



Title	Lower limb joint motion during a cross cutting movement differs in individuals with and without chronic ankle instability
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1 **Lower Limb Joint Motion During a Cross Cutting Movement Differs in**
2 **Individuals With and Without Chronic Ankle Instability**

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

3
4 **Abstract:**

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

7 **Design:** Cross-sectional study.

8 **Setting:** Motion analysis laboratory.

9 **Participants:** Twelve subjects with CAI and twelve healthy controls.

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

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

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

23 **KeyWords:** ankle sprain; biomechanics; neuromuscular control; proximal joints
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INTRODUCTION

27 Lateral ankle sprain is one of the most common injuries in many sports,
28 including basketball, volleyball, and football (Fong, Hong, Chan, Yung, & Chan, 2007).
29 The recurrence rate has been reported to exceed 70% in basketball (Yeung, Chan, So,
30 & Yuan, 1994). Approximately 40–75% of individuals who sprain their ankle go on to
31 develop chronic ankle instability (CAI) (Gerber, Williams, Scoville, Arciero, & Taylor,
32 1998), defined as recurrent ankle sprain, repetitive ‘giving way’ of the ankle joint, or a
33 feeling of instability in the ankle joint (Delahunt, Coughlan, Caulfield, Nightingale, Lin,
34 & Hiller, 2010). Individuals with CAI may have mechanical ankle instability (MAI) or
35 functional ankle instability (FAI). MAI is characterized by pathological laxity of lateral
36 ankle ligaments, and FAI is characterized by impaired neuromuscular control,
37 proprioception or postural control without ligamentous laxity (Delahunt et al., 2010).
38 These residual symptoms have been linked to increased risk of osteoarthritis at the
39 ankle (Valderrabano, Hintermann, Horisberger, & Fung, 2006).

40 The biomechanics of the lower limb joints in individuals with CAI have been
41 investigated during dynamic tasks. Individuals with CAI had a more inverted ankle
42 position than healthy individuals before and after heel strike during gait (Delahunt,
43 Monaghan, & Caulfield, 2006a; Monaghan, Delahunt, & Caulfield, 2006). Individuals
44 with CAI also had a more inverted ankle position than healthy individuals during
45 running (Lin, Chen, & Lin, 2011), single-leg landing (Delahunt, Monaghan, & Caulfield,
46 2006b), and lateral hop (Delahunt, Monaghan, & Caulfield, 2007). However, some
47 studies have reported findings that are inconsistent with these studies (Brown, 2011;
48 Brown, Padua, Marshall, & Guskiewicz, 2008; Kipp & Palmieri-Smith, 2012). These
49 studies have all used gait, running, and landing to evaluate the biomechanics of the
50 lower limb joints in individuals with CAI. Lateral ankle sprains often occur during

51 twisting and turning movements (McKay, Goldie, Payne, & Oakes, 2001; Woods,
52 Hawkins, Hulse, & Hodson, 2003); however, the biomechanics of the lower limb joints
53 in individuals with CAI have not been well investigated in turning or cutting
54 movements. Previous studies have shown altered plantar pressure, position of center
55 of pressure (Huang, Lin, Kuo, & Liao, 2011), and leg muscle activity (Suda & Sacco,
56 2011) during a lateral shuffle movement (sideward lateral cutting) in individuals with
57 CAI and, during a v-cutting movement, vertical ground reaction force (GRF) was
58 greater on the side of the unstable ankle than on the contralateral side of the uninjured
59 ankle (Dayakidis & Boudolos, 2006). These studies focused on the lateral shuffle and
60 v-cutting movements, but the biomechanics during cross-turn or -cutting movements
61 have not yet been investigated. The cross-turn movement involves a change of
62 direction to the lateral side against the supporting leg, thus the center of plantar
63 pressure may shift laterally, and forced inversion motion may occur at the ankle of the
64 supporting leg. These tasks may put the ankle at risk of giving way or laterally
65 spraining in individuals with CAI.

