercise protocol consisted of a cycle including forward, side, and backward running, L-shape running, side hopping, cone jumps, and tuck jumps. This cycle was repeated until rate of perceived exertion (RPE) reached 17 and heart rate (HR) reached 85% of the maximum. Three-dimensional kinematics and kinetics of the lower extremity were collected and analyzed using functional analysis of variance. All participants reached an RPE level of 17.89 ± 1.02 and HR of 180.64 ± 7.87 (maximal HR 96.11%) at the last cycle of the fatigue protocol. Several group-by-fatigue interactions were noted. Patients with CAI exhibited increased hip external rotation angle and moment, increased angle and decreased moment of knee valgus, and increased hip and knee extension moments after the fatiguing exercise compared with copers and/or controls. Under fatigue conditions, patients with CAI exhibited biomechanical changes in the proximal joint, a stiffer landing position, and biomechanics associated with ankle injuries. Fatigue resistance training should be a key focus during the rehabilitation of these patients to improve their lower-extremity stability.

Key words: ankle injuries, ankle lateral ligaments, fatigue, muscle fatigue.

Introduction

Lateral ankle sprain (LAS) is a common sports-related injury and many individuals with a history of LAS may experience chronic ankle instability (CAI) (Roos et al., 2017). This pathologic condition is characterized by recurrent LAS and persistent symptoms, including episodes of the ankle giving way, pain, swelling, loss of function, and joint instability (Hertel and Corbett, 2019). Previous research has found that patients with CAI demonstrated altered net joint moment, resulting in altered movement during dynamic tasks compared with the healthy ankle group and/or LAS copers, who return to pre-injury levels of activity without further LAS and symptoms (Kim et al., 2018a; Son et al., 2017; Wikstrom and Brown, 2014). Additionally, further research has demonstrated that altered biomechanical characteristics observed in sports-specific movement may lead to the early onset of post-traumatic ankle osteoarthritis, resulting in decreased physical activity level and health-related quality of life (Doherty et al., 2016; Golditz et al., 2014; Hertel and Corbett, 2019; Hubbard-Turner and Turner, 2015; Lee et al., 2021; Simon and Docherty, 2018).

Patients with CAI exhibit altered movement strategies, relying on proximal joints to compensate for ankle deficiencies (Brown et al., 2011; Theisen and Day, 2019). This compensatory mechanism involves motor adaptations in both proximal and distal segments to support the stability of the injured segment (Riemann and Lephart, 2002). Changes in movement patterns among patients with LAS and CAI may result from neuromuscular control changes (e.g., muscle function alteration and delayed activation of lower-extremity muscles) (Brown et al., 2011; Jeon et al., 2021b; Theisen and Day, 2019). In addition, kinetic change, one of the proximal-dominant strategies used by patients with CAI, such as reduced knee extension moment and increased hip extension moments, may contribute to movement patterns different from that of the healthy ankle group (Kim et al., 2018a). These changes in patients with CAI may increase the risk of non-contact injuries by increasing tissue loading on the lower extremities, leading to pain and dysfunction (Brown et al., 2011; Jeon et al., 2021a). Although a few studies have shown that ankle deficiency can be a risk factor for proximal joint injuries (Kramer et al., 2007; Terada et al., 2014), more scientific evidence is needed, especially in sports-related activities.

Fatigue is approximately twice as likely to cause injury in high-level sports (Frisch et al., 2011), and more severe injuries tend to be reported in the second half of sports games, especially in the last 15 min (Fuller et al., 2016; Price et al., 2004). Thus, the effect of fatigue on movement patterns cannot be ignored, especially in those with recurring injuries, such as patients with CAI. Movement changes in patients with CAI may be more prominent under fatigue because fatigue may alter moment production at the joint and subsequently induce sport-related injuries

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of the lower extremities (Verschueren et al., 2020). Under fatigue, patients with CAI exhibit greater decreases in dynamic balance control than controls, and knee and/or hip movements played a more critical role than ankle movements (Gribble et al., 2004; 2007; Meeuwisse et al., 2007).

Most studies use local muscle fatigue protocol using isokinetic dynamometers or simple repetition tasks (Bagherian et al., 2018; Gribble et al., 2007; Kuenze et al., 2011; Webster and Nussbaum, 2016). While this approach highlights the role of individual muscles or joints, these simple protocols do not accurately represent fatigue in actual sports. Submaximal fatiguing exercises over prolonged time create greater central and peripheral fatigue in muscles than acute maximal intense exercises (Yoon et al., 2007). Sports require dynamic tasks, such as multi-directional running, acceleration, deceleration, and hopping and jumping, often with intermittent submaximal or maximal force. Therefore, a fatiguing protocol that mimics actual sports activities may better investigate movement pattern changes after a sports event. Furthermore, since patients with CAI may have deficits in feedback and feedforward motor control (Hertel, 2008), it is crucial to observe the proactive and reactive movement phases, including the time of non-contact injury onset, as part of the overall movement patterns. Although evidence indicates that CAI is a risk factor for lower-extremity injuries, current biomechanical outcomes are insufficient to demonstrate increased sensitivity to movement patterns under fatigue of patients with CAI.

Given that copers did not develop pathologic conditions despite previous LAS, comparing the movements of patients with CAI to those of copers and controls may reveal mechanisms of recurrent LAS or other injuries under fatigue (Wikstrom and Brown, 2014). Furthermore, observing lower-extremity biomechanics from combined CAI and fatigue effects may provide evidence to (1) establish rehabilitation strategies for the ankle and proximal joints and (2) suggest the need for training under fatigue in patients with CAI. To our knowledge, no previous study has investigated the lower-extremity joint angle and moment patterns in the multiplanar plane under fatigue conditions among patients with CAI, copers and controls. Therefore, this study aimed to investigate the interaction effects of CAI and fatigue on the patterns of lower-extremity kinematics and kinetics during a single-leg landing. We hypothesized that the joint angle and moment patterns of the lower extremity in patients with CAI will differ compared to those in LAS copers and controls, with these differences being more pronounced under fatigue conditions.

