Songklanakarin J. Sci. Technol.
46 (6), 551–557, Nov. – Dec. 2024

http://www.sjst.psu.ac.th

Original Article

Changes in lower limb muscle activity after fatigue protocols during a side cutting movement in subjects with functional instability of the ankle joint

Donlaya Promkeaw[1], Supannikar Yingyongsaksri[1], Ploypailin Namkorn[1],
and Theerasak Boonwang[2*]

[1] *Physical Therapy, School of Integrative Medicine,*
Mae Fah Luang University, Mueang, Chiang Rai, 57000, Thailand

[2] *Sports and Health Science, School of Health Science,*
Mae Fah Luang University, Mueang, Chiang Rai, 57000, Thailand

Received: 6 June 2024; Revised: 9 October 2024; Accepted: 28 October 2024

Abstract

This study explored muscle activity changes in the proximal lower limbs following fatigue during side cutting movements in 20 individuals with chronic ankle instability (CAI) compared to 20 healthy controls. Electromyography (EMG) data for the Vastus Medialis (VM), Vastus Lateralis (VL), Semitendinosus (SM), and Biceps Femoris (BF) were recorded during walking and running side cutting before and after inducing fatigue. Maximal voluntary contraction (MVC) tests determined maximal torque and EMG values. Results in walking and running side cutting showed significant increases in muscle activation in the VM, VL, SM, and BF muscles in individuals with CAI post-fatigue, whereas the control group exhibited nonsignificant changes. This increased muscle activation in the CAI group likely serves as a protective mechanism to stabilize the ankles and prevent further sprains, especially during fatigued states. This study for understanding these patterns highlights the importance of designing rehabilitation programs for individuals with chronic ankle instability (CAI). These programs should focus not only on the ankle but also on the proximal lower limb muscles to improve stability and reduce the risk of future injuries.

Keywords: fatigue, ankle instability, side cutting, lower extremity, sports activities

1. Introduction

Ankle sprains, often due to sudden inversion, constitute about 7.3% of sports injuries, with nearly half occurring during sports activities (Fong, Hong, Chan, Yung, & Chan, 2007; Roos *et al.*, 2017). Improperly managed, 40% can lead to chronic ankle instability (CAI), characterized by recurrent sprains, instability, pain, and swelling, increasing the risk of ankle osteoarthritis, thereby reducing daily activity movements and sports participation (Houston, Van Lunen, & Hoch, 2014; Wikstrom *et al.*, 2010). Individuals with CAI frequently exhibit compensatory movement alterations in the proximal components of the lower limbs (Feger, Donovan, Hart, & Hertel, 2015; Koshino *et al.*, 2014). However, physical therapy often focuses on distal lower limb muscles, neglecting proximal joints and lower limb muscles, potentially resulting in reduced functional performance and increased risk of recurring injuries in these patients. This effect is most pronounced when muscles are fatigued, leading to compensation (Houston *et al.*, 2014; Powden, Hoch, & Hoch, 2017). Muscle fatigue not only affects lower limb kinematics by decreasing joint range of motion but also by altering daily activities movements, ultimately heightening the risk of injury (Silva, Struber, Daniel, & Nougier, 2021; Zhang *et al.*, 2022). In addition, a previous study suggested that lower limb kinematics during side cutting movements might reveal

---

*Corresponding author
Email address: theerasak.boo@mfu.ac.th

kinematic changes associated with the risk of injury in ankle instability and components of daily activities, particularly during deceleration and rapid directional changes (Caulfield & Garrett, 2002; Chappell *et al.*, 2005; Lin, Lin, & Lee, 2019). Nevertheless, there is currently a lack of evidence regarding the muscle activity of proximal lower limb muscles experiencing fatigue during side cutting movement, and in individuals with CAI this highlights the importance of including proximal lower limb muscles rehabilitation in treatment programs. Therefore, this study aimed to investigate proximal lower limb muscles' (vastus medialis (VM), vastus lateralis (VL), semitendinosus (SM), and bicep femoris (BF)) activities with fatigue during walking and running side cutting in individuals with or without CAI. The findings may provide evidence to support rehabilitation strategies that promote stability and reduce the risk of future injuries of these individuals.

