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<b>Author(s)</b>	Koshino, Yuta; Ishida, Tomoya; Yamanaka, Masanori; Ezawa, Yuya; Okunuki, Takumi; Kobayashi, Takumi; Samukawa, Mina; Saito, Hiroshi; Tohyama, Harukazu
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1 Kinematics and Muscle Activities of the Lower Limb during a Side-Cutting Task in Subjects  
2 with Chronic Ankle Instability

3

4 Yuta Koshino<sup>1,2</sup>, Tomoya Ishida<sup>1,3</sup>, Masanori Yamanaka<sup>1</sup>, Yuya Ezawa<sup>4</sup>, Takumi Okunuki<sup>1,4</sup>,  
5 Takumi Kobayashi<sup>1,5</sup>, Mina Samukawa<sup>1</sup>, Hiroshi Saito<sup>1</sup>, Harukazu Tohyama<sup>1</sup>

6 <sup>1.</sup> Faculty of Health Sciences, Hokkaido University, Sapporo, Hokkaido, Japan.

7 <sup>2.</sup> Rehabilitation Center, NTT East Japan Sapporo Hospital, Sapporo, Hokkaido, Japan.

8 <sup>3.</sup> Department of Rehabilitation, Hokushin Orthopedic Hospital, Sapporo, Hokkaido, Japan.

9 <sup>4.</sup> Department of Rehabilitation, Matsuda Orthopedic Memorial Hospital, Sapporo,  
10 Hokkaido, Japan.

11 <sup>5.</sup> Department of Physical Therapy, Hokkaido Chitose Institute of Rehabilitation Technology,  
12 Chitose, Hokkaido, Japan.

13

14 Corresponding author: Masanori Yamanaka, PT, Ph.D.

15 Faculty of Health Science, Hokkaido University

16 West-5, North-12, Kita-ku, Sapporo, 060-0812, Japan.

17 Tell: +81-11-706-3383

18 Fax: +81-11-706-3383

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

20

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1 **Abstract**

2 **Purpose:** The purpose of the present study was to evaluate lower limb kinematics and  
3 muscular activities during walking, side-turning while walking, and side-cutting movement in  
4 athletes with chronic ankle instability and compare the results to those of athletes without  
5 chronic ankle instability.

6 **Methods:** Lower limb kinematics and muscular activities were evaluated in 10 athletes with  
7 chronic ankle instability and 10 healthy control athletes using a three-dimensional motion  
8 analysis system and surface electromyography during the 200-ms pre-initial contact (IC) and  
9 stance phases while walking, side-turning while walking, and side-cutting.

10 **Results:** During walking or side-turning while walking, there were no significant differences  
11 in kinematics or muscle activities between the subjects with and without chronic ankle  
12 instability. For the side-cutting task, however, ankle inversion angles during the 200-ms  
13 pre-IC and late stance phases [effect sizes (ESs) = 0.95–1.43], the hip flexion angle (ESs =  
14 0.94–0.96), and muscular activities of the gastrocnemius medialis (ESs = 1.04–1.73) during  
15 the early stance phase were significantly greater in the athletes with chronic ankle instability  
16 than in the healthy control athletes.

17 **Conclusions:** Alterations of kinematics in athletes with chronic ankle instability were found  
18 not only at the ankle but also at hip joints during the side-cutting movement. These alterations  
19 were not detected during walking or side-turning while walking. The findings of the present  
20 study indicate that clinicians should take into account the motion of the hip joint during the  
21 side-cutting movement in persons with chronic ankle instability.

22

23 **Level of Evidence:** Level III.

24 **Key Words:** Ankle sprain; Neuromuscular control; Ankle biomechanics; Motion analysis;  
25 turn

## 26 **Introduction**

27           Chronic ankle instability is a common sequela of a lateral ankle sprain [1, 29]. It has  
28 been defined as recurrent ankle sprain, episodes of “giving way,” or subjective instability.  
29 Several causative factors relating to chronic ankle instability has been proposed, including  
30 impaired neuromuscular control, proprioception, and postural control [6, 17]. Chronic ankle  
31 instability has also been linked to an increased risk of ankle osteoarthritis [27]. Determining  
32 the pathology of chronic ankle instability is important for preventing recurrent ankle sprain.

33           Previous studies reported that subjects with chronic ankle instability had altered  
34 kinematics during dynamic activities in the ankle [7-9, 22], knee [5, 15, 26], and hip joint [3,  
35 9]. Altered muscle activities during dynamic tasks were observed around the ankle joint, such  
36 as in the peroneus longus, gastrocnemius, and tibialis anterior muscles [7-9, 25]. In addition,  
37 muscular activity patterns of the entire lower limb for chronic ankle instability subjects,  
38 including proximal muscles around the hip joint, are different from those in subjects without  
39 chronic ankle instability during transition from double-leg to single-leg stance [28], during a  
40 single-leg rotational squat [30] and during sudden ankle inversion [2]. However, activity  
41 patterns of the proximal muscles are commonly investigated under limited conditions. It is  
42 important to identify muscular and kinematic changes of the entire lower limb in subjects with  
43 chronic ankle instability during actual dynamic activities of daily living or sports-related  
44 tasks.