66 Previous studies have suggested that individuals with MAI or FAI have altered
67 kinematics of the hip and knee joints during a stop jump (Brown, Padua, Marshall, &
68 Guskiewicz, 2011) and a single-leg landing (Caulfield & Garrett, 2002; Delahunt et al.,
69 2006b; Gribble & Robinson, 2010), but there is not yet a consensus on this topic. The
70 kinematics of the proximal joints may change to compensate for instability or
71 decreased function of the ankle in individuals with CAI. Such changes may be
72 pre-existing, thus playing a role in the development of CAI. Quantifying the kinematics
73 of the lower limb joints in individuals with CAI during cross-turn and -cutting
74 movements may help us to understand the movement patterns used, and why these
75 individuals experience 'giving way' or recurrent ankle sprains. In addition, we believe

76 that understanding the patterns of movement aids in the development of rehabilitation
77 interventions that specifically address deficits or factors that contribute to the
78 pathogenesis of CAI. Therefore, the purpose of this study was to determine the
79 kinematics of the hip, knee, and ankle joints during cross-turn and -cutting movements
80 in individuals with CAI. We hypothesized that individuals with CAI would have altered
81 hip and knee kinematics, and greater ankle inversion, than healthy control subjects.

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METHODS

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Subjects

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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.

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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

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

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120 **Equipment**

121 Twenty-five reflective markers were placed on the skin of the lower limbs using
122 double-sided adhesive tape. Markers were placed according to a modified Helen
123 Hayes marker set (Kadaba, Ramakrishnan, & Wootten, 1990): At the sacrum, and
124 bilaterally on the anterior superior iliac spine, greater trochanters, lateral aspect of the
125 thighs, lateral and medial femoral epicondyles, lateral aspect of the shanks, lateral

126 and medial malleoli, posterior heels, and first, second and fifth metatarsal heads. All
127 subjects wore the same type of shoes (Artic Mesh M, Adidas, Herzogenaurach,
128 Germany) in a fitting size. Holes were cut in the shoes to enable markers to be placed
129 directly on the skin of the foot. Lower limb kinematic and GRF data were collected
130 using six digital cameras (Hawk cameras, Motion Analysis Corporation, Santa Rosa,
131 CA, USA) and a force plate (Kistler, Winterthur, Switzerland) that were
132 time-synchronized and sampled at 200 Hz and 1000 Hz, respectively.

133

134 **Procedure**

135 After a static trial was collected with the subject standing, the medial femoral
136 condyle and medial malleoli markers on the non-test leg were removed before the
137 movement tasks were performed. Subjects were instructed to perform a cross-turn
138 movement and a cross-cutting movement. The cross-turn movement was based on
139 the movement presented by Houck & Yack (Houck & Yack, 2003). The subjects
140 walked straight on a walkway at their natural speed while looking straight ahead so as
141 not to look the force plate. They then planted their test limb on the force plate and
142 changed direction to the side of the supporting leg at 45° and walked for
143 approximately 2.5 m (Figure 1a). The cross-cutting movement was based on the
144 movement described in a previous study (Ford, Myer, Toms, & Hewett, 2005).
145 Subjects were positioned in a crouched position 0.4 m in front of the force plate with
146 their knees flexed to approximately 45°. Upon hearing an audio cue played by the
147 examiner, subjects were instructed to perform a forward jump onto the force plate.
148 Then, with their test limb planted on the force plate, they performed a 45° crossover
149 cut and ran as fast as possible for approximately 2.5 m (Figure 1b). Subjects were
150 allowed to practice the movements three to five times until they could successfully

151 perform the cross-turn and -cutting movements. The two tasks were then presented in
152 random order. Kinematic and GRF data were collected from three valid trials for each
153 task. Trials were excluded if the entire foot did not make contact with the force plate or
154 if any markers were lost during testing. Subjects were allowed to rest for
155 approximately 1 min between each trial, and for 5 min between the two tasks.

156

157 **Data Reduction and Analysis**

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

176 between lateral and medial malleoli. The calcaneus coordinate system was located at
177 the most distal and inferior point of calcaneus posterior surface.

