Lower Limb Joint Motion During a Cross Cutting Movement Differs in Individuals With and Without Chronic Ankle Instability

Yuta Koshino[1,2], Masanori Yamanaka[3,4], Yuya Ezawa[1], Tomoya Ishida[1,5], Takumi Kobayashi[4], Mina Samukawa[3], Hiroshi Saito[3], Naoki Takeda[6]

[1]Graduate School of Health Sciences, Hokkaido University, West-5, North-12, Kita-ku, Sapporo 060-0812, Japan

[2]Rehabilitation Center, NTT East Japan Sapporo Hospital, West-15, South-1, Chuo-ku, Sapporo 060-0061, Japan

[3]Department of Rehabilitation Science, Faculty of Health Sciences, Hokkaido University, West-5, North-12, Kita-ku, Sapporo 060-0812, Japan

[4]Hokuto Endowed Chair in Prevention of Joint Disease, Faculty of Health Sciences, Hokkaido University, West-5, North-12, Kita-ku, Sapporo 060-0812, Japan

[5]Department of Rehabilitation, Hokushin Orthopedic Hospital, 3-1-18, Kikusui Motomachi 3 jo, Shiroishi-ku, Sapporo 003-0823, Japan

[6]Department of Orthopedic Surgery, Hokuto Hospital,7-5, Inada-cho Kisen, Obihiro 080-0833, Japan

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Correspondence to: Masanori Yamanaka, PT, PhD

Faculty of Health Sciences, Hokkaido University, North-12, West-5, Kita-ku, Sapporo 060-0812, Japan, Tel: +81-11-706-3383; Fax: +81-11-706-3383

E-mail: yamanaka@hs.hokudai.ac.jp

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Abstract:

Objective: To compare the kinematics of lower limb joints between individuals with and without chronic ankle instability (CAI) during cross-turn and -cutting movements.

Design: Cross-sectional study.

Setting: Motion analysis laboratory.

Participants: Twelve subjects with CAI and twelve healthy controls.

Main outcome measures: Hip flexion, adduction, and internal rotation, knee flexion, and ankle dorsiflexion and inversion angles were calculated in the 200 ms before initial ground contact and from initial ground contact to toe-off (stance phase) in a cross-turn movement during gait and a cross-cutting movement from a forward jump, and compared across the two groups.

Results: In the cross-cutting movement, the CAI group exhibited greater hip and knee flexion than the control group during the stance phase, and more hip abduction during the period before initial contact and the stance phase. In the cross-turn movement the joint kinematics were similar in the two groups.

Conclusions: CAI subjects exhibited an altered pattern of the proximal joint kinematics during a cross-cutting movement. It is important for clinicians to assess the function of the hip and knee as well as the ankle, and to incorporate coordination training for the entire lower limb into rehabilitation after lateral ankle sprains.

KeyWords: ankle sprain; biomechanics; neuromuscular control; proximal joints

INTRODUCTION

Lateral ankle sprain is one of the most common injuries in many sports, including basketball, volleyball, and football (Fong, Hong, Chan, Yung, & Chan, 2007). The recurrence rate has been reported to exceed 70% in basketball (Yeung, Chan, So, & Yuan, 1994). Approximately 40–75% of individuals who sprain their ankle go on to develop chronic ankle instability (CAI) (Gerber, Williams, Scoville, Arciero, & Taylor, 1998), defined as recurrent ankle sprain, repetitive 'giving way' of the ankle joint, or a feeling of instability in the ankle joint (Delahunt, Coughlan, Caulfield, Nightingale, Lin, & Hiller, 2010). Individuals with CAI may have mechanical ankle instability (MAI) or functional ankle instability (FAI). MAI is characterized by pathological laxity of lateral ankle ligaments, and FAI is characterized by impaired neuromuscular control, proprioception or postural control without ligamentous laxity (Delahunt et al., 2010). These residual symptoms have been linked to increased risk of osteoarthritis at the ankle (Valderrabano, Hintermann, Horisberger, & Fung, 2006).