Methods

Design

This cross-sectional study employed a repeated-measures design with group comparisons. The independent variables were group (patients with CAI, LAS copers and healthy controls) and time (pre-fatigued and post-fatigue). The dependent variables were the joint angle and moment of the ankle, knee, and hip joint in sagittal, frontal, and horizontal planes during single-leg drop landing.

Participants

The *a priori* sample size was determined based on a previous study investigating the effects of CAI and fatigue on lower-extremity biomechanical variables during the single-leg drop landing (Lee et al., 2017). Using G*power software (v.3.1.9.2, Kiel, Germany), we estimated that 19 participants per group were needed to detect statistical significance at an α level of 0.05, 80% power and a partial eta squared of 0.15. A total of 60 physically active participants were recruited from a local university community (Table 1).

All three groups participated in regular recreational activities, including running, more than three times per week. Participants with a history of lower-extremity surgery were excluded. None of the participants had any history of lower-extremity acute injury within the previous 3 months, lower-extremity fractures, balance disorders, neuropathies, diabetes or other conditions known to affect the neuromuscular system. Before the study, all participants read and signed an informed consent agreement that was approved by the institutional review board of Yonsei University (7001988-202001-HR-779-02).

The inclusion criteria for patients with CAI were based on the International Ankle Consortium position statement as follows (Gribble et al., 2013): (1) a history of at least one significant LAS, which occurred at least 12 months before study enrolment and was associated with

Table 1. Participants' characteristics.

Characteristics	Patients with CAI (n = 20)	LAS copers (n = 20)	Controls (n = 20)
Sex (male, female)	12, 8	12, 8	15, 5
Age (years)	26.30±4.95	27.85±4.50	27.45±3.80
Height (cm)	174.41±8.39	173.64±7.72	174.66±7.33
Weight (kg)	71.57±16.60	71.95±13.61	69.26±9.47
Number of sprains	9.03±12.68	1.35±0.49	0.0±0.0
Ankle Instability Instrument #	7.15±1.98	2.15±0.57	0.0±0.0
FAAM: ADL subscale score (%)	87.35±1.86	99.88±0.37	100±0.0
FAAM: Sports subscale score (%)	74.1±8.18	99.55±1.11	100±0.0
Tegner activity score (level)	7.25±1.65	7.60±1.90	6.85±1.35
Last cycle of fatigue protocol			
Heart rate (bpm)	180.35±9.61	180.80±5.99	180.2±7.77
% of max heart rate	95.66±5.33	96.27±2.92	96.21±3.89
RPE scale	17.95±1.05	17.70±0.86	18.05±1.15

Number of 'yes' answers to yes/no questions. All data are expressed as mean±standard deviation, except for sex (expressed as numbers). ADL: activities of daily living; CAI: chronic ankle instability; FAAM: Foot and Ankle Ability Measure; LAS: lateral ankle sprain; RPE: rating of perceived exertion.

inflammatory symptoms, such as pain and swelling, (2) at least two episodes of the joint giving way within the previous 6 months, and (3) a score above the cut-off value in a validated ankle instability-specific questionnaire. For this study, two measures were used: The Ankle Instability Instrument (AII; answering ‘yes’ to at least five yes/no questions) and the Foot and Ankle Ability Measure (FAAM; Activities of Daily Living subscale [FAAM-ADL] score cut-off of <90%, and Sports subscale [FAAM-Sports] score cut-off of <80%). If patients with CAI reported bilateral instability and symptoms, the self-reported ‘worse’ limb was used for the analysis.

The inclusion criteria for LAS copers (Wikstrom and Brown, 2014) were as follows: (1) a history of at least one severe LAS that occurred more than 12 months prior, (2) a return to weight-bearing physical activity without repeated LAS and symptoms in the past 12 months, (3) a ‘yes’ answer to no more than three questions on the AII, and (4) disability scores no lower than 99% on the FAAM-ADL and 97% on the FAAM-Sports.

The inclusion criteria for controls were as follows: (1) no history of LAS, (2) no ‘yes’ answers on the AII, and (3) disability scores >99% on the FAAM-ADL and FAAM-Sports subscales. Moreover, all group participants were involved in regular recreational activities more than three times per week.

Procedures

After the single-leg drop-landing task and procedure were explained, the rating of perceived exertion (RPE) and heart rate (HR) were measured in non-active conditions after participants had rested for 3 min in the sitting position. All participants were asked to fill out self-report measures, including the AII, FAAM-ADL, FAAM-Sports, and Tegner activity scale. Body measurements—including height, body weight, leg length, and knee and ankle width—were collected and applied to the model for motion capture. Participants wore spandex shorts, T-shirts, and the same model of running shoes (FTY No. CLU 60001; Adidas, Herzogenaurach, Germany). Following this, participants walked at a self-selected pace for 5 minutes to warm up and then performed a series of stretches targeting the lower extremity muscles. To perform the single-leg drop landing, each participant was instructed to stand on a box 30 cm in height with either their injured limb or dominant leg and to drop onto the center of a force plate positioned in front of the box at 50% of the participant’s height (Kuenze et al., 2015; Figure 1A). Participants were instructed to keep their arms folded across their chest during single-leg drop landing to minimize upper extremity movement and reduce its influence on lower extremity biomechanics (Hoch et al., 2015). Additionally, the participants were instructed to look straight ahead and hold their foot position for three seconds after landing without adjusting it. Participants were instructed to step off from the box to minimize upwards vertical movement. No other instructions were given regarding landing techniques to avoid biasing the natural performance of the task. Motions were considered failed trials if participants (1) contacted the force plate with the non-standing limb, (2) used the upper extremity or did not keep their arms across the chest to help maintain balance or (3) hopped or slid with the standing limb after landing. The single-leg drop-landing task was repeated after the fatigue protocol. After the completion of the fatigue protocol, motion capture of the landing task was performed within 3 minutes. Only one successful trial was collected for each limb’s acquired kinematic and kinetic data to minimize fatigue recovery due to several trials.