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

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

197

198 **Statistical Analysis**

199 Demographic data were compared across groups (CAI, control) using
200 independent *t* tests. Curve analyses were conducted to detect group differences in

201 time-averaged kinematic data in the entire pre-IC and stance phases (Delahunt et al.,
202 2007; Delahunt et al., 2006b; Drewes, McKeon, Kerrigan, & Hertel, 2009a; Drewes et
203 al., 2009b; Monaghan et al., 2006). Comparisons between groups were made using
204 independent *t* tests when the data were normally distributed and *Mann-Whitney* tests
205 when the data were not normally distributed. The data distributions were assessed
206 using the *Shapiro-Wilk* test. In addition, a two-way ANOVA was conducted to test for
207 the effects of groups and tasks on the approach speed, time of stance (ms), and
208 maximum vertical GRF (N/kg). A Sidak correction was used when there were
209 significant effects. Statistical significance was set at $P < .05$. Statistical analysis was
210 performed using IBM SPSS Statistics 17 (IBM Corporation, Armonk, New York, USA).

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RESULTS

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

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

224 In the cross-turn movement, there were no significant differences between the
225 groups for any joint angles ($P > .05$; Figure 2 and 3). In the cross-cutting movement,

226 the CAI group exhibited significantly greater hip flexion from 6% to 50% of the stance
227 phase than the control group ($P < .05$; power = 0.52 to 0.83; effect size = 0.86 to 1.25;
228 Figure 2), and the mean group difference was 5.51° . In addition, the CAI group
229 exhibited significantly greater hip abduction from the pre-IC 200ms to 45% of the
230 stance phase than the control group ($P < .05$; power = 0.53 to 0.80; effect size = 0.87
231 to 1.19; Figure 2), and the mean group difference was 4.04° . The CAI group also
232 exhibited significantly greater knee flexion from 35% to 64% ($P < .05$; power = 0.51 to
233 0.61; effect size = 0.85 to 0.96; Figure 3) and 69% to 87% ($P < .05$; power = 0.54 to
234 0.64; effect size = 0.88 to 0.99; Figure 3) of the stance phase than the control group,
235 and the mean group differences were 7.63° and 9.54° , respectively. There were no
236 significant differences between the groups in the hip internal/external rotation angle or
237 the ankle dorsiflexion/plantarflexion and inversion/eversion angles ($P > .05$; Figure 2
238 and 3).

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DISCUSSION

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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

251 a single-leg drop landing, and Brown et al. (Brown et al., 2011) reported that
252 individuals with MAI exhibited greater hip flexion than the copers and individuals with
253 FAI during a stop-jump task. Other studies have reported individuals with CAI
254 exhibited greater knee flexion (Caulfield & Garrett, 2002) or less knee flexion (Gribble
255 & Robinson, 2010) than control individuals during a single-leg landing. The results of
256 this study partially support the presence of changes in sagittal plane hip and knee
257 kinematics in individuals with CAI that has been reported by previous studies (Brown
258 et al., 2011; Caulfield & Garrett, 2002). However, because the movement tasks are
259 different, it is difficult to directly compare the results of this study with those of previous
260 studies. The cross-cutting movement included a change of direction and was a
261 multi-plane movement, and is therefore different from a landing. The nature of this
262 task may explain why CAI subjects displayed not only more hip and knee flexion, but
263 also more hip abduction, than control subjects. It has been suggested that CAI is
264 associated with central changes in sensorimotor function, including supraspinal motor
265 control mechanisms (Hass, Bishop, Doidge, & Wikstrom, 2010) and feed-forward
266 neuromuscular control (Wikstrom, Bishop, Inamdar, & Hass, 2010). Beckman and
267 Buchanan (Beckman & Buchanan, 1995) hypothesized that a feed-forward
268 mechanism may allow the central nervous system to recruit proximal muscles to
269 compensate for an inadequate ankle response in individuals with pathologic ankle
270 hypermobility. In the present study, during the cross-cutting movement, differences in
271 frontal plane hip motion were observed in CAI subjects before IC, i.e., before the GRF
272 had acted on the lower limb. The alterations in proximal joint kinematics may be
273 attributed to centrally mediated changes.

