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Compensatory Kinetics During the Side-Hop Test in Individuals With Chronic Ankle Instability

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Context: Individuals with chronic ankle instability (CAI) exhibit altered movement strategies during side-cutting tasks. However, no researchers have assessed how altered movement strategies affect cutting performance.

Objective: To investigate compensatory strategies in the side-hop test (SHT), with a focus on the entire lower extremity, among individuals with CAI.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: A total of 40 male soccer players comprising a CAI group (n = 20; age = 20.35 ± 1.15 years, height = 173.95 ± 6.07 cm, mass = 68.09 ± 6.73 kg) and a control group (n = 20; age = 20.45 ± 1.50 years, height = 172.39 ± 4.39 cm, mass = 67.16 ± 4.87 kg).

Intervention(s): Participants performed 3 successful SHT trials.

Main Outcome Measure(s): We calculated SHT time, torque, and torque power in the ankle, knee, and hip joints during the SHT using motion-capture cameras and force plates. Confidence intervals for each group that did not overlap by >3 points consecutively in the time series data indicated a difference between groups.

Results: Compared with the control group, the CAI group showed (1) no delayed SHT time; (2) lower ankle-inversion torque (range = 0.11–0.13 N·m/kg) and higher hip-extension (range = 0.18–0.72 N·m/kg) and -abduction torque (0.26 N·m/kg); (3) less concentric power in ankle dorsiflexion-plantar flexion (0.18 W/kg) and inversion-eversion (0.40 W/kg), more concentric power in hip flexion-extension (0.73 W/kg), and more eccentric power in knee varus-valgus (0.27 W/kg).

Conclusions: Individuals with CAI were likely to rely on hip-joint function to compensate for ankle instability and demonstrated no differences in SHT time compared with the control group. Therefore, the movement strategies of individuals with CAI could differ from those of individuals without CAI, even if SHT time is not different.

Key Words: ankle sprains, functional performance test, injury prevention, return to sport

Key Points

- The chronic ankle instability (CAI) group showed no delay in side-hop test time versus the control group and displayed a hip-dominant movement strategy.
- The altered movement strategies of the CAI group could contribute to compensation for ankle dysfunction.
- Clinicians should consider using side-hop test time in their assessments of patients with CAI.

Ankle sprains are the most frequent lower extremity injuries in sport activities[1] and are reported to have a high incidence in ball sports.[2] Anandacoomarasamy and Barnsley[3] found that most individuals (74%) who experienced ankle sprains had chronic symptoms from 1.5 to 4.0 years after the initial ankle sprain. *Chronic ankle instability* (CAI) is a sequela after an initial ankle sprain, with residual symptoms including recurrent ankle sprains, episodes of the ankle "giving way," ankle-joint instability, pain, and functional impairment.[4] According to a systematic review,[5] the authors of several studies have noted CAI in ball sports, with recurrent ankle sprain rates of 61% in soccer and 60% in basketball and persistent ankle symptom rates of 45% in soccer and 30% in basketball. The latest CAI model consists of several major components, including motor-behavioral impairments.[6] These motor-behavioral impairments indicate deficiencies and alterations in muscle contraction and movement patterns, and individuals with CAI may exhibit altered movement characteristics during athletic activities compared with individuals who do not have CAI.[6]

Ankle sprains have been reported to occur frequently during landing and cutting in sport activities.[7] Given the approximately 700 direction changes per soccer game,[8] cutting movements in individuals with CAI should be considered from the perspective of injury prevention due to the risk of ankle-sprain reinjury. Researchers[9–11] have observed that, compared with individuals without CAI, individuals with CAI had smaller ankle-dorsiflexion angles, greater vertical ground reaction forces (GRFs), and a compensatory hip-dominant strategy that redistributed load on the lower extremity from the ankle joint to the hip joint during side cutting. These findings could be useful for preventing recurrent ankle sprains and other lower extremity injuries. However, these studies have only shown how individuals with CAI differed in their movement strategies during side-cutting tasks; the effects of these differences on athletic performance have not been investigated. In other words, whether the altered movement strategies exhibited by individuals with CAI negatively affect their athletic ability is unclear. Fox[12] described biomechanical factors that contributed to reducing the anterior cruciate ligament (ACL) injury risk and improved cutting performance. Therefore, the altered movement in individuals with CAI needs to be evaluated from injury-prevention and performance-improvement perspectives.

The side-hop test (SHT) is a performance test with high validity in identifying patients who have CAI.[13] This test requires individuals to perform 10 fast round trips with a single limb over 2 parallel lines placed 30-cm apart, and the time to finish the trial is recorded.[14] Given that the SHT is a performance test associated with the ankle joint, researchers have used it to examine the kinematic characteristics of the ankle joint,[15–17] but we do not believe that anyone has focused on the entire lower extremity. Considering the reported compensatory hip-dominant strategy during side-cutting in individuals with CAI,[9–11] it is possible that the hip joint would also compensate for ankle-joint dysfunction, even in the SHT. Thus, we need to investigate the knee and hip joints as well as the ankle joint in the SHT to understand the interaction of these lower extremity joints.