45           Brown et al. [4] examined lower limb kinematics during a variety of movement tasks  
46 (walk, run, step down, drop jump, stop jump) and suggested that deceleration and rapid  
47 directional change during movement may reveal kinematic changes related to ankle instability.  
48 To the best of our knowledge, however, no study has examined the kinematics and muscular  
49 activities of the entire lower limb in subjects with chronic ankle instability during a  
50 change-of-direction task, such as a side-cutting movement, despite the fact that this movement

51 has a high risk of causing a lateral ankle sprain [23, 31]. Identifying the changes in the  
52 kinematics and muscular activities in subjects with chronic ankle instability during a variety  
53 of movement tasks, including turning or cutting movements, may help to develop a  
54 rehabilitation program for patients with a lateral ankle sprain. The purpose of the present  
55 study was to compare the kinematics and muscular activities of the lower limb during walking,  
56 a side-turn while walking, and a side-cutting movement between chronic ankle instability  
57 athletes and healthy control athletes. The hypothesis of the present study was that differences  
58 in kinematics and myoelectrical activities between the two groups would be observed more  
59 often during the side-cutting task than during the other two tasks.

60

## 61 **Materials and Methods**

62 Ten athletes with chronic ankle instability (9 men, 1 woman; age  $21.0 \pm 0.9$  years;  
63 height  $1.74 \pm 0.08$  m; weight  $65.9 \pm 7.2$  kg) and 10 age- and sex-matched healthy athletes  
64 without chronic ankle instability (9 men, 1 woman; age  $20.8 \pm 1.8$  years; height  $1.74 \pm 0.07$   
65 m; weight  $66.5 \pm 8.3$  kg) were recruited from the university. All subjects were instructed  
66 about the experimental procedure and were required to sign informed consent forms before  
67 participating.

68 The inclusion criteria for the chronic ankle instability group were partially based on  
69 the recommendations of the International Ankle Consortium [16]: (1) at least one significant  
70 lateral ankle sprain that resulted in protected weight bearing and/or immobilization; (2) a  
71 history of two or more lateral sprains to the same ankle; (3) multiple episodes of the ankle  
72 “giving way”; (4) based on the study of Wright et al. [32], a Cumberland Ankle Instability  
73 Tool (CAIT) score of  $\leq 25$ . No one was undergoing rehabilitation at the time of testing.  
74 Inclusion criteria for the control group were no history of lower limb injuries, ankle joint  
75 instability, and/or an episode of “giving way.” An inclusion criterion for all subjects was

76 participating in sports activities at least twice a week. The exclusion criteria for all subjects  
77 were: (1) a history of fracture and surgery in the lower limb and major musculoskeletal  
78 injuries (other than a history of lateral ankle sprain in the chronic ankle instability group); (2)  
79 inflammation and swelling of the ankle at the time of testing; (3) a history of acute injuries to  
80 other joints of the lower limb within the past 3 months [16]. If the subjects with chronic ankle  
81 instability had bilateral unstable ankles, the more affected side (determined by the CAIT  
82 score) was studied. The chronic ankle instability and control groups were matched on test  
83 limb dominance, which was defined as the side used for kicking a stationary ball (9 dominant  
84 legs and 1 nondominant leg).

85

### 86 ***Procedure***

87 A static trial was performed with the subject standing. The subjects then performed  
88 three movement tasks: normal walking, side-turn during normal walking, and side-cutting  
89 movement. For the walking task, the subjects walked straight on a walkway at their natural  
90 speed while looking straight ahead (Fig. 1a). For the side-turn during walking, the subjects  
91 walked straight on a walkway at their natural speed, then planted their test limb on the force  
92 plate and changed direction to the medial side at 45°, then continued walking for  
93 approximately 2.5 m (Fig. 1b). For the side-cutting task, the subjects were positioned in a  
94 crouched position with their knee flexed at approximately 45° in front of the force plate (0.4  
95 m) [14]. When an audio cue was played by the examiner, the subject performed a forward  
96 jump, with the test limb being required to contact the force plate. The subject then performed  
97 a sidestep cut at 45° and ran approximately 2.5 m as rapidly as possible (Fig. 1c).

98 Before the tasks were recorded, the subjects were allowed to practice until they could  
99 successfully perform them. The three tasks were performed in random order. The subjects  
100 were allowed to rest for approximately 1 minute between trials and 5 minutes between tasks.

101 Kinematic, ground reaction force (GRF), and electromyography (EMG) data from three valid  
102 trials were collected for each task. Trials were excluded if the entire foot did not make contact  
103 with the force plate or if any markers were lost during testing. No subject complained of any  
104 discomfort or pain during the testing.

105 After recording all movement trials, 5-second maximum voluntary isometric  
106 contractions (MVICs) were recorded to normalize the EMG amplitude during all movement  
107 trials. Other than for the gastrocnemius medialis, the MVICs were performed against manual  
108 resistance [18]. For recording the MVIC of the gastrocnemius medialis, subjects maintained a  
109 single-leg heel-raised position.

110

### 111 ***Data collection and reduction***

112 Kinematic data were recorded using EvaRT software (Motion Analysis Corporation,  
113 Santa Rosa, CA, USA) with six digital cameras (Hawk cameras; Motion Analysis  
114 Corporation) and a force plate (Type 9286; Kistler AG, Winterthur, Switzerland) that were  
115 sampled at 200 Hz and 1000 Hz, respectively. Modified Helen Hays marker sets with 25  
116 retroreflective markers were attached to the skin of the lower limbs of each subject. All  
117 subjects wore the same type of shoes in appropriate sizes (Artic Mesh M; Adidas,  
118 Herzogenaurach, Germany). Holes were cut in the shoes so the markers could be attached  
119 directly to the skin. The joint angles were calculated with SIMM 4.2.1 software  
120 (MusculoGraphics Inc., Santa Rosa, CA, USA) [10]. All joint angles in the static standing  
121 position were set at 0° for each subject.