Fatiguing exercise protocol

The fatiguing exercise protocol used in this study was developed based on a systematic review, which pooled studies that showed a significant result in RPE, with an effect size greater than 0.6. (Kim et al., 2018b; Kim et al., 2024). This protocol could be adapted to mimic the conditions in the second half of a competition or training. It consisted of a 5-m forward dash, a 5-m side running, a 5-m backward dash, running in a 20-m L shape, 20 side hops, 3 cone jumps, and 10 tuck jumps (Figure 1C). The fatiguing exercise protocol was repeated until the participant’s RPE reached 17 and higher (very hard) or the HR reached 85% of the maximum (the maximal HR was calculated as 207–[0.7 × age]) (Gellish et al., 2007; Figure 1B).

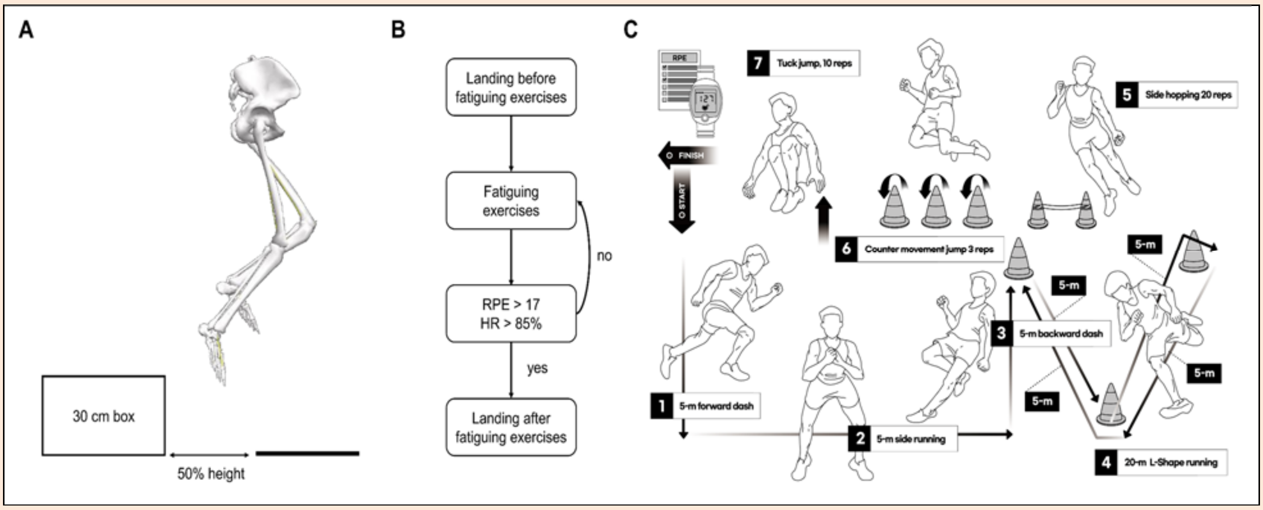

Figure 1. Study procedure. (A) Single-leg drop-landing task, (B) flowchart of the measurement and fatigue protocol and (C) lower-extremity fatiguing exercise protocol.

A Polar chest strap was placed over the participant's sternum to measure HR and a monitor watch (T31 coded transmitter; Polar Electro, Kempele, Finland) was used. Borg's scale (scores ranging from 6 to 20) was used to record participants' RPE (Borg, 1982). Consequently, in the present study, we defined the participants as being in a fatigue condition when RPE (≥17) (Kim et al., 2015) and HR (≥85%) (Eng et al., 2004) met the criteria. To confirm their fatigue status, the participants' HR and RPE were measured at the end of each protocol cycle when participants reached the finish line. Among the several formulas for indirectly calculating the maximum HR, the most reliable one, described earlier, was used in this study (Gellish et al., 2007).

Instrumentation

Kinematic data were captured at 200 Hz by a system of eight infrared cameras (MX-F20; Vicon Motion Systems, Oxford, UK) and motion capture software (Nexus version 1.8.5; Vicon) for static and dynamic calibrations within the capture space in a laboratory setting. Kinetic data were collected at 1,000 Hz using a force plate (ORG-6; Advanced Mechanical Technology, Inc., Watertown, MA, USA) and a threshold of 20 N was used to identify the initial contact (IC).

The Visual3D marker set for the lower extremity, consisting of 29 reflective markers and 16 cluster markers in four sets for segment tracking, was attached to each participant for capturing and motion analysis. The markers were placed over the iliac crest top; anterior–superior iliac spine; posterior–superior iliac spine; center of the sacrum; greater trochanter; lateral and medial epicondyles; lateral and medial malleoli; first, second and fifth metatarsals; and posterior–superior/posterior-inferior/lateral aspects of the calcaneus. All markers were securely attached to the skin with Kinesio tape to ensure stability.

Data processing

Collected data were imported into Visual3D (v.6.01.06; C-Motion Inc., Germantown, MD, USA) for data reduction and analysis. A kinematic model that consisted of eight skeletal segments (bilateral foot, shank, thigh segments, and pelvis) was created from the static trial. Lower-extremity angles, including the hip, knee and ankle joints, were determined using the default Cardan sequence method in the Visual3D X-Y-Z convention (flexion or extension, abduction or adduction, and internal or external rotation) (Wu et al., 2002). The net internal joint moment of the three joints, frontal, sagittal, and transverse planes and force plate data were calculated with a standard inverse-dynamics approach and normalized with body mass. Data were collected from 200 ms before to 200 ms after the IC to investigate the individual movement strategies for preparing to land (pre-landing phase) and adaptive strategy for loading after landing (post-landing phase). We selected a total of 400 ms time window to analyze the 'pre-injury period' and 'injury period' considering the LAS that occurred within 200 ms of the IC (Terada and Gribble, 2015). All biomechanics data were filtered at 10 Hz with a fourth-order low-pass Butterworth filter.