In addition, no authors have explored the kinetic characteristics of the SHT, and limited kinematic and electromyographic data are available to help clinicians understand the SHT. Ankle sprains occur when the ankle-inversion and internal-rotation moment generated from GRFs increase the load on the anterior talofibular and calcaneofibular ligaments.[18] Individuals with CAI could not effectively attenuate the impact load during landing in dynamic tasks, leading to increased reliance on the hip joint.[11] They also exhibited altered mechanics during landing that could lead to recurrent ankle sprains,[19] and assessing the kinetics is crucial to understand their motor-control strategies. Therefore, investigating kinetics in the SHT would provide information essential to understanding how individuals with CAI perform during the landing impact.

Thus, the purpose of our study was to evaluate compensatory strategies, focusing on the entire lower extremity, for the SHT in individuals with CAI. We hypothesized that (1) SHT time would not differ between individuals with and those without CAI and (2) individuals with CAI would exhibit higher hip torque and torque power than healthy individuals.

METHODS

Participants

A total of 40 male collegiate soccer players participated in the study. We divided the participants into CAI (n = 20) and control (CON) groups (n = 20), matched for sex, age, height, and mass (Table 1). Based on the International Ankle Consortium recommendations,[4] the selection criteria for the CAI group were as follows: (1) self-reported history of $\geq$2 ankle sprains, (2) history of ankle sprains requiring at least 24 hours of nonweightbearing activity or immobilization, (3) self-reported giving way, (4) Cumberland Ankle Instability Tool score $\leq$24, and (5) unilateral ankle instability. The selection criteria for the CON group were as follows: (1) no ankle instability at the time of measurement and (2) no history of the ankle giving way. Individuals were excluded if they had at least 1 of the following: (1) previous musculoskeletal surgery of the lower extremity, (2) previous fracture of the lower extremity requiring repair, (3) musculoskeletal injury of the lower extremity requiring at least 1 day of physical inactivity within the 3 months before the test date, and (4) no involvement in normal exercise activities at the time of measurement. All participants provided written informed consent, and the study was approved by the University of Tsukuba Research Ethics Committee (No. 021-122).

Table 1. Morphometric Data and Cumberland Ankle Instability Tool Scores

Variable	Group, Mean ± SD		P Value
	Chronic Ankle Instability	Control	
Age, y	20.35 ± 1.15	20.45 ± 1.50	.82
Height, cm	173.95 ± 6.07	172.39 ± 4.39	.37
Mass, kg	68.09 ± 6.73	67.16 ± 4.87	.63
Cumberland Ankle Instability Tool, points	20.75 ± 3.99	29.40 ± 0.80	<.001

Experimental Procedures

We attached 47 retroreflective markers (15-mm diameter) to anatomic landmarks on participants' bodies and collected 3-dimensional (3D) coordinates at 250 Hz using 10 Vicon MX+ cameras (Vicon Motion Systems Ltd). We used 2 force platforms (model 9287C; Kistler Instrumente AG) to collect the GRFs at 1000 Hz. We defined the *global coordinate system* as the x-axis (anteroposterior) in front of the participant at the beginning of the test, the y-axis (medial and lateral) perpendicular to the x-axis, and the z-axis (vertical).

Participants performed the SHT in an indoor laboratory setting. They practiced the trial before measurements were collected. The CAI group used the limb with ankle instability as the test limb during the SHT, and the CON group used the *dominant leg*, which was defined as the preferred limb for kicking a ball in soccer. In addition, the participants wore familiar indoor shoes during the experiment. Each person stood on a single limb, placed both hands on the hips, and started hopping laterally at the start signal. A trial was considered a *failure* if the supporting limb stepped on the line more than twice, the free limb touched the ground, or the hands left the hips. We recorded 3 successful trials and used the average of those trials for analysis. A rest period of at least 1 minute was allowed between the trials to minimize the effects of fatigue.

Data Analysis

The SHT time and ground contact time (GCT) were calculated using the GRF data collected from the force plates. *Ground contact* was defined as the time when the vertical component of the GRF exceeded 20 N and *takeoff* as the time when the vertical component of the GRF fell below 20 N. We temporally synchronized the obtained 3D coordinates for each body part and the GRF data using Nexus software (version 2.0; Vicon Motion Systems Ltd). The 3D coordinates and GRF data were smoothed at 10 Hz using a fourth-order Butterworth low-pass digital filter with no phase shift. We interpolated the GRF data at 250 Hz using a spline function to synchronize with the 3D coordinate data. Following the methods of

Table 2. Side-Hop Test Time and Ground Contact Time During Each Phase

Variable	Group, Mean ± SD (Range)		P Value	Cohen d Effect Size
	Chronic Ankle Instability	Control		
Side-hop test time, s	6.67 ± 0.73 (5.28–8.22)	6.65 ± 0.60 (5.53–7.45)	.93	0.03
Ground contact time, ms				
Medial-hop contact phase	196.92 ± 19.53 (158.00–231.00)	201.10 ± 19.12 (171.67–234.00)	.51	0.21
Lateral-hop contact phase	203.52 ± 21.54 (168.33–244.00)	205.73 ± 21.68 (169.00–248.67)	.75	0.10

a previous study,[10] rigid link models (foot, shank, thigh, and pelvis segments) were created from the 3D coordinate data. We computed the angular velocities of the joints via the time differentiation of the joint angles calculated using the Cardan rotation sequence. Net internal torque at the hip, knee, and ankle joints was determined using inverse dynamics analysis. Torque power was calculated as the product of the joint angular velocity and the net internal torque. Torque and torque power were normalized to participants' body weights (kilograms).