122 Activities of the gluteus maximum, gluteus medius, rectus femoris, semitendinosus,  
123 peroneus longus, tibialis anterior, and gastrocnemius medialis muscles were recorded using a  
124 wireless surface EMG system (WEB-1000; Nihon Kohden Corporation, Tokyo, Japan) with  
125 surface-type electrode telemeters that sampled at 1000 Hz. The maximum amplitudes during

126 the MVICs were used to normalize the EMG data during all movement trials (%MVIC).

127 The coefficient of multiple correlation (CMC) was calculated to evaluate the  
128 within-day repeatability of all kinematic and EMG waveform data [21]. The repeatability was  
129 good to excellent in both groups for all kinematic waveform data (walking CMC = 0.92–0.99,  
130 side-turn CMC = 0.73–0.99, side-cutting CMC = 0.75–0.99), and for all EMG waveform data  
131 (walking CMC = 0.77–0.92, side-turn CMC = 0.73–0.92, side-cutting CMC = 0.71–0.97).

132 The institutional review board of the Faculty of Health Sciences, Hokkaido  
133 University approved this study (Approval number: 11-57).

134

### 135 *Statistical analysis*

136 All tasks were divided into a pre-initial contact (IC) phase (200 ms before IC) and a  
137 stance phase (time-normalized to 100%, from IC to toe-off). IC was defined as the instant the  
138 vertical GRF first exceeded 10 N. Toe-off was defined as the first time it fell below 10 N after  
139 IC. Mean values of the normalized EMG data were calculated by averaging the pre-IC phase  
140 and every 10% windows of stance phase, respectively. The independent *t* test or  
141 Mann–Whitney test was used to detect group differences in the kinematic and EMG data. In  
142 addition, the effects of the groups and tasks on the maximum vertical GRF were determined  
143 by two-way analysis of variance and the post hoc Sidak test. All significance levels were set  
144 at  $P < 0.05$ . Statistical analyses were performed using IBM SPSS Statistics version 17 (IBM  
145 Corporation, Armonk, NY, USA). In addition, effect sizes (ESs) were calculated to indicate  
146 the magnitude of the differences using G\*Power 3.1. The sample size was calculated using the  
147 *t* test model of G\*Power 3.1 based on our pilot study comprising seven subjects (four healthy  
148 subjects and three chronic ankle instability subjects). More than eight subjects per group were  
149 required to detect a group difference in the ankle inversion angle during the side-cutting task  
150 (80% power,  $\alpha = 0.05$ ). Ten subjects per group were included to compensate for possible

151 defective data.

152

## 153 **Results**

154           There were no significant differences between the two groups regarding age, height,  
155 or body weight (n.s.). The CAIT score of the chronic ankle instability group ( $19.6 \pm 3.6$ ) was  
156 significantly lower than that of the control group ( $29.8 \pm 0.6$ ,  $P < 0.001$ ). There were  $7.9 \pm 4.0$   
157 previous lateral ankle sprains in the chronic ankle instability group and none in the control  
158 group.

159           For walking and side-turn tasks, there were no significant differences between the  
160 groups at any of the joint angles (n.s.) (Figs. 2 and 3). For side-cutting movement, the chronic  
161 ankle instability group exhibited significantly greater hip flexion than the control group from  
162 11% to 18% of the stance phase ( $P < 0.05$ , ESs = 0.94–0.96) (Fig. 4). The mean group  
163 difference was  $5.2^\circ$ . The chronic ankle instability group also exhibited significantly greater  
164 ankle inversion than the control group during the two time periods: from pre-IC 200 ms to  
165 pre-IC 165 ms ( $P < 0.05$ , ESs = 0.99–1.25), and from 78% to 100% of the stance phase ( $P <$   
166  $0.05$ , ESs = 0.95–1.43) (Fig. 4). The mean group differences were  $7.7^\circ$  and  $6.4^\circ$ , respectively.  
167 No group differences were found for the other angles (n.s.) (Fig. 4).

168           For walking and side-turn tasks, there were no significant group differences in the  
169 mean EMG activities for any of the muscles (n.s.) (Figs. 5 and 6). For the side-cutting  
170 movement (Fig. 7), the chronic ankle instability group exhibited significantly higher mean  
171 activity of the gastrocnemius medialis than the control group during 10–30% of the stance  
172 phase ( $P < 0.05$ , ESs = 1.04–1.73). No group differences were found in the other muscles'  
173 activities (n.s.) (Fig. 7).

174           For the maximum vertical GRF (Table 1), there were no significant group effects  
175 during any of the tasks (n.s.), although a significant task effect was found ( $P < 0.001$ ). The

176 maximum vertical GRF in the side-cutting task was significantly greater than that in the  
177 walking and side-turn movement ( $P < 0.001$  for each). There was no significant difference in  
178 the maximum vertical GRF between walking and the side-turn movement (n.s.).