Statistical analysis

A one-way analysis of variance (ANOVA) was performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA) to assess participants' demographics, including age, height, and body weight. Means and 95% confidence intervals with a significance level of 0.05 were calculated for kinematics and kinetics across the three groups. Additionally, we plotted joint angles and moments of the lower extremity among patients with CAI, copers and controls in pre-fatigue and post-fatigue conditions.

A functional ANOVA (FANOVA) (Park et al., 2017) was used to compare the differences between pre-fatigue and post-fatigue conditions for sagittal, frontal, and horizontal plane joint angles and moments among the three groups during the pre-landing and post-landing phases of single-leg drop landing ($P < 0.05$). FANOVA facilitated the comparison of the joint angles and kinetics, which presents as a polynomial function (a normal set of data or 'function') rather than discrete values. This robust statistical approach is very powerful in detecting meaningful differences within large data sets, allowing for the identification of differences in their interaction with dependent variables at any point during the pre-landing and post-landing phases. Significant differences were identified if the curve and its effect size (95% confidence intervals) did not cross the zero line, indicating significant differences existed in group and fatigue interaction effects ($P < 0.05$; Figure 2) and providing an estimate of the effect size (Park et al., 2017). FANOVA was performed using the R software (version 4.1.3) with the FDA package.

Results

Participant demographics

No among-group differences existed for participant demographics, including age ($F_{(2,\ 57)} = 0.656$, $P = 0.523$), height ($F_{(2,\ 57)} = 0.092$, $P = 0.913$), and weight ($F_{(2,\ 57)} = 0.231$, $P = 0.794$; Table 1).

Fatiguing exercise protocols

All participants (27.20 ± 4.42 years, 174.24 ± 7.70 cm, and 70.93 ± 13.37 kg) reached an RPE level of 17 (very hard) by the last cycle of the fatigue protocol (17.89 ± 1.02 RPE scale). In addition, the mean HR (180.64 ± 7.87) and percentage of maximal HR (96.11% ± 4.09%) observed in the last cycle of the fatigue protocol were similar to or higher than the results from previous studies analyzing landing biomechanics under fatigue conditions (Benjaminse et al., 2008; Brazen et al., 2010). Furthermore, in an earlier study that developed the fatigue protocol used in the present study, blood lactate levels increased up to approximately 20 mmol/L after the fatigue protocol, and both HR (176.25 ± 18.22 bpm) and RPE scale (18.14 ± 0.91) were reported, similar to our data (Kim et al., 2018b). Therefore, it is likely that the fatigue protocol we used induced significant neuromuscular fatigue in the lower extremities.

Joint angle patterns

Figure 3 illustrates the kinematic patterns of the hip, knee, and ankle in the three planes before and after fatigue exercises, highlighting the intervals showing significant group-by-fatigue interaction effects. We observed interaction effects in the hip external rotation, knee valgus, and ankle abduction angle during the landing ($P < 0.05$).

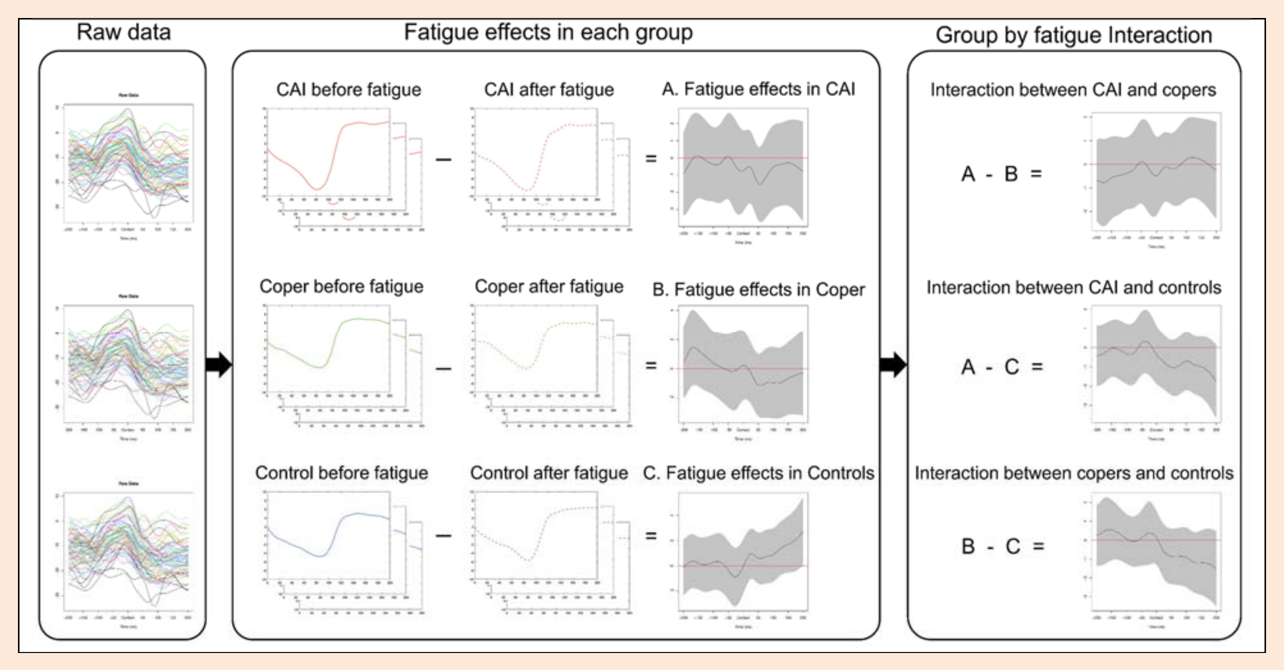

Figure 2. **Analysis procedure of group-by-fatigue interaction effects using functional analysis of variance procedure.**