Applying an earlier method,[16,17] we used GRF data to divide the SHT into 2 ground contact phases: the medial-hop contact phase (MC) and the lateral-hop contact phase (LC). The *MC* is the phase when contact is made on the medial side of the test limb, and the *LC* is the phase when contact is made on the lateral side. We analyzed all data in this study for 8 of the 10 round-trip segments of the SHT, excluding the first and tenth round-trip segments.[16,17] All variables were calculated for the MC and LC data, respectively. To present the time series data for torque and torque power, we normalized these data from ground contact (0%) to takeoff (100%) as 100%. We performed data analysis using MATLAB (version R2021b; The MathWorks, Inc).

Statistical Analysis

We investigated differences between the CON and CAI groups for morphologic characteristics, SHT time, and GCT using an unpaired *t* test at a significance level of 5%. We calculated means and 90% CIs for the time-normalized torque and torque power during the MC and LC. Confidence intervals for each group that did not overlap >3 points consecutively in the time series data indicated a difference between the groups.[20] When differences were present, we determined the mean difference between groups and the Cohen *d* effect size.[21] Effect sizes were interpreted as *large* ($\geq$ 0.80), *moderate* (0.50–0.79), *small* (0.20–0.49), or *trivial* ($\leq$ 0.20). Statistical analysis was performed using SPSS (version 27; IBM Corp), MATLAB R2021b, and Excel (version 2020; Microsoft Corp).

RESULTS

Time

The SHT times and GCTs are provided in Table 2. We observed no differences between the CAI and CON groups in SHT time or GCT during the MC and LC.

Torque

Time series data of the torque and torque power in the MC and LC are shown in Figures 1 and 2 and Figures 3 and 4, respectively. Figures 1 and 3 illustrate the time series data in the sagittal plane, and Figures 2 and 4 illustrate these data in the frontal plane during each phase. During the MC, the CAI group exhibited lower ankle-inversion torque in 21% to 24% of ground contact (mean difference = −0.11 ± 0.01 N·m/kg; *d* = 0.76 [90% CI = 0.21, 1.28]) and 63% to 76% of ground contact (mean difference = −0.13 ± 0.02 N·m/kg; *d* = 0.72 [90% CI = 0.17, 1.24]), higher hip-extension torque in 20% to 75% of ground contact (mean difference = −0.72 ± 0.24 N·m/kg; *d* = 1.20 [90% CI = 0.61, 1.74]), and higher hip-abduction torque in 22% to 44% of ground contact (mean difference = −0.26 ± 0.03 N·m/kg; *d* = 0.82 [90% CI = 0.26, 1.35]) than the CON group (Figures 1 and 2). Similarly, during the LC, the CAI group demonstrated higher hip-extension torque in 0% to 7% of ground contact (mean difference = −0.18 ± 0.01 N·m/kg; *d* = 0.87 [90% CI = 0.31, 1.40]) and 11% to 70% of ground contact (mean difference = −0.58 ± 0.18 N·m/kg; *d* = 1.06 [90% CI = 0.48, 1.59]) than the CON group (Figures 3 and 4).

Torque Power

During the MC, the CAI group showed less concentric power in ankle inversion-eversion at 73% to 85% of ground contact (mean difference = −0.40 ± 0.04 W/kg; *d* = 0.82 [90% CI = 0.26, 1.34]) and more eccentric power in knee varus-valgus at 36% to 46% of ground contact (mean difference = −0.27 ± 0.02 W/kg; *d* = 0.94 [90% CI = 0.37, 1.47]) compared with the CON group (Figures 1 and 2). During the LC, the CAI group exhibited less concentric power in ankle dorsiflexion-plantar flexion at 94% to 98% of ground contact (mean difference = −0.18 ± 0.05 W/kg; *d* = 0.85 [90% CI = 0.29, 1.37]), more concentric power in ankle inversion-eversion at 86% to 91% of ground contact (mean difference = 0.14 ± 0.01 W/kg; *d* = 0.74 [90% CI = 0.19, 1.26]), and more concentric power in hip flexion-extension at 55% to 68% of ground contact (mean difference = 0.73 ± 0.07 W/kg; *d* = 0.84 [90% CI = 0.28, 1.36]) compared with the CON group (Figures 3 and 4).