179

## 180 **Discussion**

181 The principal finding of this study was that the subjects with chronic ankle instability  
182 exhibited altered kinematic patterns of the hip and ankle joints compared with the healthy  
183 controls during the side-cutting movement. The patterns during the normal walking and  
184 side-turn while walking, however, were not different between the two groups. These results  
185 supported our hypothesis that the group differences in the kinematics would be observed more  
186 frequently during the side-cutting task. These findings are also partially consistent with  
187 previous findings, which indicated that kinematic differences between mechanical ankle  
188 instability, functional ankle instability, and “coper” (having a history of ankle sprain but did  
189 not develop chronic ankle instability) groups were detected more often in the progression of  
190 movement tasks [4]. In the present study, the side-cutting movement showed greater impact  
191 force than walking or the side-turn movement. The subjects were required to perform impact  
192 absorption, a rapid change of direction, and deceleration for the side-cut movement. This  
193 movement is common in court sports and presents a potential risk of lateral ankle sprain [23,  
194 31]. Sports-related movements require more complex joint control for the lower limb than  
195 movements that occur during activities of daily living (i.e., walking, turning), as was  
196 demonstrated by the changes in the kinematics of the chronic ankle instability subjects. The  
197 changes related to chronic ankle instability may be associated with the difficulty of the  
198 movement tasks and may be task-dependent.

199 Compared with the control subjects, the chronic ankle instability subjects exhibited  
200 greater hip joint flexion and ankle inversion during the side-cutting movement. Brown et al.

201 [3] reported increased hip flexion and external rotation in mechanical ankle instability  
202 subjects during a stop-jump task. Previous studies reported that subjects with ankle instability  
203 showed an increased inversion angle during sports-related tasks [8, 9, 22]. To the best of our  
204 knowledge, this is the first study to show that the chronic ankle instability subjects exhibited  
205 significantly greater hip flexion and ankle inversion than the controls during the side-cut  
206 movement. The altered ankle kinematics could help explain why they are susceptible to their  
207 ankles giving way or to lateral ankle sprains during the side-cut movement. Also, the chronic  
208 ankle instability subjects might have attempted to adjust their bodies so the center of mass  
209 was lower, thereby gaining dynamic stability using mainly hip flexion. In addition, the  
210 kinematic changes may be the result of compensatory movement strategies used during the  
211 acute phase of a lateral ankle sprain [11, 12].

212         The hypothesis of the present study that differences in myoelectrical activity between  
213 the two groups would be observed more frequently during the side-cutting task was not  
214 supported. Feger et al. [13] reported that there were no differences in muscle activity, but that  
215 the onset time and activation time of lower limb muscles were altered in chronic ankle  
216 instability subjects during walking. The analysis of muscle activity pattern that includes a  
217 temporal element, rather than a simple quantitative assessment of muscle activity, may reveal  
218 the neuromuscular changes associated with chronic ankle instability. The chronic ankle  
219 instability subjects in the present study, however, exhibited increased mean activity of the  
220 gastrocnemius medialis during the early-stance phase of the side-cutting task. Gastrocnemius  
221 activity has important roles in absorbing impact and increasing ankle stiffness to protect the  
222 ankle joint [20]. Our subjects with chronic ankle instability might have increased their  
223 gastrocnemius medialis activity to stabilize their ankle joints or reduce the ankle load  
224 immediately after ground contact.

225         Concerning the study's clinical relevance, it is important that clinicians observe the

226 movements of lower limb joints during sports-related tasks to assess adequately whether their  
227 movement patterns render the patient vulnerable to lateral ankle sprain. Training for dynamic  
228 activities, including rapid direction change and deceleration, should be incorporated into any  
229 rehabilitation program after lateral ankle sprain. Clinicians should also assess hip function,  
230 such as muscle strength and/or range of motion for rehabilitation after a lateral ankle sprain.  
231 The clinician should educate the patient about vulnerable ankle positions. It is also important  
232 to correct any ankle malpositioning observed during the side-cutting movement by using an  
233 external ankle support to prevent recurrent ankle sprains or their “giving way.”

234         Several limitations associated with this study should be acknowledged. First, the  
235 side-cutting movement was an anticipated condition. Side-cutting movements during sports  
236 activities are commonly unanticipated. Identifying the kinematics and neuromuscular control  
237 during an unanticipated side-cutting movement might be helpful for subjects with chronic  
238 ankle instability [19, 24]. Second, we could not determine whether the observed changes in  
239 the chronic ankle instability subjects were present before or after injury. A longitudinal  
240 follow-up study should be conducted to clarify this issue. Third, we did not evaluate any  
241 methods for correcting the observed changes in the chronic ankle instability subjects. A future  
242 study should examine the effect of braces on the hip and ankle during the side-cutting  
243 movement in subjects with chronic ankle instability.

244

## 245 **Conclusions**

246         Kinematics and muscular activities of the hip, knee, and ankle during walking,  
247 side-turning while walking, and side-cutting movement were evaluated in athletes with  
248 chronic ankle instability and healthy athletes (controls). Compared with the controls, the  
249 chronic ankle instability subjects exhibited increased hip flexion and ankle inversion and  
250 greater gastrocnemius medialis activity during the side-cutting movement.

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351 **Figure captions**

352 **Fig. 1** Illustrations of the tasks: walking (a), side-turn while walking (b), and side-cutting  
353 movement (c).