The biomechanics of the lower limb joints in individuals with CAI have been investigated during dynamic tasks. Individuals with CAI had a more inverted ankle position than healthy individuals before and after heel strike during gait (Delahunt, Monaghan, & Caulfield, 2006a; Monaghan, Delahunt, & Caulfield, 2006). Individuals with CAI also had a more inverted ankle position than healthy individuals during running (Lin, Chen, & Lin, 2011), single-leg landing (Delahunt, Monaghan, & Caulfield, 2006b), and lateral hop (Delahunt, Monaghan, & Caulfield, 2007). However, some studies have reported findings that are inconsistent with these studies (Brown, 2011; Brown, Padua, Marshall, & Guskiewicz, 2008; Kipp & Palmieri-Smith, 2012). These studies have all used gait, running, and landing to evaluate the biomechanics of the lower limb joints in individuals with CAI. Lateral ankle sprains often occur during twisting and turning movements (McKay, Goldie, Payne, & Oakes, 2001; Woods, Hawkins, Hulse, & Hodson, 2003); however, the biomechanics of the lower limb joints in individuals with CAI have not been well investigated in turning or cutting movements. Previous studies have shown altered plantar pressure, position of center of pressure (Huang, Lin, Kuo, & Liao, 2011), and leg muscle activity (Suda & Sacco, 2011) during a lateral shuffle movement (sideward lateral cutting) in individuals with CAI and, during a v-cutting movement, vertical ground reaction force (GRF) was greater on the side of the unstable ankle than on the contralateral side of the uninjured ankle (Dayakidis & Boudolos, 2006). These studies focused on the lateral shuffle and v-cutting movements, but the biomechanics during cross-turn or -cutting movements have not yet been investigated. The cross-turn movement involves a change of direction to the lateral side against the supporting leg, thus the center of plantar pressure may shift laterally, and forced inversion motion may occur at the ankle of the supporting leg. These tasks may put the ankle at risk of giving way or laterally spraining in individuals with CAI.

Previous studies have suggested that individuals with MAI or FAI have altered kinematics of the hip and knee joints during a stop jump (Brown, Padua, Marshall, & Guskiewicz, 2011) and a single-leg landing (Caulfield & Garrett, 2002; Delahunt et al., 2006b; Gribble & Robinson, 2010), but there is not yet a consensus on this topic. The kinematics of the proximal joints may change to compensate for instability or decreased function of the ankle in individuals with CAI. Such changes may be pre-existing, thus playing a role in the development of CAI. Quantifying the kinematics of the lower limb joints in individuals with CAI during cross-turn and -cutting movements may help us to understand the movement patterns used, and why these individuals experience ‘giving way’ or recurrent ankle sprains. In addition, we believe that understanding the patterns of movement aids in the development of rehabilitation interventions that specifically address deficits or factors that contribute to the pathogenesis of CAI. Therefore, the purpose of this study was to determine the kinematics of the hip, knee, and ankle joints during cross-turn and -cutting movements in individuals with CAI. We hypothesized that individuals with CAI would have altered hip and knee kinematics, and greater ankle inversion, than healthy control subjects.

METHODS

Subjects

The participants were recruited from among athletes belonging to a variety of sport clubs at our university. A total of 24 athletes participated in this study. Based on our pilot study (comprising four CAI and four control athletes), we performed a priori power analysis using the *t* test model of G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). As a result, a sample size of 22 to 24 subjects (11 to 12 subjects per group) was found to be necessary to achieve a power of 0.80 for the ankle inversion angle. Participants were instructed on the experimental procedure and were required to sign informed consent forms before the study began. Ethics approval was obtained from the university Institutional Review Board.

Twelve athletes (ten males; two females) met the following criteria and formed the CAI group based on the previous studies (Delahunt et al., 2006a; Gribble et al., 2013): (1) a history of at least one lateral ankle sprain requiring non-weight bearing and/or immobilization and/or abnormal gait; (2) a history of at least two lateral ankle sprains; (3) at least one lateral ankle sprain within the past two years; (4) episodes of the ankle ‘giving way’; (4) a Cumberland Ankle Instability Tool (CAIT) score of 27 or less (Delahunt et al., 2010; Hiller, Refshauge, Bundy, Herbert, & Kilbreath, 2006); (5) not receiving rehabilitation at the time of testing. The remaining twelve athletes (ten males; two females) had no history of lower limb injuries, ankle joint instability or episodes of 'giving way' and formed the age- (within two years) and gender-matched healthy control group. Subjects were excluded if they met the following criteria based on a previous study (Gribble et al., 2013): (1) a history of fracture or surgery in the lower limb or major musculoskeletal injuries (other than a history of lateral ankle sprain in the CAI group); (2) inflammation and swelling at the ankle at the time of testing; (3) a history of acute injuries of other joints of the lower limb within three months. All subjects were participating in sports activities at least two times a week. The subjects participated in a variety of sports (e.g. basketball, lacrosse, track and field, tennis, sepak takraw, and soccer). Most subjects engaged in sports involving jumping, landing and cutting tasks. If CAI subjects had CAI in both ankles, the more affected side, as determined by CAIT score, was studied. The CAI and control group were matched on dominance of the limb tested (nine dominant and three non-dominant limbs tested). The dominant leg was determined by asking which leg the subject would use to kick a stationary ball (Rein, Fabian, Zwipp, Mittag-Bonsch, & Weindel, 2010).