DISCUSSION

Focusing on the entire lower extremity, we investigated kinetic characteristics during the SHT of individuals with CAI. No differences were identified between groups in SHT time or GCT. The CAI group had lower torque in the ankle joint and higher torque in the hip joint, and the torque power differed depending on the phase. This is the first study to evaluate kinetics during the SHT in individuals with CAI who had SHT time comparable with that of healthy individuals without CAI. Whereas SHT time between the CAI and CON groups was not different, the CAI group exhibited altered kinetic characteristics. Kotsifaki et al[22] reported that, even if the performance results were symmetric in an assessment test, the biomechanics of the lower extremity were

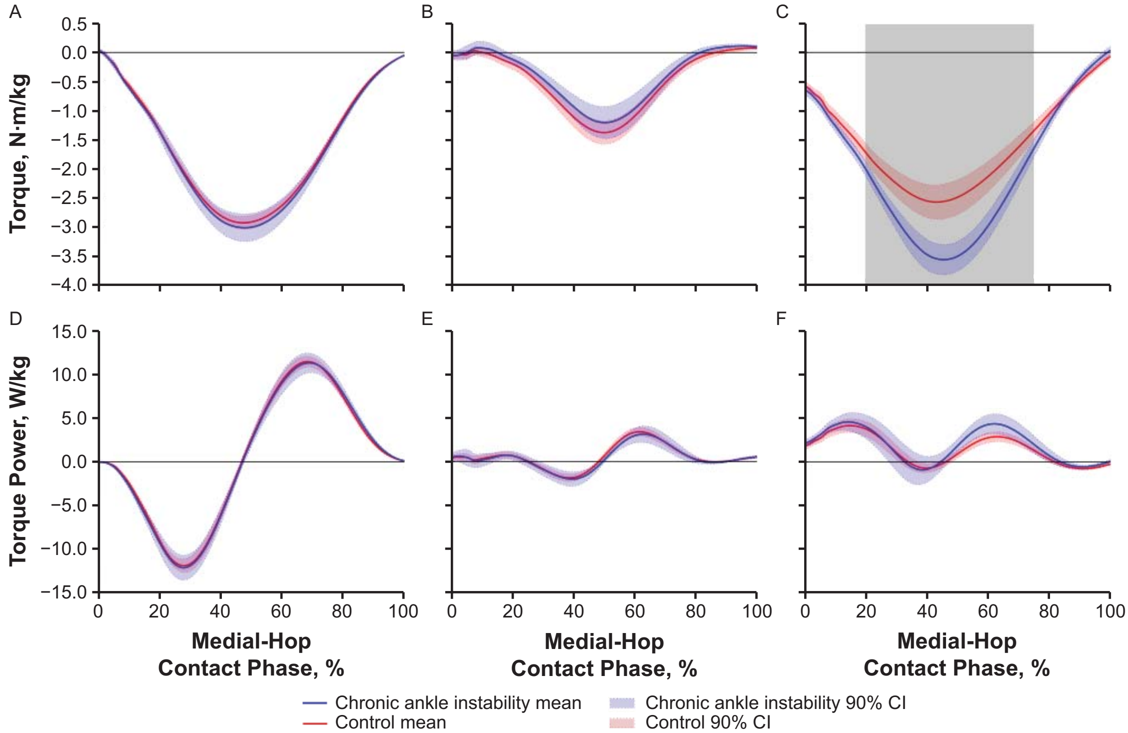

Figure 1. Time series data of torque and torque power in the sagittal plane in the medial-hop contact phase. A, Ankle dorsiflexion-plantar-flexion torque. B, Knee flexion-extension torque. C, Hip flexion-extension torque. D, Ankle-torque power. E, Knee-torque power. F, Hip-torque power. Gray shaded areas indicate when the 90% CIs of the groups did not overlap, representing a difference.

not necessarily symmetric. Therefore, even if no delay in SHT time was observed, individuals with CAI might compensate for ankle instability via a hip-dominant movement strategy.

Whereas previous researchers noted that individuals with CAI demonstrated delayed SHT time,[14,23–25] our results are inconsistent with those findings. Conversely, in line with our results, Wikstrom et al[26] observed no delay in SHT time for