354

355 **Fig. 2** Average joint angles (mean  $\pm$  SEM) during walking. Horizontal axes indicate the  
356 pre-initial contact (pre-IC) phase and 100% stance phase.

357

358 **Fig. 3** Average joint angles (mean  $\pm$  SEM) during the side-turn while walking. Horizontal  
359 axes indicate the pre-IC phase and 100% stance phase.

360

361 **Fig. 4** Average joint angles (mean  $\pm$  SEM) during the side-cutting movement. Horizontal axes  
362 indicate the pre-IC phase and 100% stance phase. Gray box areas indicate the periods of  
363 significant differences between the chronic ankle instability and control groups ( $P < 0.05$ ).

364

365 **Fig. 5** Average muscle activities (mean  $\pm$  SEM) during walking. Horizontal axes indicate the  
366 pre-IC phase and 100% stance phase.

367

368 **Fig. 6** Average muscle activities (mean  $\pm$  SEM) during the side-turn while walking.

369 Horizontal axes indicate the pre-IC phase and 100% stance phase.

370

371 **Fig. 7** Average muscle activities (mean  $\pm$  SEM) during the side-cutting movement. Horizontal  
372 axes indicate the pre-IC phase and 100% stance phase. A gray box area indicates the period of  
373 significant differences between the chronic ankle instability and control groups ( $P < 0.05$ ).

1 **Table 1.** Maximum vertical ground reaction forces (N/kg) of the chronic ankle instability and  
2 control groups during all movement tasks

	Walking	Side-turn	Side-cutting <sup>a</sup>
Chronic ankle instability	11.2 (1.0)	11.6 (0.8)	19.4 (2.1)
Control	11.5 (0.5)	11.5 (0.5)	19.5 (2.0)

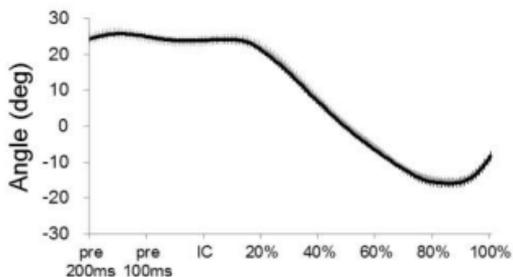
3 All values are mean (SD)

4 <sup>a</sup> indicates significantly greater than the walking and side-turn tasks ( $P < 0.001$ )