Equipment

Twenty-five reflective markers were placed on the skin of the lower limbs using double-sided adhesive tape. Markers were placed according to a modified Helen Hayes marker set (Kadaba, Ramakrishnan, & Wootten, 1990): At the sacrum, and bilaterally on the anterior superior iliac spine, greater trochanters, lateral aspect of the thighs, lateral and medial femoral epicondyles, lateral aspect of the shanks, lateral and medial malleoli, posterior heels, and first, second and fifth metatarsal heads. All subjects wore the same type of shoes (Artic Mesh M, Adidas, Herzogenaurach, Germany) in a fitting size. Holes were cut in the shoes to enable markers to be placed directly on the skin of the foot. Lower limb kinematic and GRF data were collected using six digital cameras (Hawk cameras, Motion Analysis Corporation, Santa Rosa, CA, USA) and a force plate (Kistler, Winterthur, Switzerland) that were time-synchronized and sampled at 200 Hz and 1000 Hz, respectively.

Procedure

After a static trial was collected with the subject standing, the medial femoral condyle and medial malleoli markers on the non-test leg were removed before the movement tasks were performed. Subjects were instructed to perform a cross-turn movement and a cross-cutting movement. The cross-turn movement was based on the movement presented by Houck & Yack (Houck & Yack, 2003). The subjects walked straight on a walkway at their natural speed while looking straight ahead so as not to look the force plate. They then planted their test limb on the force plate and changed direction to the side of the supporting leg at 45° and walked for approximately 2.5 m (Figure 1a). The cross-cutting movement was based on the movement described in a previous study (Ford, Myer, Toms, & Hewett, 2005). Subjects were positioned in a crouched position 0.4 m in front of the force plate with their knees flexed to approximately 45°. Upon hearing an audio cue played by the examiner, subjects were instructed to perform a forward jump onto the force plate. Then, with their test limb planted on the force plate, they performed a 45° crossover cut and ran as fast as possible for approximately 2.5 m (Figure 1b). Subjects were allowed to practice the movements three to five times until they could successfully perform the cross-turn and -cutting movements. The two tasks were then presented in random order. Kinematic and GRF data were collected from three valid trials for each task. Trials were excluded if the entire foot did not make contact with the force plate or if any markers were lost during testing. Subjects were allowed to rest for approximately 1 min between each trial, and for 5 min between the two tasks.

Data Reduction and Analysis

Three-dimensional marker trajectories were filtered using a fourth-order, low-pass Butterworth filter with a 12-Hz cutoff frequency (O'Conner & Bottum, 2009). Missing data in the marker trajectories were interpolated using the EvaRT4.3.57 software (Motion Analysis Corporation, Santa Rosa, CA, USA). The lower limb joints angles were calculated with SIMM 4.2.1 software (MusculoGraphics Inc., Santa Rosa, CA, USA) (Delp, Loan, Hoy, Zajac, Topp, & Rosen, 1990). The SIMM model was scaled to each subject's segment length obtained from the marker coordinates in the static trial and the measurements of the foot length and width. The mass and inertia properties of the segments were personalized for each subject, based on the mass and segment lengths of each subject. The distribution of the segment mass parameters was based on the data presented by DeLeva (DeLeva, 1996). The coordinate systems of the body segments were oriented such that the X-axis was anterior-posterior, the Y-axis was superior-inferior, and the Z-axis was medial-lateral in the anatomical position (Delp, 1990). The pelvis coordinate system was located at the midpoint of the line that connected the two anterior superior iliac spines. The femur coordinate system was located at the center of the femoral head. The tibia coordinate system was located at the midpoint between the femoral condyles in the anatomical position and fixed in the tibia. The talus coordinate system was located at the midpoint between lateral and medial malleoli. The calcaneus coordinate system was located at the most distal and inferior point of calcaneus posterior surface.

The hip joint was a ball and socket joint with three degrees of freedom (flexion/extension, adduction/abduction, and internal/external rotation). The knee joint had one degree of freedom (flexion/extension) (Walker, Rovick, & Robertson, 1988). The axes of the talocrural and subtalar joints were not orthogonal, as defined by Inman (Inman, 1976). The ankle joint was modeled with two degrees of freedom, with plantarflexion/dorsiflexion and inversion/eversion occurring about the talocrural and subtalar joints respectively. Joint rotations were expressed relative to the subject's measured static position. SIMM software was used to perform kinematics analysis with a global optimization method, which reduces the effects of artifacts due to skin movement (Lu & O'Connor, 1999).

The cross-turn and -cutting movements were divided into the pre-initial contact (IC) phase and the stance phase. IC was defined as the instant when the vertical GRF first exceeded 10 N, and toe-off was defined as the instant when the GRF first fell below 10 N after IC. The pre-IC phase was defined as the 200 ms interval before IC, as commonly used in previous studies (Delahunt et al., 2007; Delahunt et al., 2006a, 2006b; Monaghan et al., 2006), while the stance phase was normalized to 100% from IC to toe-off. The approach speeds (m/s) of the cross-turn and -cutting movements were calculated based on the velocity of the sacral marker's coordinate (direction of movement) over the 10 frames before IC.