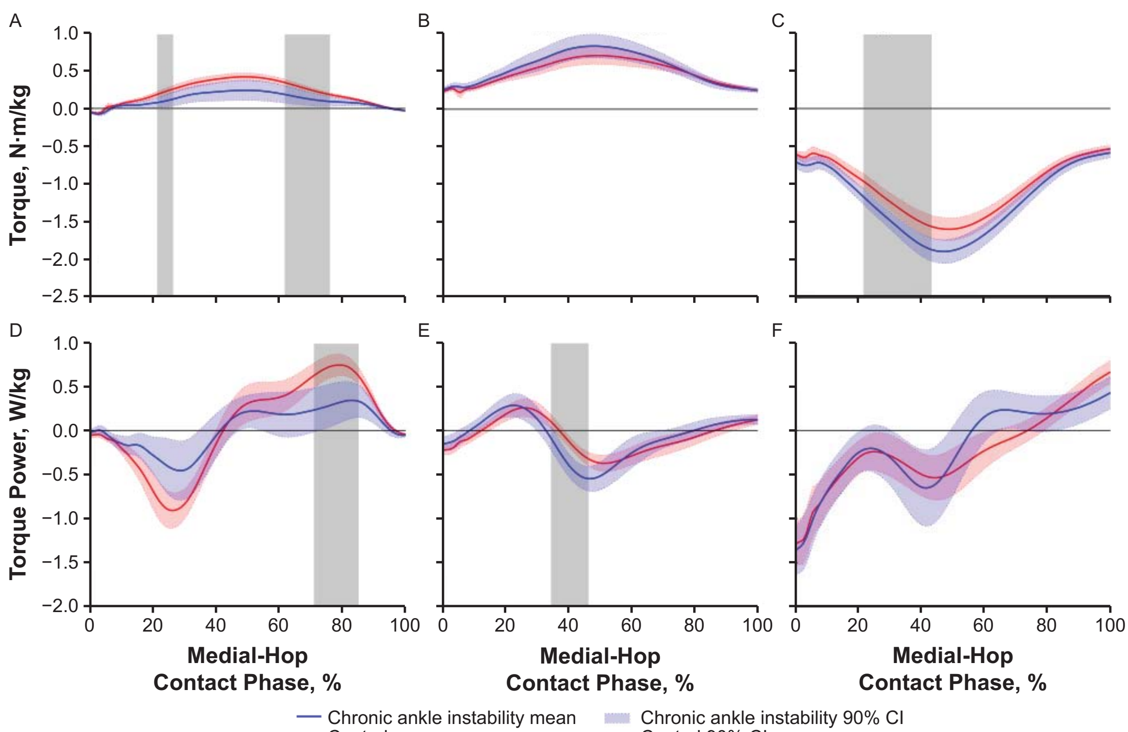

Figure 2. Time series data of torque and torque power in the frontal plane in the medial-hop contact phase. A, Ankle inversion-eversion torque. B, Knee varus-valgus torque. C, Hip adduction-abduction torque. D, Ankle-torque power. E, Knee-torque power. F, Hip-torque power. Gray shaded areas indicate when the 90% CIs of both groups did not overlap, representing a difference.

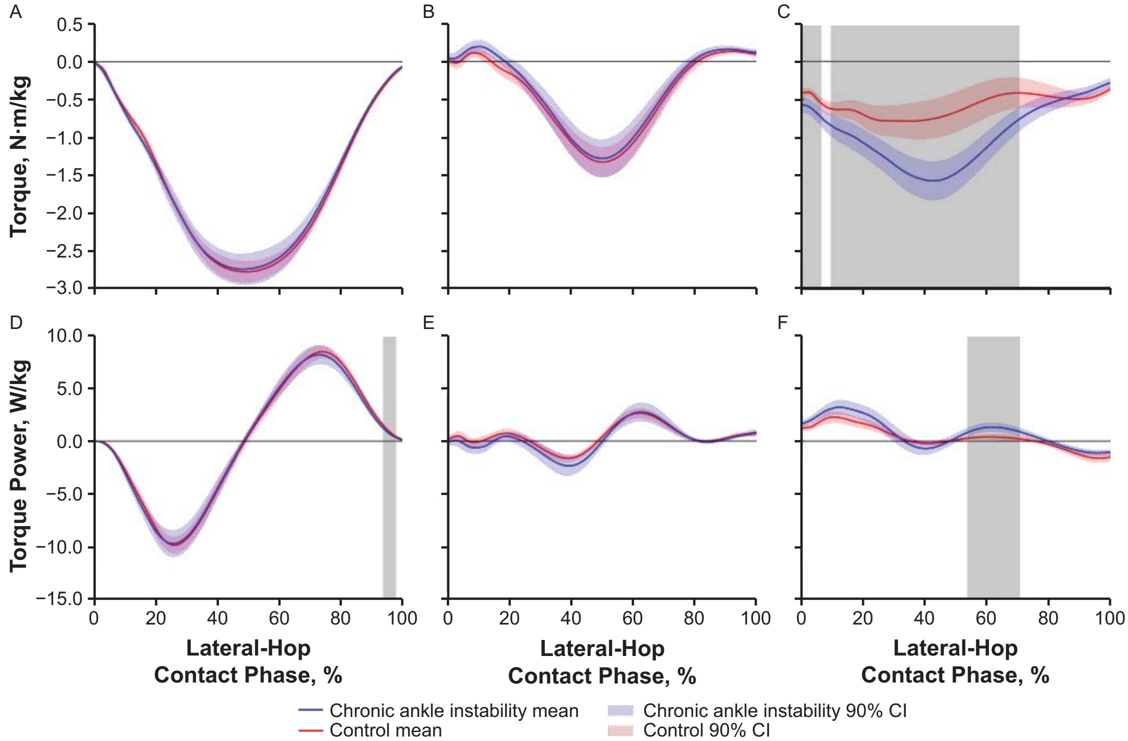

Figure 3. Time series data of torque and torque power in the sagittal plane in the lateral-hop contact phase. A, Ankle dorsiflexion-plantar-flexion torque. B, Knee flexion-extension torque. C, Hip flexion-extension torque. D, Ankle-torque power. E, Knee-torque power. F, Hip-torque power. Gray shaded areas indicate when the 90% CIs of both groups did not overlap, representing a difference.

individuals with CAI. In other words, our findings are consistent with those of Wikstrom et al,[26] suggesting that the SHT is a valid test for identifying patients with CAI[13]; however, in some cases, CAI may not affect the SHT time. In the context of ACL injury, the single-legged hop for distance did not differ between the limbs of individuals who had undergone reconstruction and healthy individuals for hop distance but did differ in lower extremity biomechanics.[22] Thus, assessing an athlete's