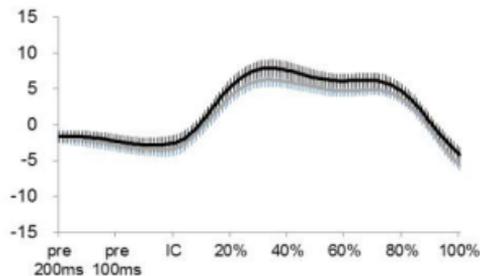


# Walking

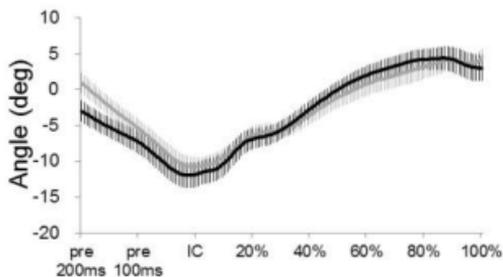
## Hip flexion



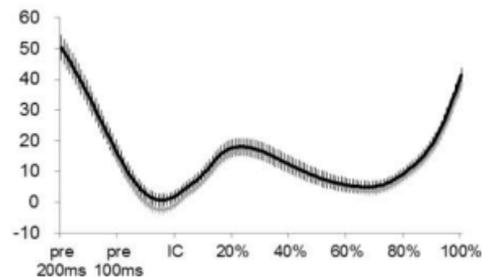
## Hip adduction



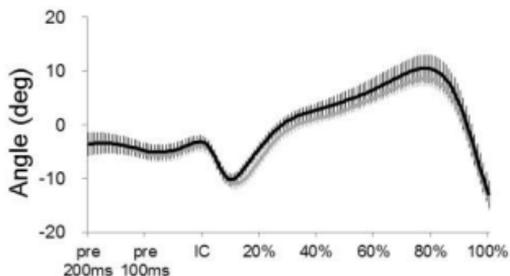
## Hip internal rotation



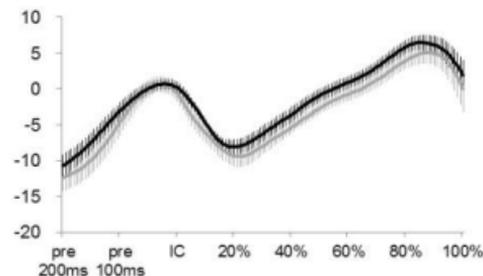
## Knee flexion



## Ankle dorsiflexion



## Ankle inversion

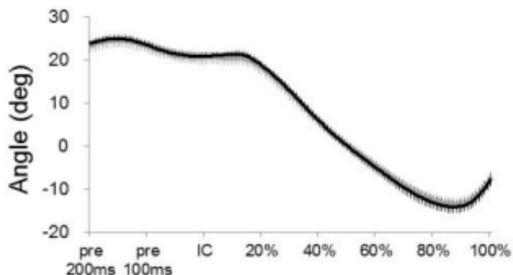


— Chronic ankle instability

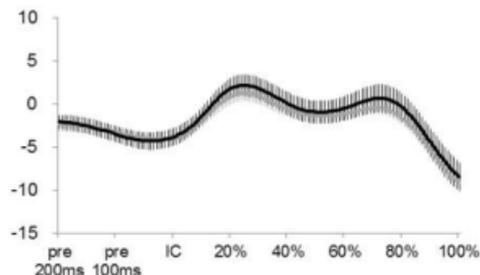
— Control

# Side-turn while walking

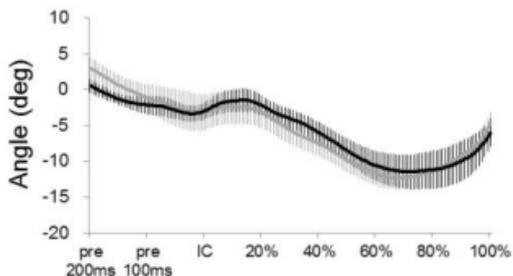
## Hip flexion



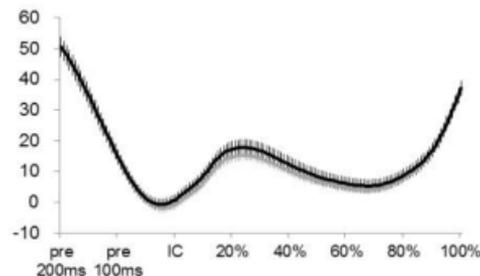
## Hip adduction



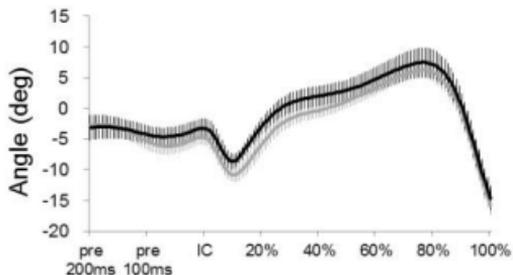
## Hip internal rotation



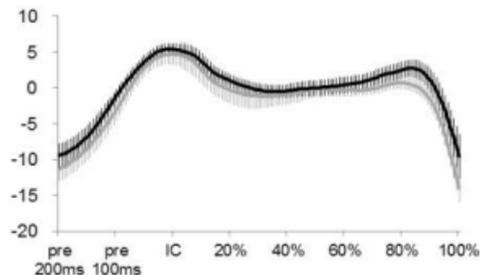
## Knee flexion



## Ankle dorsiflexion



## Ankle inversion

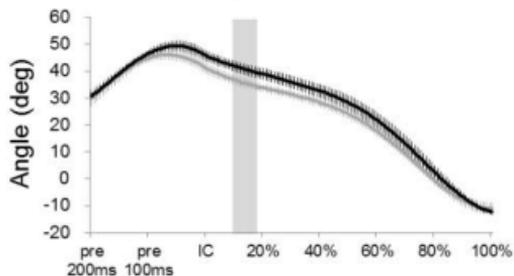


— Chronic ankle instability

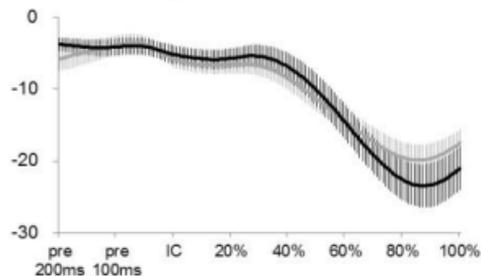
— Control