Statistical Analysis

Demographic data were compared across groups (CAI, control) using independent *t* tests. Curve analyses were conducted to detect group differences in time-averaged kinematic data in the entire pre-IC and stance phases (Delahunt et al., 2007; Delahunt et al., 2006b; Drewes, McKeon, Kerrigan, & Hertel, 2009a; Drewes et al., 2009b; Monaghan et al., 2006). Comparisons between groups were made using independent *t* tests when the data were normally distributed and *Mann-Whitney* tests when the data were not normally distributed. The data distributions were assessed using the *Shapiro-Wilk* test. In addition, a two-way ANOVA was conducted to test for the effects of groups and tasks on the approach speed, time of stance (ms), and maximum vertical GRF (N/kg). A Sidak correction was used when there were significant effects. Statistical significance was set at $P < .05$. Statistical analysis was performed using IBM SPSS Statistics 17 (IBM Corporation, Armonk, New York, USA).

RESULTS

The characteristics of the two groups are shown in Table 1. The CAI and control groups had similar age, height, and body weight ($P > .05$; Table 1). The CAI group had a significantly lower CAIT score than the control group ($P < .001$; Table 1). The CAI group had experienced 7.3 ± 3.9 lateral ankle sprains, whereas the control group had no history of lateral ankle sprain.

The approach speeds, time of stance, and maximum vertical GRF values were similar between the two groups and were significantly different between the tasks (Table 2). The cross-cutting movement was associated with a greater approach speed ($P < .001$), shorter time of stance ($P < .001$), and greater maximum vertical GRF ($P < .001$) than the cross-turn movement.

In the cross-turn movement, there were no significant differences between the groups for any joint angles ($P > .05$; Figure 2 and 3). In the cross-cutting movement, the CAI group exhibited significantly greater hip flexion from 6% to 50% of the stance phase than the control group (*P* < .05; power = 0.52 to 0.83; effect size = 0.86 to 1.25; Figure 2), and the mean group difference was 5.51°. In addition, the CAI group exhibited significantly greater hip abduction from the pre-IC 200ms to 45% of the stance phase than the control group (*P* < .05; power = 0.53 to 0.80; effect size = 0.87 to 1.19; Figure 2), and the mean group difference was 4.04°. The CAI group also exhibited significantly greater knee flexion from 35% to 64% (*P* < .05; power = 0.51 to 0.61; effect size = 0.85 to 0.96; Figure 3) and 69% to 87% (*P* < .05; power = 0.54 to 0.64; effect size = 0.88 to 0.99; Figure 3) of the stance phase than the control group, and the mean group differences were 7.63° and 9.54°, respectively. There were no significant differences between the groups in the hip internal/external rotation angle or the ankle dorsiflexion/plantarflexion and inversion/eversion angles (*P* > .05; Figure 2 and 3).

DISCUSSION

The principal finding of this study was that the hip and knee joint kinematics during a cross-cutting movement were different in individuals with and without CAI. To our knowledge, this is one of the first studies to demonstrate altered kinematics of the lower limb in individuals with CAI during a cross-cutting movement. The findings partially support our hypothesis that CAI subjects would have different hip and knee kinematics to control subjects. Previous studies have reported that individuals with ankle instability exhibited different kinematic patterns of the hip or knee joints during a variety of dynamic movements. Delahunt et al. (Delahunt et al., 2006b) reported that individuals with FAI exhibited less hip external rotation than control individuals during a single-leg drop landing, and Brown et al. (Brown et al., 2011) reported that individuals with MAI exhibited greater hip flexion than the coper and individuals with FAI during a stop-jump task. Other studies have reported individuals with CAI exhibited greater knee flexion (Caulfield & Garrett, 2002) or less knee flexion (Gribble & Robinson, 2010) than control individuals during a single-leg landing. The results of this study partially support the presence of changes in sagittal plane hip and knee kinematics in individuals with CAI that has been reported by previous studies (Brown et al., 2011; Caulfield & Garrett, 2002). However, because the movement tasks are different, it is difficult to directly compare the results of this study with those of previous studies. The cross-cutting movement included a change of direction and was a multi-plane movement, and is therefore different from a landing. The nature of this task may explain why CAI subjects displayed not only more hip and knee flexion, but also more hip abduction, than control subjects. It has been suggested that CAI is associated with central changes in sensorimotor function, including supraspinal motor control mechanisms (Hass, Bishop, Doidge, & Wikstrom, 2010) and feed-forward neuromuscular control (Wikstrom, Bishop, Inamdar, & Hass, 2010). Beckman and Buchanan (Beckman & Buchanan, 1995) hypothesized that a feed-forward mechanism may allow the central nervous system to recruit proximal muscles to compensate for an inadequate ankle response in individuals with pathologic ankle hypermobility. In the present study, during the cross-cutting movement, differences in frontal plane hip motion were observed in CAI subjects before IC, i.e., before the GRF had acted on the lower limb. The alterations in proximal joint kinematics may be attributed to centrally mediated changes.