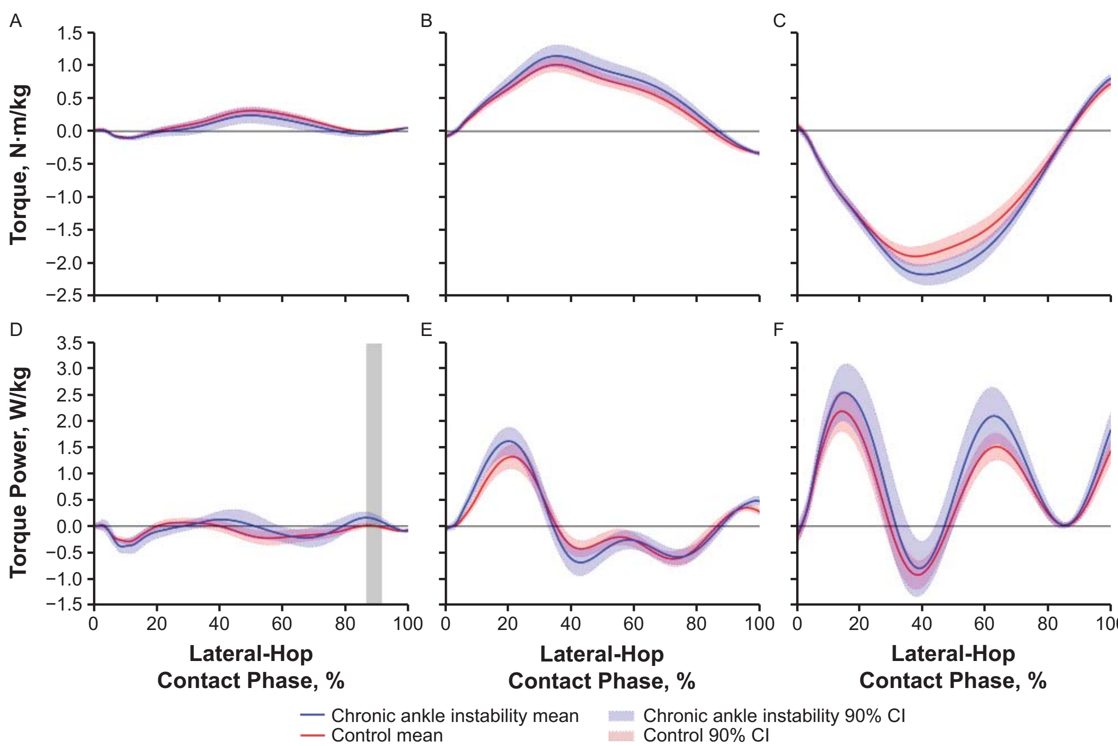

Figure 4. Time series data of torque and torque power in the frontal plane in the lateral hop contact phase. A, Ankle inversion-eversion torque. B, Knee varus-valgus torque. C, Hip adduction-abduction torque. D, Ankle-torque power. E, Knee-torque power. F, Hip-torque power. Gray shaded areas indicate when the 90% CIs of both groups did not overlap, representing a difference.

condition using only the time or distance as quantitative outcomes would not be optimal. Movement strategies also need to be considered. Some researchers[9–11] have described various movement alterations (ie, kinematics, kinetics, and muscle activity) during side-cutting tasks in individuals with CAI. However, they only investigated the effect of CAI on side-cutting movement and did not consider cutting performance. Hence, even if time in the SHT is comparable, the movement strategy could differ depending on whether individuals have CAI.

The CAI group had a lower ankle-inversion torque than the CON group in the early and late phases of the MC. This result indicates a decrease in energy-absorption capacity in the early phase and the propulsive force in the late phase in the CAI group. Ankle-eversion angle was shown to contribute to energy absorption in the MC.[17] However, we detected a lower ankle-inversion torque in the CAI group, suggesting that the ankle-inversion muscles were not contributing sufficiently to energy absorption. In contrast, the CAI group demonstrated more eccentric power in knee varus-valgus in the MC than the CON group. At this time, knee-varus torque and negative torque power were evident, indicating that the knee joint was displaced toward the valgus direction. Therefore, the eccentric torque power to resist knee valgus was possibly greater in the CAI group. The lower extremity is connected through the kinetic chain, and we thought that energy absorption would be achieved by the knee joint, which is located more proximally, because the ankle-inversion muscles cannot produce force. The CAI group also exhibited higher hip-abduction torque than the CON group in the same phase, suggesting that the hip joint contributed to energy absorption, given that energy absorption in the MC occurs in the knee joint. Although we identified no difference in torque power in the frontal plane of the hip joints, as proximal joints, the hip and knee could compensate for the instability and weakness of the ankle joint.