After the protocols, patients with CAI increased peak hip external rotation up to 4.53°, while copers increased peak internal rotation up to 1.13° (198-196 ms and 76-46 ms pre-IC) and controls increased peak internal rotation up to 3.17° (200-136 ms and 86-66 ms pre-IC). After the protocol, patients with CAI increased peak knee valgus up to 3.51°, copers decreased peak varus up to 0.61° (46-12 ms pre-IC) and controls increased peak varus up to 0.71° (82 ms pre-IC to 52 ms post-IC). After exercises, patients with CAI decreased peak ankle abduction up to 2.6°, while copers increased up to 2.76° (200-172 ms pre-IC).

Joint moment patterns

Figure 4 shows kinetic patterns of the lower extremity in normal and fatigue conditions during landing, indicating the time showing significant group-by-fatigue interaction effects. We observed interaction effects in hip extension and external rotation, knee extension and valgus, as well as ankle plantarflexion and inversion moment during the landing ($P < 0.05$).

After the protocols, patients with CAI increased peak hip extension moment up to 1.27 Nm/kg, copers decreased up to 0.15 Nm/kg (36–60 ms and 106–174 ms post-IC) and controls decreased up to 0.28 Nm/kg (IC to 16 ms post-IC, and 38–64 ms and 106–200 ms post-IC). After exercises, patients with CAI increased peak hip external rotation moment up to 0.04 Nm/kg, while copers decreased up to 0.32 Nm/kg (32–34 ms and 196–200 ms post-IC).

After the protocols, patients with CAI increased peak knee flexion moment up to 0.57 Nm/kg, while copers decreased up to 0.29 Nm/kg during the initial phase of landing (IC to 8 ms post-IC). In the middle phase of landing, patients with CAI increased knee extension moment up to 0.57 Nm/kg after the protocols, while copers decreased extension moment up to 3.34 (108–200 ms post-IC) and controls decreased flexion moment up to 0.36 Nm/kg (24–34 ms and 62–96 ms post-IC). After exercises, copers increased knee extension moment up to 0.47 Nm/kg, while controls decreased up to 0.37 Nm/kg (32–50 ms and 54–68 ms post-IC). In the late phase of landing, copers decreased peak knee extension moment up to 0.51 Nm/kg, while controls increased up to 0.34 Nm/kg after exercises (132-200 ms post-IC). Patients with CAI decreased peak knee valgus moment up to 0.59 Nm/kg after the protocol, while copers decreased only up to 0.07 Nm/kg (46–56 ms post-IC).

After the protocols, patients with CAI decreased their peak ankle plantarflexion moment up to 0.36 Nm/kg, while copers increased up to 0.62 Nm/kg (22–28 ms post-IC). After exercises, patients with CAI (IC to 18 ms post-IC, and 36–58 ms post-IC) and copers (8–30 ms and 42–70 ms post-IC) increased ankle plantarflexion moment up to 0.70 Nm/kg, while controls decreased up to 0.89 Nm/kg. Patients with CAI had similar ankle inversion moment patterns, while copers increased eversion moment up to 0.1 Nm/kg (24–30 ms post-IC) after exercises.

Discussion

This study aimed to identify the combined effects of group and fatigue on the lower-extremity joint kinematic and kinetic patterns among patients with CAI, copers, and controls during a single-leg landing using a robust functional statistical analysis approach. The primary findings of this study were as follows: patients with CAI had (1) increased hip external rotation angle and moment, (2) increased knee valgus angle decreased knee valgus moment, (3) increased hip and knee extension moment, and (4) decreased ankle abduction angle and less ankle eversion moment than copers and/or controls after the fatiguing exercise protocol. Our results showed that the combined effects of CAI and fatigue existed at the lower-extremity joint angle and moment during the pre-landing and post-landing phases of single-leg drop landing.