Contrary to our hypothesis, the frontal plane kinematics of the ankle joint did not differ between CAI and control subjects during cross-turn and -cutting movements.

In previous studies, individuals with CAI have exhibited greater ankle inversion than control subjects during gait (Delahunt et al., 2006a; Monaghan et al., 2006; Drewes et al., 2009b), running (Lin et al., 2011), and landing (Delahunt et al., 2006b). These inconsistent findings between our study and previous reports may be due to the different tasks performed, or different inclusion criteria for CAI subjects. In addition, most previous studies have investigated the ankle kinematics of CAI subjects under barefoot conditions. Our subjects wore shoes during testing; this may be one reason for the observed nonsignificant finding. Chin et al. reported no difference in inversion angle during treadmill walking with shod condition between the CAI and control group (Chinn, Dicharry, & Hertel, 2013), likely because shoes may stimulate ankle eversion muscle activities (Kerr, Arnold, Drew, Cochrane, & Abboud, 2009). In the present study, the average time-series data for the ankle inversion angle exhibited a similar pattern during the cross-turn movement and appeared to be greater in the CAI group than in the control group during the cross-cutting movement (Figure 3), although the difference was not significant. The mean group difference was 4.5° (CAI = -11.7 ± 6.9°, control = -16.2 ± 8.6°) throughout the pre-IC and stance phases. Drew et al. showed that, in their study, the CAI subjects had greater inversion angles throughout the entire gait cycle than the healthy controls, with a mean difference of 2.07 ± 0.29° (Drewes et al., 2009b). Nonsignificant findings of ankle inversion may also be attributed to the large standard deviations observed in our sample data. Interestingly, during the cross-cutting movement, hip abduction before and after IC was greater in the CAI group than in the control group. The CAI group might have altered frontal plane hip motion to adjust the position of the supporting foot relative to the body. Increased hip abduction would mean that the foot was placed further away from the body and in the direction of the cutting movement, which may have helped avoid a sharp crossover cutting movement and prevent excessive ankle inversion motion. The cross-cutting movement was a preplanned task, therefore the CAI subjects would have been able to plan this adjustment of hip motion. Future study should investigate kinematics during an unanticipated cutting movement in order to gain a further understanding of CAI.

Ankle sagittal plane kinematic patterns were similar in the CAI and control groups during the cross-turn and -cutting movements. Previous studies have reported inconsistent findings in sagittal plane ankle kinematics, including decreased dorsiflexion during jogging and landing (Delahunt et al., 2006b; Drewes et al., 2009a), increased dorsiflexion during landing (Caulfield & Garrett, 2002), and no group differences during gait, lateral hop, and landing (Delahunt et al., 2007; Delahunt et al., 2006a; Monaghan et al., 2006; Gribble & Robinson, 2010). Brown (Brown, 2011) reported that ankle motion in the sagittal plane was different between individuals with MAI and individuals with FAI during walking and running. Inter-study variability in inclusion criteria or methodology, such as kinematic analysis, movement task, and dependent variables, may underlie the inconsistent findings. In the present study, the sagittal plane kinematics of the ankle did not change, unlike that of the hip and knee, during the cross-cutting movement. The CAI subjects may have attempted to adjust to be in a lower position with respect to their center of mass in order to gain dynamic stability primarily using hip and knee flexion. The position of the center of mass, dynamic stability, and lower limb joint kinematics should be measured simultaneously in future studies.

During the cross-turn movement, the proximal joint kinematics of CAI subjects were similar to those of control subjects. Also, previous studies showed that changes of the proximal joints kinematics in CAI subjects did not present compared with control subjects during gait (Delahunt et al., 2006a; Monaghan et al., 2006). The approach speed and time of stance during the cross-turn movement were significant slower and shorter, respectively, than those observed during the cross-cutting movement. The vertical GRF of the cross-turn movement was also significantly lower than that of the cross-cutting movement. Therefore, it is conceivable that the cross-turn movement was an easier task than the cross-cutting movement. The cross-turn movement would be easy to perform and not require complex neuromuscular control of the lower limb joints in athletes. Such an easy task may not reveal kinematic changes in the proximal joints related to CAI. Meanwhile, the CAI subjects may have felt that it was difficult to perform the sports-related movements. A lack of confidence in their ability to perform the movement may have meant that they depended on the proximal joints to compensate for the instability or decreased function of the ankle and avoid ‘giving way’ or lateral ankle sprains. Changes in the kinematics of proximal joints in individuals with CAI may be associated with the difficulty of the movement tasks, and high-difficulty tasks could reveal the changes in the movement patterns of the lower limb.