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

276 In previous studies, individuals with CAI have exhibited greater ankle inversion than
277 control subjects during gait (Delahunt et al., 2006a; Monaghan et al., 2006; Drewes et
278 al., 2009b), running (Lin et al., 2011), and landing (Delahunt et al., 2006b). These
279 inconsistent findings between our study and previous reports may be due to the
280 different tasks performed, or different inclusion criteria for CAI subjects. In addition,
281 most previous studies have investigated the ankle kinematics of CAI subjects under
282 barefoot conditions. Our subjects wore shoes during testing; this may be one reason
283 for the observed nonsignificant finding. Chin et al. reported no difference in inversion
284 angle during treadmill walking with shod condition between the CAI and control group
285 (Chinn, Dicharry, & Hertel, 2013), likely because shoes may stimulate ankle eversion
286 muscle activities (Kerr, Arnold, Drew, Cochrane, & Abboud, 2009). In the present
287 study, the average time-series data for the ankle inversion angle exhibited a similar
288 pattern during the cross-turn movement and appeared to be greater in the CAI group
289 than in the control group during the cross-cutting movement (Figure 3), although the
290 difference was not significant. The mean group difference was 4.5° (CAI = $-11.7 \pm 6.9^\circ$,
291 control = $-16.2 \pm 8.6^\circ$) throughout the pre-IC and stance phases. Drew et al. showed
292 that, in their study, the CAI subjects had greater inversion angles throughout the entire
293 gait cycle than the healthy controls, with a mean difference of $2.07 \pm 0.29^\circ$ (Drewes et
294 al., 2009b). Nonsignificant findings of ankle inversion may also be attributed to the
295 large standard deviations observed in our sample data. Interestingly, during the
296 cross-cutting movement, hip abduction before and after IC was greater in the CAI
297 group than in the control group. The CAI group might have altered frontal plane hip
298 motion to adjust the position of the supporting foot relative to the body. Increased hip
299 abduction would mean that the foot was placed further away from the body and in the
300 direction of the cutting movement, which may have helped avoid a sharp crossover

301 cutting movement and prevent excessive ankle inversion motion. The cross-cutting
302 movement was a preplanned task, therefore the CAI subjects would have been able
303 to plan this adjustment of hip motion. Future study should investigate kinematics
304 during an unanticipated cutting movement in order to gain a further understanding of
305 CAI.

306 Ankle sagittal plane kinematic patterns were similar in the CAI and control
307 groups during the cross-turn and -cutting movements. Previous studies have reported
308 inconsistent findings in sagittal plane ankle kinematics, including decreased
309 dorsiflexion during jogging and landing (Delahunt et al., 2006b; Drewes et al., 2009a),
310 increased dorsiflexion during landing (Caulfield & Garrett, 2002), and no group
311 differences during gait, lateral hop, and landing (Delahunt et al., 2007; Delahunt et al.,
312 2006a; Monaghan et al., 2006; Gribble & Robinson, 2010). Brown (Brown, 2011)
313 reported that ankle motion in the sagittal plane was different between individuals with
314 MAI and individuals with FAI during walking and running. Inter-study variability in
315 inclusion criteria or methodology, such as kinematic analysis, movement task, and
316 dependent variables, may underlie the inconsistent findings. In the present study, the
317 sagittal plane kinematics of the ankle did not change, unlike that of the hip and knee,
318 during the cross-cutting movement. The CAI subjects may have attempted to adjust to
319 be in a lower position with respect to their center of mass in order to gain dynamic
320 stability primarily using hip and knee flexion. The position of the center of mass,
321 dynamic stability, and lower limb joint kinematics should be measured simultaneously
322 in future studies.

323 During the cross-turn movement, the proximal joint kinematics of CAI subjects
324 were similar to those of control subjects. Also, previous studies showed that changes
325 of the proximal joints kinematics in CAI subjects did not present compared with control

326 subjects during gait (Delahunt et al., 2006a; Monaghan et al., 2006). The approach
327 speed and time of stance during the cross-turn movement were significantly slower and
328 shorter, respectively, than those observed during the cross-cutting movement. The
329 vertical GRF of the cross-turn movement was also significantly lower than that of the
330 cross-cutting movement. Therefore, it is conceivable that the cross-turn movement
331 was an easier task than the cross-cutting movement. The cross-turn movement would
332 be easy to perform and not require complex neuromuscular control of the lower limb
333 joints in athletes. Such an easy task may not reveal kinematic changes in the proximal
334 joints related to CAI. Meanwhile, the CAI subjects may have felt that it was difficult to
335 perform the sports-related movements. A lack of confidence in their ability to perform
336 the movement may have meant that they depended on the proximal joints to
337 compensate for the instability or decreased function of the ankle and avoid 'giving
338 way' or lateral ankle sprains. Changes in the kinematics of proximal joints in
339 individuals with CAI may be associated with the difficulty of the movement tasks, and
340 high-difficulty tasks could reveal the changes in the movement patterns of the lower
341 limb.