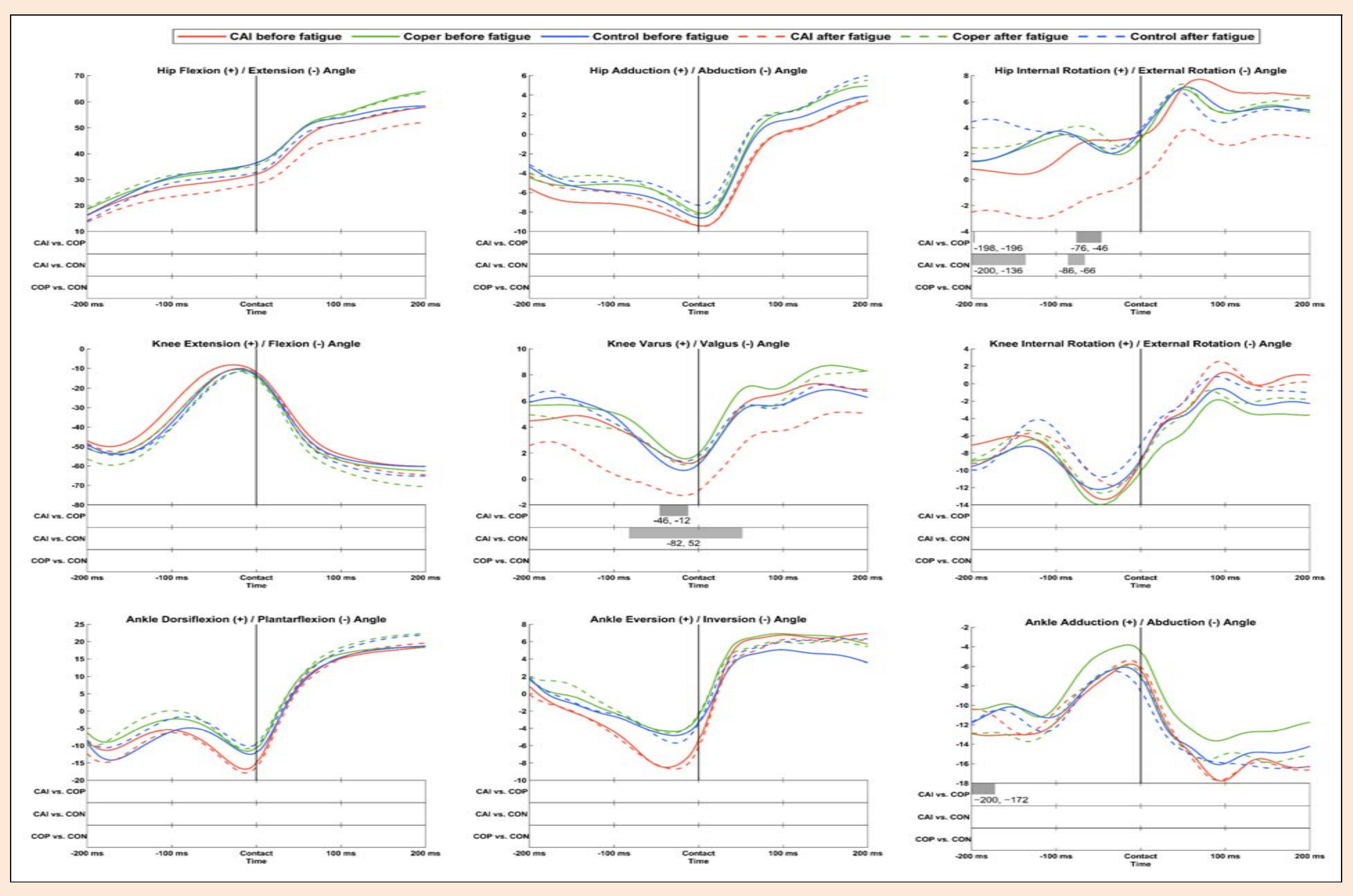

Figure 3. Lower-extremity kinematics in the sagittal, frontal and horizontal planes during the single-leg drop landing. Ensemble curves for the mean of the joint angle in patients with chronic ankle instability (red), individuals coping with a lateral ankle sprain (green) and controls (blue) in normal (solid line) and fatigue (dotted line) conditions. The black vertical line denotes the initial contact on a force plate and distinguishes the pre-landing and post-landing phases. CAI: chronic ankle instability; CON: controls; COP: copers.