Clinicians should consider the alterations in proximal joints kinematics in the rehabilitation of CAI. There may also be changes in proximal muscle activation in individuals with CAI (Van Deun, Staes, Stappaerts, Janssens, Levin, & Peers, 2007; Webster & Gribble, 2013). Although these changes may not be beneficial, it is important for clinicians to assess the function of proximal joints and muscles, as well as the ankle for rehabilitation after lateral ankle sprain. If necessary, clinicians should address the proximal changes as part of rehabilitation. Furthermore, global coordination training for the entire lower limb may be needed to restore proper kinematic patterns and prevent future lateral ankle sprains.

Some limitations associated with the present study need to be acknowledged. First, the subjective symptoms and severity of the CAI may have varied across subjects, because the inclusion criteria were based on self-reported questionnaire scores and subjective reports of episodes of instability and ‘giving way’. Furthermore, we did not perform the anterior drawer or talar tilt tests to evaluate whether or not the subjects had mechanical laxity. We defined CAI as repeated ankle sprains and episodes of ‘giving way’ with or without ankle ligamentous laxity (Hertel, 2000). The kinematics of the lower limb joints may have differed among subjects with and without MAI. Second, although the ratio of males to females was matched between the groups, there were fewer females within each group, which may have skewed our results. Third, the cross-cutting movement was an anticipated task. In a game situation, unanticipated movements, whereby athletes have to react to a ball or other players, are common. Future study should consider using an unanticipated cutting movement in order to further understand the kinematics and neuromuscular control of the lower limb in individuals with CAI. Fourth, although skin markers are commonly used to assess *in vivo* joint kinematics, the accuracy of this method is limited due to skin movement artifacts. We made an effort to minimize this error using several steps. Our kinematic analysis was performed with a global optimization method, which minimized the weighted sum of the squared differences between the measured and model-determined marker positions (Lu & O’Connor, 1999). In addition, the markers were attached to landmarks in all subjects by a single tester to enhance the reliability of marker placement and avoid potential errors caused by inter-tester differences. The effect sizes of our significant findings were strong (> 0.8) and the powers were moderate to strong. Although we acknowledge the presence of errors due to skin artifacts in this study, we believe that our significant findings represent clinically meaningful differences. Fifth, the significant findings of this study had moderate to strong power, while the nonsignificant findings were associated with low to moderate power. With respect to case of inversion during the cross-turn movement, we would have needed 965 subjects per group to achieve a level of power of 0.80, according to the post-hoc power analysis based on the mean values and standard deviations observed in our sample. It would be difficult and unrealistic to recruit this number of subjects. Finally, this study cannot determine whether the observed changes of the CAI subjects were present before or after injury. A longitudinal follow-up study should be conducted to address this issue.

CONCLUSION

In the cross-cutting movement, the CAI group exhibited greater hip and knee flexion after IC, and greater hip abduction before and after IC. In the cross-turn movement the kinematic patterns of the lower limb joints were similar in the two groups. Group differences in the ankle kinematic pattern were not observed during either movement. CAI subjects may depend on the proximal joints via centrally mediated changes to compensate for the instability or decreased function in the ankle. Such changes may be associated with difficulty in performing the movement tasks. Clinicians should assess the function of the hip and knee as well as the ankle, and conduct global coordination training for the entire lower limb, during the rehabilitation of lateral ankle sprains.

Conflict of interest

None declared.

Ethical statement

Participants were required to sign informed consent forms before the study began. Ethics approval was obtained from Institutional Review Board of the Faculty of Health Sciences of Hokkaido University.

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TABLE 1. Characteristics of the chronic ankle instability group and the control group.

Group	Gender (n)	Age (years)	Height (cm)	Mass (kg)	CAIT score[a]
CAI	Male (10) Female (2)	21.1 (0.9)	172.9 (8.2)	64.6 (8.4)	20.8 (4.4)
Control	Male (10) Female (2)	20.7 (0.5)	172.1 (8.0)	64.7 (9.3)	29.8 (0.6)

Data are presented as mean (SD). CAIT, Cumberland Ankle Instability Tool; CAI, chronic ankle instability.

[a] Statistically significant difference between CAI and control groups ($P < 0.05$).

TABLE 2. Approach speed, time of stance, and maximum vertical ground reaction force (GRF) during the cross-turn and -cutting movements in the chronic ankle instability (CAI) group and control group.

		Task	
Variable	Group	Cross-turn	Cross-cutting
Approach speed (m/s)*	CAI	2.6 (0.3)	3.2 (0.5)
	Control	2.5 (0.3)	3.0 (0.6)
Time of stance (ms)*	CAI	715.6 (46.3)	365.4 (67.6)
	Control	699.4 (41.2)	335.4 (58.0)
Maximum vertical GRF (N/kg)*	CAI	11.7 (1.0)	17.3 (2.5)
	Control	11.3 (0.6)	18.3 (2.1)

* indicates significant difference between tasks (*P* < 0.001).