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

351 Some limitations associated with the present study need to be acknowledged.
352 First, the subjective symptoms and severity of the CAI may have varied across
353 subjects, because the inclusion criteria were based on self-reported questionnaire
354 scores and subjective reports of episodes of instability and 'giving way'. Furthermore,
355 we did not perform the anterior drawer or talar tilt tests to evaluate whether or not the
356 subjects had mechanical laxity. We defined CAI as repeated ankle sprains and
357 episodes of 'giving way' with or without ankle ligamentous laxity (Hertel, 2000). The
358 kinematics of the lower limb joints may have differed among subjects with and without
359 MAI. Second, although the ratio of males to females was matched between the
360 groups, there were fewer females within each group, which may have skewed our
361 results. Third, the cross-cutting movement was an anticipated task. In a game
362 situation, unanticipated movements, whereby athletes have to react to a ball or other
363 players, are common. Future study should consider using an unanticipated cutting
364 movement in order to further understand the kinematics and neuromuscular control of
365 the lower limb in individuals with CAI. Fourth, although skin markers are commonly
366 used to assess *in vivo* joint kinematics, the accuracy of this method is limited due to
367 skin movement artifacts. We made an effort to minimize this error using several steps.
368 Our kinematic analysis was performed with a global optimization method, which
369 minimized the weighted sum of the squared differences between the measured and
370 model-determined marker positions (Lu & O'Connor, 1999). In addition, the markers
371 were attached to landmarks in all subjects by a single tester to enhance the reliability
372 of marker placement and avoid potential errors caused by inter-tester differences. The
373 effect sizes of our significant findings were strong (> 0.8) and the powers were
374 moderate to strong. Although we acknowledge the presence of errors due to skin
375 artifacts in this study, we believe that our significant findings represent clinically

376 meaningful differences. Fifth, the significant findings of this study had moderate to
377 strong power, while the nonsignificant findings were associated with low to moderate
378 power. With respect to case of inversion during the cross-turn movement, we would
379 have needed 965 subjects per group to achieve a level of power of 0.80, according to
380 the post-hoc power analysis based on the mean values and standard deviations
381 observed in our sample. It would be difficult and unrealistic to recruit this number of
382 subjects. Finally, this study cannot determine whether the observed changes of the
383 CAI subjects were present before or after injury. A longitudinal follow-up study should
384 be conducted to address this issue.

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CONCLUSION

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

398

Conflict of interest

400 None declared.

401 **Ethical statement**

402 Participants were required to sign informed consent forms before the study began.

403 Ethics approval was obtained from Institutional Review Board of the Faculty of Health

404 Sciences of Hokkaido University.

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406

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408 None declared.

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1 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)	21.1 (0.9)	172.9 (8.2)	64.6 (8.4)	20.8 (4.4)
	Female (2)				
Control	Male (10)	20.7 (0.5)	172.1 (8.0)	64.7 (9.3)	29.8 (0.6)
	Female (2)				

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

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

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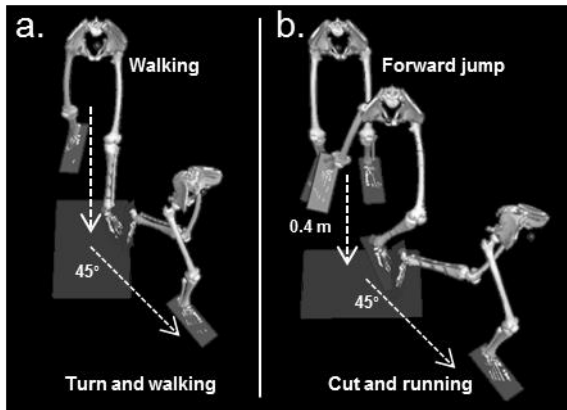
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24 TABLE 2. Approach speed, time of stance, and maximum vertical ground reaction
 25 force (GRF) during the cross-turn and -cutting movements in the chronic ankle
 26 instability (CAI) group and control group.