In contrast, the decreased ankle-inversion torque in the late phase of the MC could be related to decreased concentric power in ankle inversion-eversion. Yoshida et al[17] reported that ankle-inversion motion at the end of the MC played an important role in hopping for the next phase. However, ankle instability in the CAI group might prevent the generation of sufficient ankle-inversion motion to hop toward the LC. This dysfunction is related to higher hip-extension torque from the early to late phases of the MC versus that of the CON group. Individuals with CAI have an intralimb-reweighting compensation strategy that distributes the load from the distal to the proximal joint of the lower extremity.[11] Compared with the ankle-joint muscles, the hip-joint muscles have a larger cross-sectional area[27] and relatively shorter tendon tissue,[28] leading to greater force production. Thus, we thought that the hip joint would produce more extension torque to compensate for ankle dysfunction, allowing it to hop into the LC effectively.

In the LC, the CAI group showed kinetic differences compared with the CON group that were not observed in the MC. At the end of the LC, the CAI group exhibited less concentric power in ankle dorsiflexion-plantar flexion and more concentric power in ankle inversion-eversion than the CON group. This suggests that the CAI group would obtain propulsive power by producing ankle force in the frontal plane rather than in the sagittal plane during the LC. However, considering that approximately 75% of ankle sprains occur during landing and side-cutting,[7] the altered movement strategy of the CAI group during the SHT could include the risk of recurrent ankle sprains. In addition, Marshall et al[29] reported that greater ankle concentric power and ankle plantar-flexion moment are important for faster side-cutting movement. This finding indicates that the movement strategy of individuals with CAI may not be effective for faster side-cutting movements. Hence, whereas individuals with CAI could display SHT times similar to those of healthy individuals without CAI, they would not always meet the requirements of high performance and safe movement during the SHT.

During the LC, the CAI group showed higher hip-extension torque from the early phase to the middle phase and more concentric power in hip flexion-extension during the middle phase. These results suggest that the intralimb-reweighting compensation strategy also occurs during the LC, similar to the MC. In other words, individuals with CAI could perform the SHT faster by producing greater force at the hip joint. Researchers[30,31] have determined that hip-extension motion is important for faster side-cutting movement. As a result, individuals with CAI are thought to attain propulsive force during the LC by producing greater force at the hip joints. In particular, given that the movement pattern in the LC is similar to the side-cutting movement, a difference in hip concentric power in the sagittal plane in the LC may be related to the movement pattern of each phase. However, although individuals with CAI exhibited SHT times comparable with those of healthy individuals, they still have a risk of recurrent ankle sprains because of ankle-joint instability.

Our study had several limitations. First, the participants were limited to soccer players who regularly engaged in high-intensity sport activities. The SHT time recorded in our study was faster than that reported in previous studies.[16,17] Therefore, our results do not reflect the movement characteristics of the SHT in athletes at all competitive levels and types. Second, we could not clarify whether the movement strategies of the CAI group were altered after ankle-sprain injury. Future prospective investigations are needed to clarify the effects of CAI on movement characteristics during the SHT.

CONCLUSIONS

The movement strategies of individuals with CAI were altered even if they did not show delayed SHT times. Consistent with the results of earlier work, individuals with CAI would likely rely on hip-joint function to compensate for ankle instability, which could lead to the lack of differences in SHT time. Based on these findings, the information provided by the SHT times would be limited, and clinicians should consider the possibility that individuals with CAI may demonstrate different movement patterns during the SHT. Thus, the movement strategies of individuals with CAI could differ from those of healthy individuals without CAI during the SHT, even if no difference in SHT time was seen. A simple analysis involving smartphone videos and applications could be useful for clinicians and therapists in identifying such movement differences.

REFERENCES

1. Dvorak J, Junge A, Grimm K, Kirkendall D. Medical report from the 2006 FIFA World Cup Germany. *Br J Sports Med*. 2007;41(9):578–581. doi:10.1136/bjsm.2006.034579
2. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. 2007;42(2):311–319.

3. Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med*. 2005;39(3):e14. doi:10.1136/bjsm.2004.011676
4. Gribble PA, Delahunt E, Bleakley CM, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *J Athl Train*. 2014;49(1):121–127. doi:10.4085/1062-6050-49.1.14
5. Attenborough AS, Hiller CE, Smith RM, Stuelcken M, Greene A, Sinclair PJ. Chronic ankle instability in sporting populations. *Sports Med*. 2014;44(11):1545–1556. doi:10.1007/s40279-014-0218-2
6. Hertel J, Corbett RO. An updated model of chronic ankle instability. *J Athl Train*. 2019;54(6):572–588. doi:10.4085/1062-6050-344-18
7. McKay GD, Goldie PA, Payne WR, Oakes BW. Ankle injuries in basketball: injury rate and risk factors. *Br J Sports Med*. 2001;35(2):103–108. doi:10.1136/bjsm.35.2.103
8. Bloomfield J, Polman R, O'Donoghue P. Physical demands of different positions in FA Premier League soccer. *J Sports Sci Med*. 2007;6(1):63–70.
9. Simpson JD, Stewart EM, Turner AJ, Macias DM, Chander H, Knight AC. Lower limb joint kinetics during a side-cutting task in participants with or without chronic ankle instability. *J Athl Train*. 2020;55(2):169–175. doi:10.4085/1062-6050-334-18
10. Kim H, Son SJ, Seeley MK, Hopkins JT. Altered movement biomechanics in chronic ankle instability, coper, and control groups: energy absorption and distribution implications. *J Athl Train.* 2019;54(6):708–717. doi:10.4085/1062-6050-483-17
11. Kim H, Son SJ, Seeley MK, Hopkins JT. Kinetic compensations due to chronic ankle instability during landing and jumping. *Med Sci Sports Exerc.* 2018;50(2):308–317. doi:10.1249/MSS.0000000000001442
12. Fox AS. Change-of-direction biomechanics: is what's best for anterior cruciate ligament injury prevention also best for performance? *Sports Med*. 2018;48(8):1799–1807. doi:10.1007/s40279-018-0931-3
13. Rosen AB, Needle AR, Ko J. Ability of functional performance tests to identify individuals with chronic ankle instability: a systematic review with meta-analysis. *Clin J Sport Med*. 2019;29(6):509–522. doi:10.1097/JSM.0000000000000535
14. Docherty CL, Arnoldt BL, Gansneder BM, Hurwitz S, Gieck J. Functional-performance deficits in volunteers with functional ankle instability. *J Athl Train*. 2005;40(1):30–34.
15. Delahunt E, Monaghan K, Caufield B. Ankle function during hopping in subjects with functional instability of the ankle joint. *Scand J Med Sci Sports*. 2007;17(6):641–648. doi:10.1111/j.1600-0838.2006.00612.x
16. Yoshida M, Aoki N, Taniguchi K, Yoshida M, Katayose M. Kinematic analysis of the ankle joint on the side-hop test in subjects with ankle sprains. *Transl Sports Med*. 2018;1(6):265–272. doi:10.1002/tsm2.44
17. Yoshida M, Taniguchi K, Katayose M. Analysis of muscle activity and ankle joint movement during the side-hop test. *J Strength Cond Res*. 2011;25(8):2255–2264. doi:10.1519/JSC.0b013e3181ec86d5
18. Li Y, Ko J, Zhang S, Brown CN, Simpson KJ. Biomechanics of ankle giving way: a case report of accidental ankle giving way during the drop landing test. *J Sport Health Sci*. 2019;8(5):494–502. doi:10.1016/j.jshs.2018.01.002
19. Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics, kinetics, and muscle activity in subjects with functional instability of the ankle joint during a single leg drop jump. *J Orthop Res*. 2006;24(10):1991–2000. doi:10.1002/jor.20235
20. Marshall AN, Hertel J, Hart JM, Russell S, Saliba SA. Visual biofeedback and changes in lower extremity kinematics in individuals with medial knee displacement. *J Athl Train*. 2020;55(3):255–264. doi:10.4085/1062-6050-383-18
21. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Lawrence Erlbaum Associates; 1988.
22. Kotsifaki A, Whiteley R, Van Rossom S, et al. Single leg hop for distance symmetry masks lower limb biomechanics: time to discuss hop distance as decision criterion for return to sport after ACL reconstruction? *Br J Sports Med*. 2022;56(5):249–256. doi:10.1136/bjsports-2020-103677
23. Ko J, Rosen AB, Brown CN. Comparison between single and combined clinical postural stability tests in individuals with and without chronic ankle instability. *Clin J Sport Med*. 2017;27(4):394–399. doi:10.1097/JSM.0000000000000354
24. Linens SW, Ross SE, Arnold BL, Gayle R, Pidcoe P. Postural-stability tests that identify individuals with chronic ankle instability. *J Athl Train*. 2014;49(1):15–23. doi:10.4085/1062-6050-48.6.09
25. Sharma N, Sharma A, Singh Sandhu J. Functional performance testing in athletes with functional ankle instability. *Asian J Sports Med*. 2011;2(4):249–258. doi:10.5812/asjsm.34741
26. Wikstrom EA, Tillman MD, Chmielewski TL, Cauraugh JH, Naugle KE, Borsa PA. Self-assessed disability and functional performance in individuals with and without ankle instability: a case control study. *J Orthop Sports Phys Ther*. 2009;39(6):458–467. doi:10.2519/jospt.2009.2989
27. Yamaguchi GT, Sawa AG-U, Moran MJ, Fessler MJ, Winters JM. A survey of human musculotendon actuator parameters. In: Winters JM, Woo SL-Y, eds. *Multiple Muscle Systems: Biomechanics and Movement Organization*. Springer-Verlag; 1990:717–773.
28. Alexander RM, Ker RF. The architecture of leg muscles. In: Winters JM, Woo SL-Y, eds. *Multiple Muscle Systems: Biomechanics and Movement Organization*. Springer-Verlag; 1990:568–577.
29. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey EC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res*. 2014;28(10):2845–2851. doi:10.1519/JSC.0000000000000463
30. Welch N, Richter C, Franklyn-Miller A, Moran K. Principal component analysis of the biomechanical factors associated with performance during cutting. *J Strength Cond Res*. 2021;35(6):1715–1723. doi:10.1519/JSC.0000000000003022
31. Havens KL, Sigward SM. Cutting mechanics: relation to performance and anterior cruciate ligament injury risk. *Med Sci Sports Exerc.* 2015;47(4):818–824. doi:10.1249/MSS.0000000000000470

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