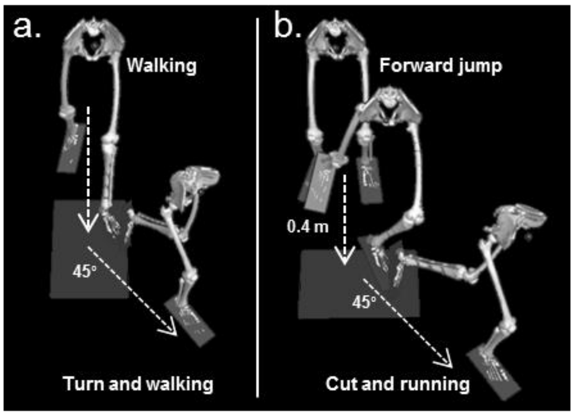

Figure 1. Illustration of the cross-turn movement (a) and the cross-cutting movement (b).

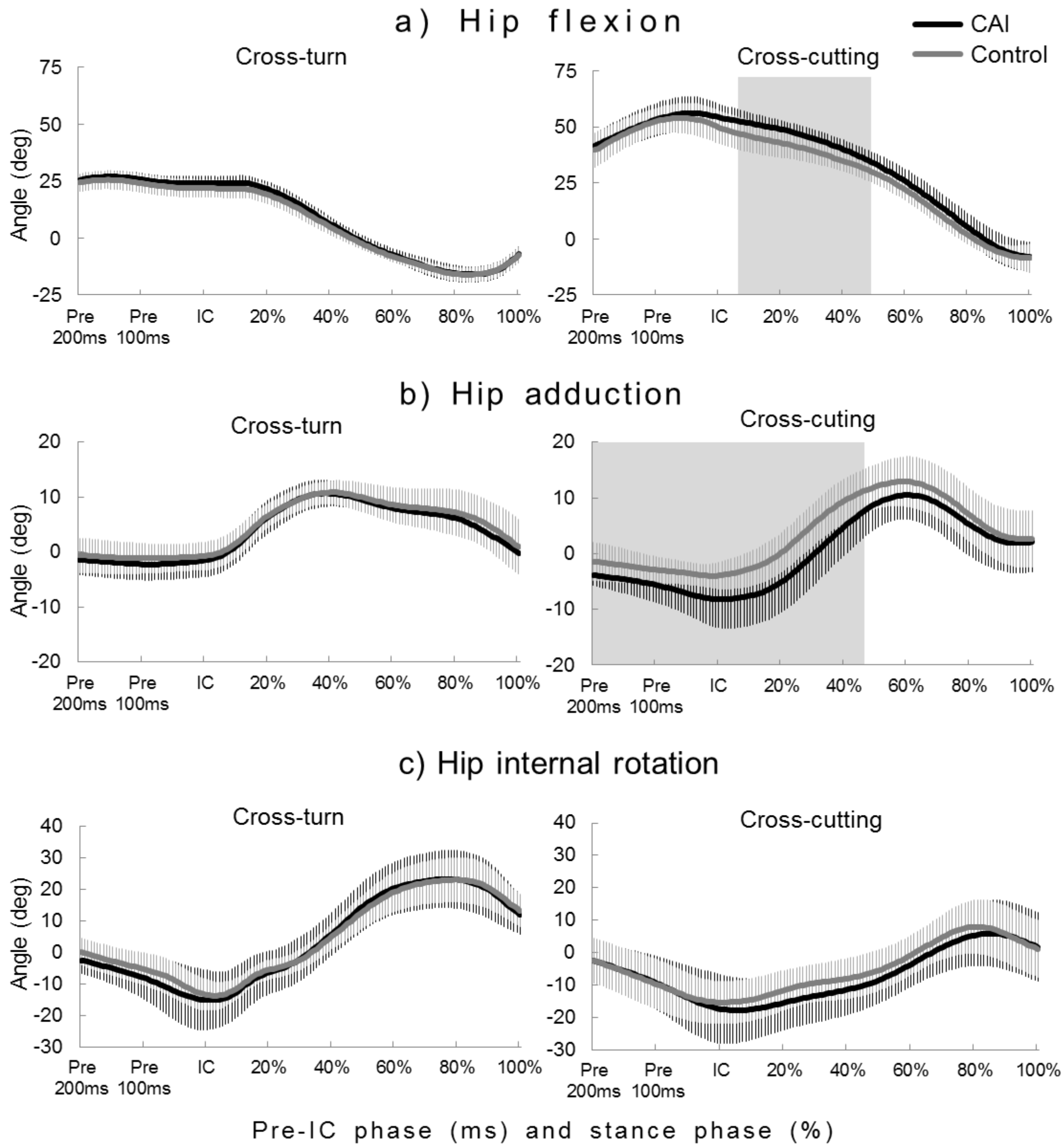

Figure 2. Mean time-series data of (a) hip flexion (+)/extension (-), (b) adduction (+)/abduction (-), and (c) internal (+)/external (-) rotation angles during cross-turn and -cutting movements. IC indicates initial contact. The horizontal axes indicate pre-IC phase and 100% stance phase. The gray boxed areas indicate the periods of significant differences between groups ($P < 0.05$).