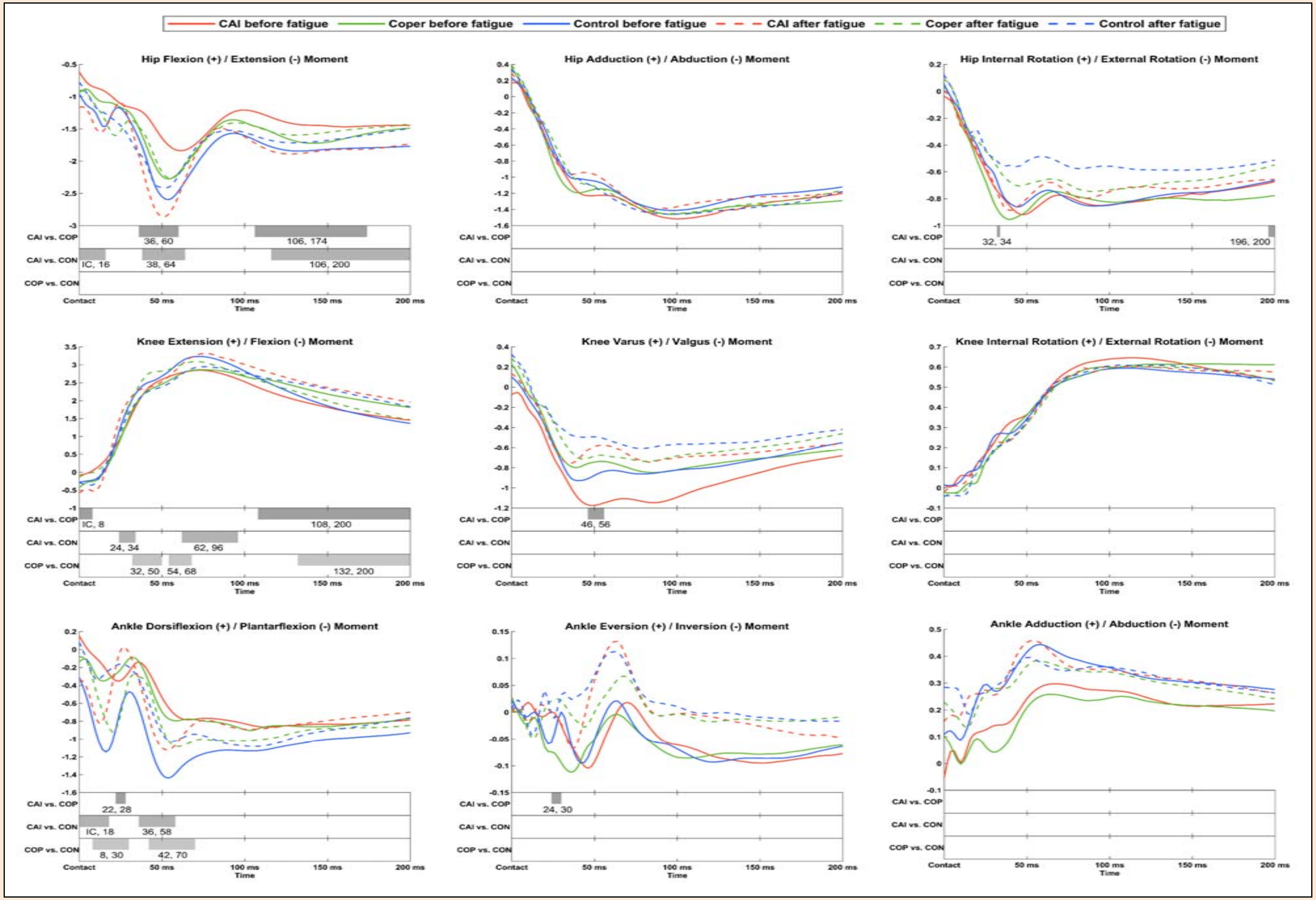

Figure 4. Lower-extremity kinetics in the sagittal, frontal and horizontal planes during the single-leg drop landing. Ensemble curves for the mean of the joint angle in patients with chronic ankle instability (red), individuals coping with a lateral ankle sprain (green) and controls (blue) in normal (solid line) and fatigue (dotted line) conditions. CAI: chronic ankle instability; CON: controls; COP: copers.

During the pre-landing phase, patients with CAI demonstrated hip external rotation positions following the fatigue exercise, unlike copers and controls. This altered kinematics indicates that patients with CAI compensate for instability by using hip muscles and establishing a base of support in the medio-lateral direction before ground contact. The pre-programming and loading response patterns in fatigue conditions may differ from those in normal conditions. For example, Delahunt et al. (Delahunt et al., 2006) showed that patients with CAI had decreased external hip rotation during single-leg drop jumps. Doherty et al. (Doherty et al., 2016) reported increased hip internal rotation angle in patients with CAI than in copers during the whole pre- and post-landing phases of single-leg drop landing. Greater lower-extremity stability is needed for proper landing under fatigue, so patients with CAI seem to adopt a hip-dominant strategy before IC (Powers, 2010). In the post-landing phase, patients with CAI also showed a hip-dominant strategy with increased hip external rotation moment compared to copers and controls. This hip moment in the horizontal plane may promote greater dynamic control during landing tasks under fatigue. Our data indicate that hip kinematic (internal rotation) and kinetic (external rotation) patterns in the transverse plane occurred in opposite directions post-landing, showing hip internal rotation angles decelerated by hip external rotator muscles. This strategy may be an effort to compensate for ankle joint instability by utilizing the proximal joint in patients with CAI under fatigue. Our findings concur, suggesting the importance of properly utilizing the proximal joint during the pre- and post-landing phases in patients with CAI, especially under fatigue conditions. Future research should examine whether improving hip muscle strength and neuromuscular control decreases the risk of recurrent ankle injuries.

With increased hip external rotation during pre-landing, this hip-dominant strategy may help stability but could alter distal joint motion, such as that of the knee. Our results indicated increased knee valgus angle in patients with CAI under fatigue around IC. These adaptations likely occur because patients with CAI alter neural activity and muscle recruitment in adjacent joints to compensate for the injured distal joint (Gribble et al., 2004). During single-leg drop landings, as the line of force shifts medially to the knee joint in a unilateral stance (Levangie, 2005), the increased hip external rotation angle during pre-landing may contribute to increased knee valgus during post-landing. This supports previous findings that ACL strain begins to increase during pre-landing, with peak strain corresponding to peak ground reaction force; thus, pre-landing plays a key role in determining the post-landing load response (Cerulli et al., 2003). Hewett et al. reported that knee angle and loading were significant ACL injury predictors in female athletes (Hewett et al., 2005). Therefore, given that increased knee valgus can increase ACL injury risk (Hewett et al., 2005), hip rotation changes due to the combined CAI and fatigue effects may contribute to other lower-extremity injuries in the kinetic chain.

After the fatiguing exercise protocol, patients with CAI had a more decreased hip flexion during landing than copers and controls. This indicates that patients with CAI failed to flex movements using the proximal joints in the sagittal plane even if lower-extremity should flex enough to compensate for the deficit in the ankle (e.g. dorsiflexion limit) (Son et al., 2017). Our results align with previous studies showing stiff landing with less lower-extremity flexion in patients with CAI (Doherty et al., 2016; Theisen and Day, 2019). Sufficient hip flexion is a common way of dissipating the force that affects body structures during landing. Consequently, patients with CAI who exhibit less hip flexion in fatigued conditions experience greater impact forces during landing, potentially increasing the risk of non-contact injuries (Terada et al., 2014; Theisen and Day, 2019). Since the hip joint has mechanical advantages, including greater cross-sectional area, longer muscle fibers and relatively shorter tendons over the knee and ankle joints, it can compensate for other joints in the lower extremities after injury (Jack and Winters, 1990).

After a fatiguing exercise protocol, patients with CAI exhibited more hip and knee extension moments, but the ankle plantarflexion moment varied with landing timing compared to copers and controls. Some of our results align with previous research, which showed that patients with CAI had less ankle plantarflexion and knee extension moment while more hip extension moment during landing and jumping than controls (Kim et al., 2018a). This might be because patients with CAI had deficits in plantarflexor strength and activation resulting from recurrent LAS, representing motor control adaptation within the lower extremity (Flevas et al., 2017; Jeon et al., 2021b). Under fatigue, patients with CAI may need greater extension and plantarflexion moment in global lower-extremity joints in the sagittal plane to dissipate external force during landing. Therefore, considering the addition of endurance focused exercises in rehabilitation programs should be considered to absorb shock and reduce injury risk under fatigue in rehabilitation programs. Since only the moment in the sagittal plane showed the interaction effects in our fatigue research, future studies developing a multi-joint rehabilitation program should verify whether these moment patterns can be changed even under fatigue conditions.