# Side-cutting

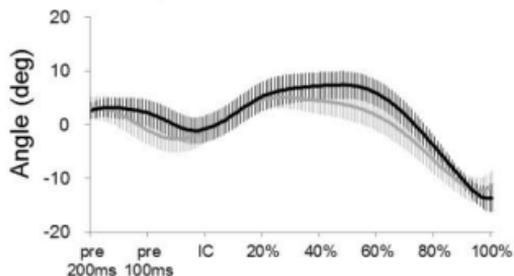
## Hip flexion



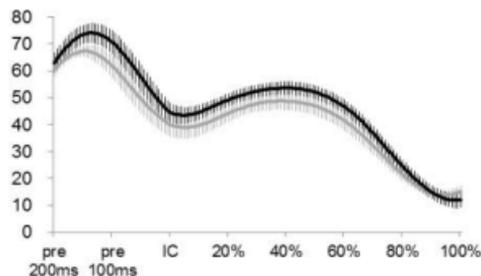
## Hip adduction



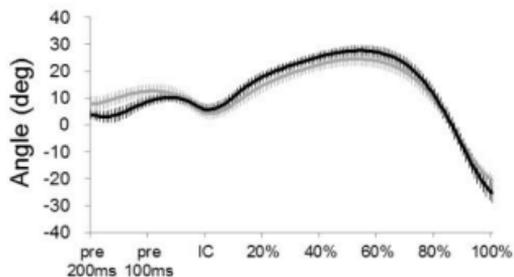
## Hip internal rotation



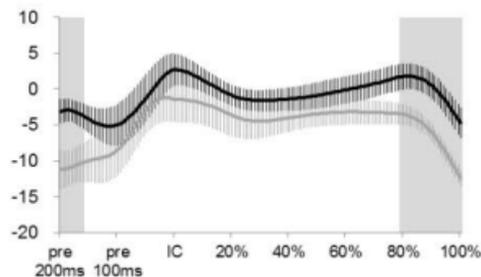
## Knee flexion



## Ankle dorsiflexion



## Ankle inversion

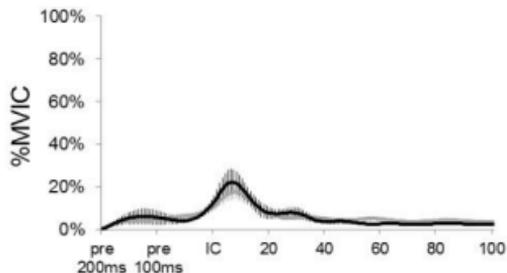


— Chronic ankle instability

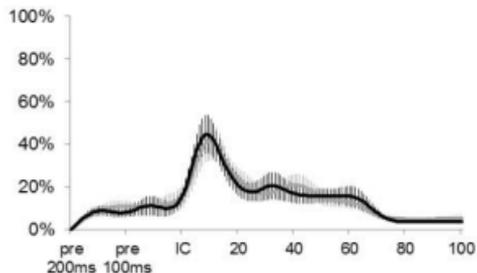
— Control

# Walking

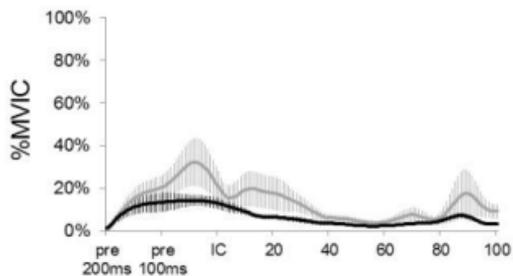
## Gluteus maximum



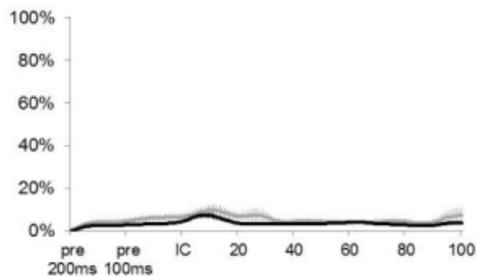
## Gluteus medius



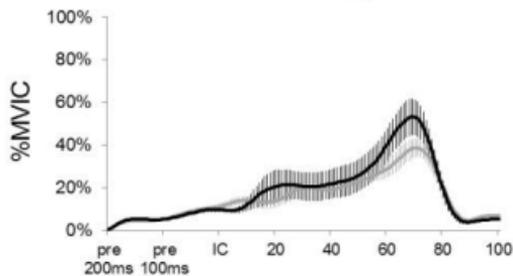
## Semitendinosus



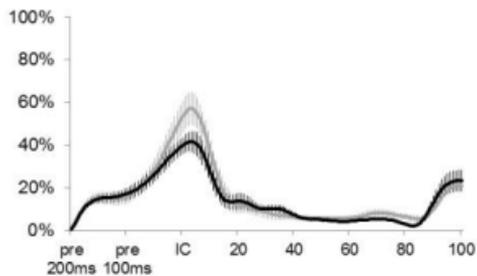
## Rectus femoris



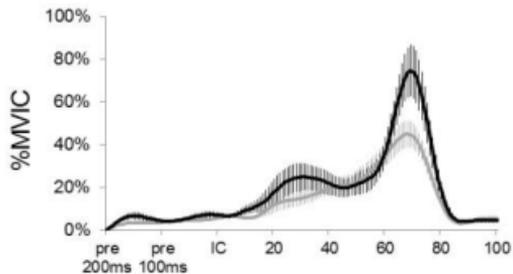
## Peronius longus



## Tibialis anterior



## Gastrocnemius medialis

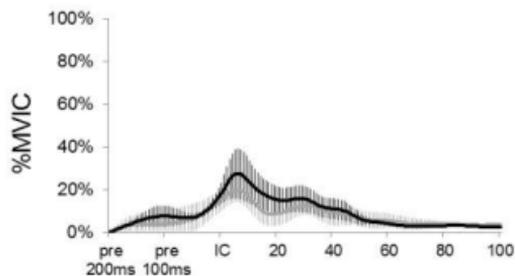


— Chronic ankle instability

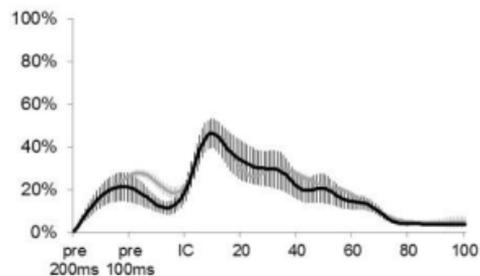
— Control