Variable	Group	Task	
		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)

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



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

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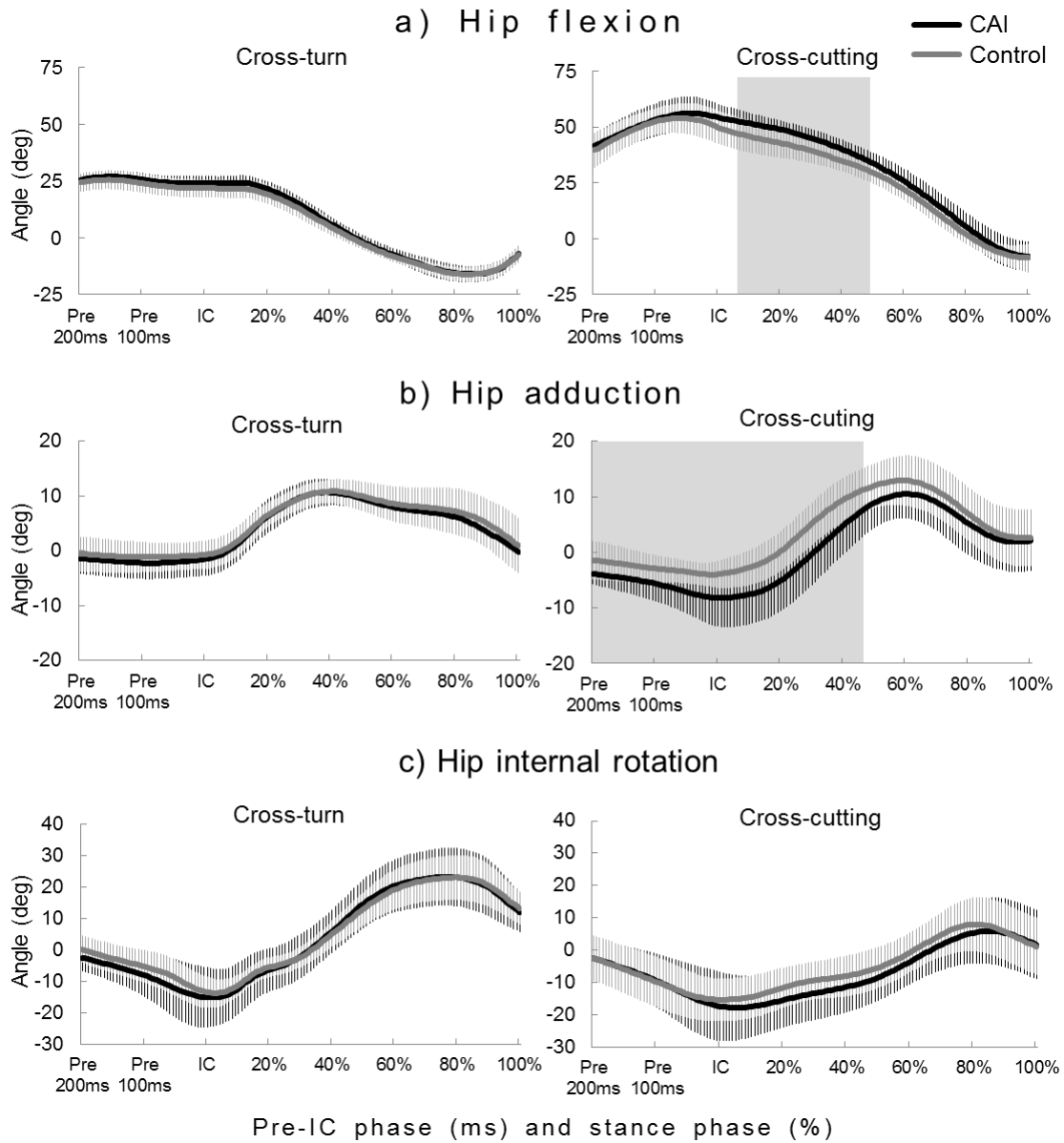
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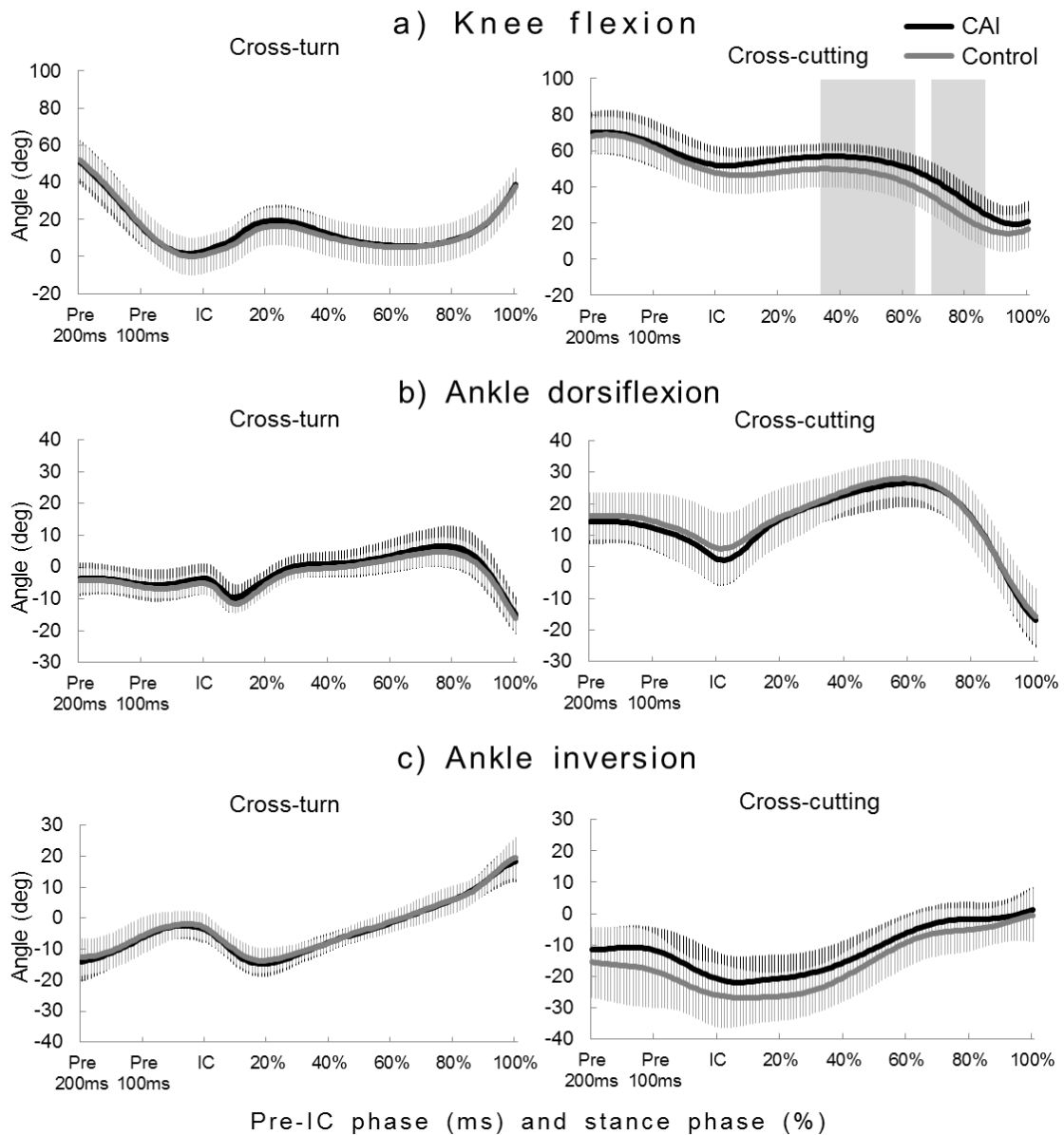
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Figure 2. Mean time-series data of (a) hip flexion (+)/extension (-), (b) adduction (+)/abduction (-), and (c) internal (+)/external (-) rotation angles during cross-turn and -cutting movements. IC indicates initial contact. The horizontal axes indicate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



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