Our fatigue protocol induced lower-extremity muscle fatigue through common sports movements (e.g. multi-directional running, hopping, and jumping). Nevertheless, compared to patients with CAI, copers demonstrated an increased eversion moment early in landing and an increased ankle abduction angle during the pre-landing phase under fatigue conditions. These biomechanics indicate that copers have defensive strategies to prevent recurrent LAS after an acute injury. Generally, patients with CAI increased peroneal activation to protect their ankle when not fatigued; however, they exhibited decreased neuromuscular control of the peroneal muscle during the pre- and post-landing, resulting in reduced frontal plane stability after exercises (Labanca et al., 2021; Webster et al., 2016). Furthermore, given that ankle abduction contributes to pronation position, a decreased ankle abduction angle in patients with CAI under fatigue conditions may contribute to ankle inversion position (Herbaut and Delannoy, 2020). Consequently, patients with CAI appear to have difficulty preventing recurrent LAS when fatigued.

Previous research has established that fatigue exacerbates neuromuscular control deficits in patients with CAI, leading to reduced stability during dynamic tasks (Bagherian et al., 2018; Gribble et al., 2007; Kuenze et al., 2011; Webster and Nussbaum, 2016; Webster et al., 2016). Furthermore, changes in biomechanics not only in the ankle but also in the lower extremities were reported, which may predispose patients with CAI to an increased risk of further injury, as highlighted in the aforementioned studies. The current findings reinforce existing literature by demonstrating that patients with CAI possess lower extremity angles and moments alteration during single-leg drop landing. Therefore, our data provide valuable insights for clinicians and trainers developing rehabilitation protocols for patients with CAI, aiming to enhance fatigue resistance. We recommended that future intervention and assessment studies for patients with CAI focus on the entire lower-extremity movement patterns and coordination, even in fatigue-induced situations.

Limitations

Our cross-sectional design leaves it unclear whether the identified alterations resulted from injury effects or existed before the injury. Therefore, future prospective studies are needed to clarify the cause of movement strategy alteration in patients with CAI during fatigue conditions. Although we used a 30-cm box height and a distance of 50% of the participant's height to create a standard landing task, these parameters may vary depending on the participants' physical performance and leg length. Future research should consider normalizing drop height, such as box height, a percentage of the participant's height or maximum vertical jump height, to ensure consistent task difficulty. We measured only one trial of the single-leg drop-landing task to prevent recovery from fatigue and reduce data variance, as each participant may need different times or attempts to perform several successful trials under extreme fatigue. While the time between the completion of the fatigue protocol and the motion capture of the landing task was controlled, the number of missed trials was not recorded. Although the single-trial investigation demonstrates high reliability in biomechanical studies (Diss, 2001; Ford et al., 2007), this design may have limitations in investigating each participant's movement strategy with data.

CONCLUSION

During landing, patients with CAI exhibited altered biomechanics compared to copers and controls, with these differences being more pronounced after fatiguing exercises. These biomechanical characteristics indicate that patients with CAI had significant biomechanical alterations in proximal joints and landing strategies in the sagittal plane, increasing their risk for recurrent LAS under fatigue conditions. Enhancing endurance capacity (i.e. fatigue resistance) should be a key focus during the rehabilitation of patients with CAI to improve lower-extremity stability during dynamic tasks and reduce the risk of recurrent LAS and other lower-extremity injuries. Future studies should investigate the effectiveness of interventions for patients with CAI under fatigue and normal conditions.

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Key points

- During single-leg drop landing, patients with CAI had altered lower-extremity angle and moment patterns compared with copers and/or controls under fatigue conditions
- Clinicians and researchers should consider the addition of endurance focused exercises in rehabilitation programs for patients with CAI.
- Future studies should verify whether interventions affect the ankle joint and proximal joints even in fatigue-induced situations to prevent lower-extremity injuries.

AUTHOR BIOGRAPHY

Hyung Gyu JEON
Employment
Department of Physical Education, Yonsei University
Degree
PhD
Research interests
Sports Biomechanics, Injury Prevention, Sports Rehabilitation, Ankle Injury
E-mail: hgjeon@yonsei.ac.kr

Inje LEE
Employment
Department of Sports Rehabilitation Medicine, Kyungil University
Degree
PhD
Research interests
Ankle Sprain, Anterior Knee Pain, Injury Prevention, Sports Biomechanics, Sports Performance
E-mail: injelee@kiu.kr

Hyunsoo KIM
Employment
Department of Kinesiology, West Chester University
Degree
PhD
Research interests
Human movement, Musculoskeletal Injuries, Lateral ankle sprain, Chronic ankle instability
E-mail: HKim@wcupa.edu

Heeseong JEONG
Employment
Department of Sports and Health Management, Mokwon University
Degree
PhD
Research interests
Sports Epidemiology, Sports Injury Prevention and Performance improvement, Sport AI
E-mail: jhs@mokwon.ac.kr

Sunghe HA
Employment
Department of Sports Rehabilitation Medicine, Kyungil University
Degree
PhD
Research interests
Sports Biomechanics, Concussion, Injury Prevention, Sports Rehabilitation
E-mail: hasunghe7@gmail.com

Byong Hun KIM
Employment
Department of Sports Medicine, Dongguk University WISE Campus
Degree
PhD
Research interests
Ankle injuries, Sports Biomechanics
E-mail: bhkim2022@dongguk.ac.kr

Sae Yong LEE
Employment
Department of Physical Education, Yonsei University
Degree
PhD
Research interests
Sports Rehabilitation, Sports Biomechanics, Injury Prevention, Performance Improvements in Sport
E-mail: sylee1@yonsei.ac.kr

✉ **Sae Yong Lee, PhD**
Department of Physical Education, Yonsei University, Seoul, Republic of Korea