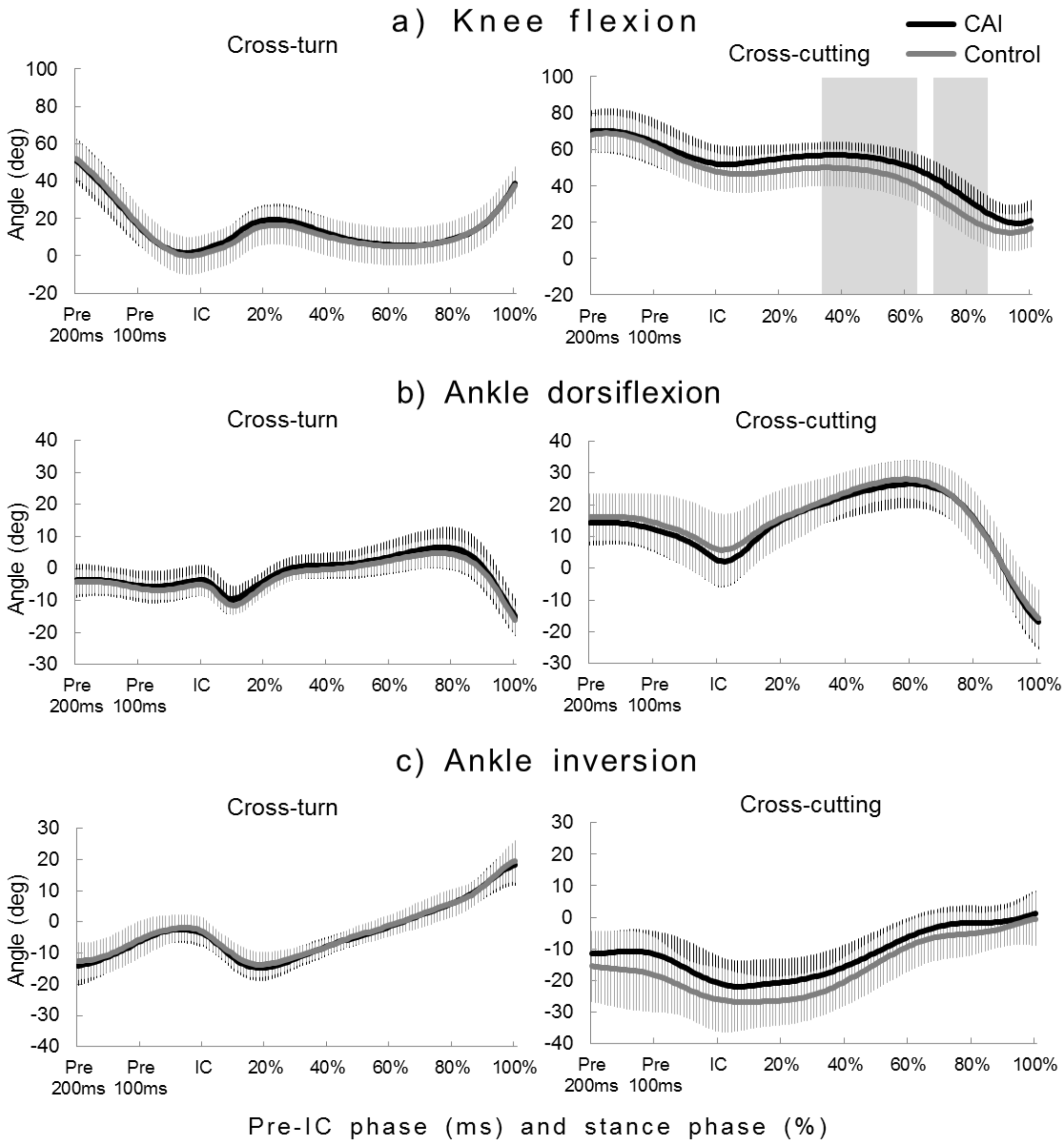

Figure 3. Mean time-series data of (a) knee flexion (+)/extension (-), (b) ankle dorsiflexion (+)/plantarflexion (-), and (c) inversion (+)/eversion (-) angles during cross-turn and -cutting movements. IC indicates initial contact. The horizontal axes indicate pre-IC phase and 100% stance phase. The gray boxed areas indicate the periods of significant differences between groups ($P < 0.05$).