# Side-turn while walking

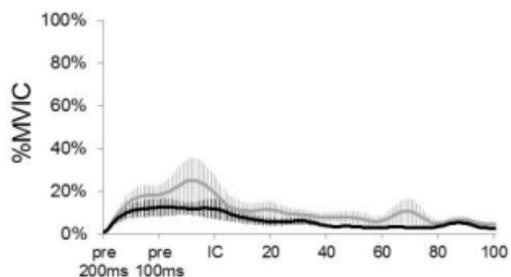
## Gluteus maximum



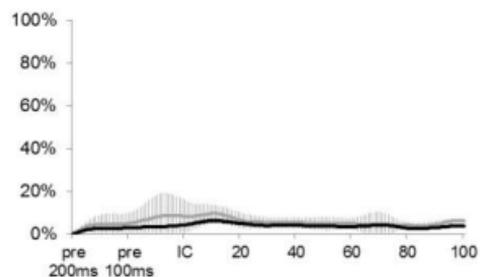
## Gluteus medius



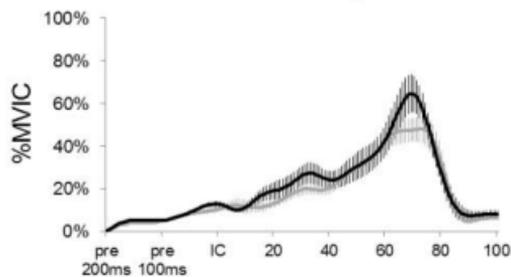
## Semitendinosus



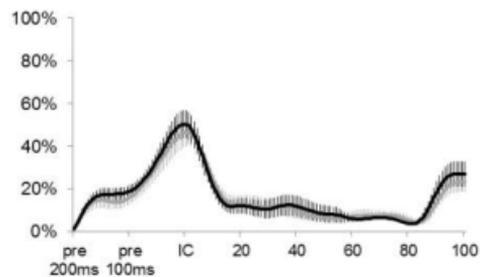
## Rectus femoris



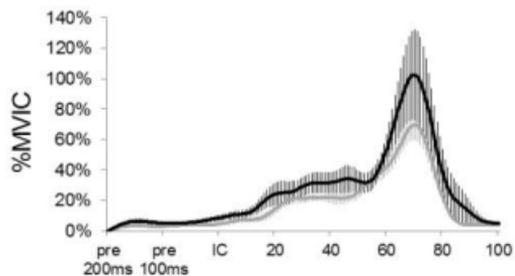
## Peronius longus



## Tibialis anterior



## Gastrocnemius medialis

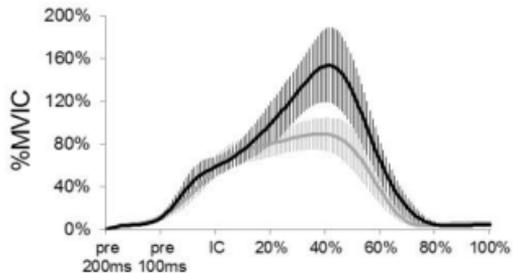


— Chronic ankle instability

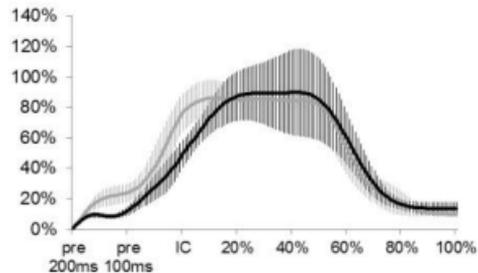
— Control

# Side-cutting

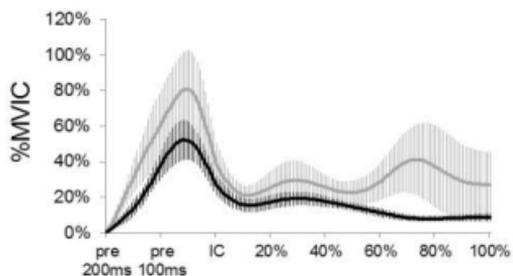
## Gluteus maximum



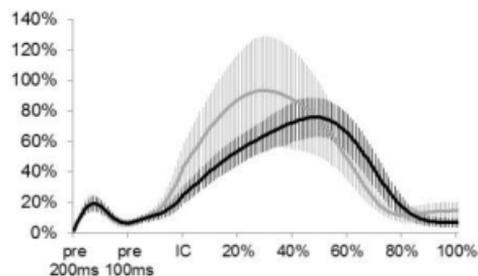
## Gluteus medius



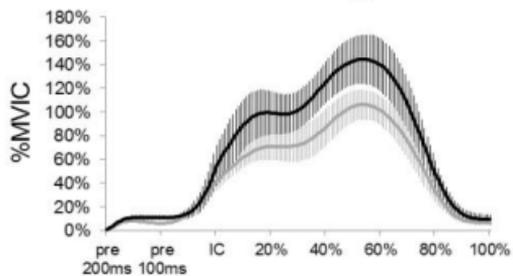
## Semitendinosus



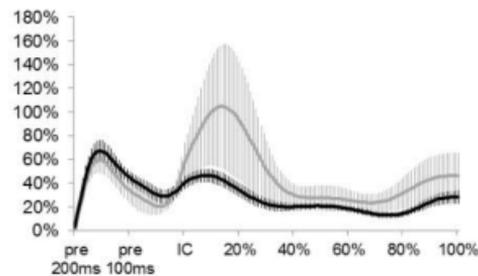
## Rectus femoris



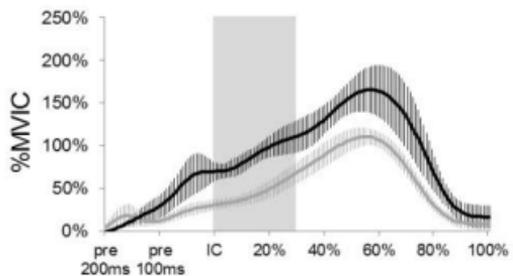
## Peronius longus



## Tibialis anterior



## Gastrocnemius medialis



— Chronic ankle instability

— Control