2. Materials and Methods

2.1 Participants

20 participants in each group were at least 18 years old and engaged in competitive or recreational sports. The sample size was estimated using G*Power software with a significance level of 0.05, $Z_{\alpha/2}$ at 1.96, Z_{β} at 0.84, and an effect size of 0.40 (Xu, Song, Ming, Zhang, & Ni, 2022).

The inclusion criteria for participants with CAI followed the recommendations from the international ankle consortium (Gribble *et al.*, 2014), which included individuals with (1) a self-reported history of 2 or more lateral ankle sprains (LASs), with one of those LASs occurring within the 12 months preceding the study; (2) history of LASs that required non–weight-bearing activity or immobilization for more than 24 hours; (3) self-reported history of the affected ankle giving way; or (4) a cumberland ankle instability tool (CAIT) score of ≤ 24. Inclusion criteria for the control group were no history of lower limb injuries, or of ankle joint instability. Exclusion criteria for both groups were (1) a history of surgery or fracture to either lower extremity, (2) any musculoskeletal injury to the lower extremity in the 3 months before the study, or (3) diagnosis of musculoskeletal conditions like scoliosis, disc herniation, and pain symptom etc., or neurological disorders such as multiple sclerosis, etc. All participants provided written informed consent, and the study was approved by human research ethics committee Mae Fah Luang university ethics (Code: EC22179-25).

2.2 Experimental approach and procedures

After being briefed on the protocol upon arrival at the laboratory, the participants' characteristics were interviewed, and they were familiarized with both walking and running side cutting trials. Prior to conducting the walking and running side cutting trials, EMG electrodes were attached to the skin over the selected muscles as shown in Figure 2. Subsequently, participants practiced and performed maximal voluntary contractions (MVC) with the VM, VL, SM, and BF muscles (CAI side for CAI group and dominant side for Control group). They then performed the walking and running side cutting trials before and after inducing fatigue. The temperature of the environment was monitored during the experiments, which took place between 1:00 PM and 5:00 PM (Darendeli, Ertan, & Enoka, 2023).

2.3 EMG recordings

A wireless EMG system (Trigno Wireless EMG system, Delsys, Boston, MA, USA) was employed to record muscle activity for all participants in both groups (Hermens *et al.*, 1999; Poitras *et al.*, 2019). The data were sampled at 1,000 Hz. Before attaching the electrodes, the skin was cleaned by rubbing it with alcohol for 5 seconds (Poitras *et al.*, 2019).

2.4 Maximal voluntary contractions (MVC)

Each muscle was equipped with wireless sensors at specific insertion points and evaluated for MVC using a 5-seconds isometric contraction to standardize MC-Level as a percentage (%MVC), following the electromyographer's guidelines (Perotto, 2011). The signals were sampled at a frequency of 1,000 Hz and filtered with a band-pass of 20-450 Hz for assessing muscle activity pattern and 10-500 Hz for evaluating muscle fatigue rate. Each MVC task lasted 5 seconds, and 3 trials were performed for each muscle with 1 minute of rest between trials (Besomi *et al.*, 2019).

2.5 Fatigue

Before the fatiguing protocols, participants wore a fingertip oximeter to record oxygen values and heart rate. Subsequently, the researcher induced fatigue in the participants by instructing them to step up and down a wooden box 20 inches high for men and 18 inches high for women continuously and as quickly as possible and safely until the participants' heart rate reached 70 percent of their maximum heart rate (Bragada *et al.*, 2022; Gwinn *et al.*, 1992; Francis, 1987), then performed the following walking or running side cutting (based on random order, 1-week rest period between movements). They were asked to step up and down the box continuously, alternating with side cutting movements (Figure 2).

2.6 Side cutting task

Participants dynamic warm-up took around 5 minutes. The warm-up included 2 sets of high knees, submaximal jogging, exaggerated gait swings, and lunges. Following this, they carried out the side cutting task (Koshino *et al.*, 2014, 2016).

During the walking side cutting task, the participants walked straight for 10 meters on a walkway at their usual pace without looking at the force plate. Subsequently, they positioned their test leg on the force plate, pivoted to the side of the supporting leg at a 45-degree angle, and proceeded to walk approximately 3 meters in that direction. Additionally, the participants performed the same protocol while running side cutting as fast as possible. This cross-cutting motion was modeled after a movement detailed in a prior study (Koldenhoven, Simpson, Forsyth, Donovan, & Torp, 2022; Koshino *et al.*, 2014). A total of 3 successful trials of the side cutting task were completed and recorded.

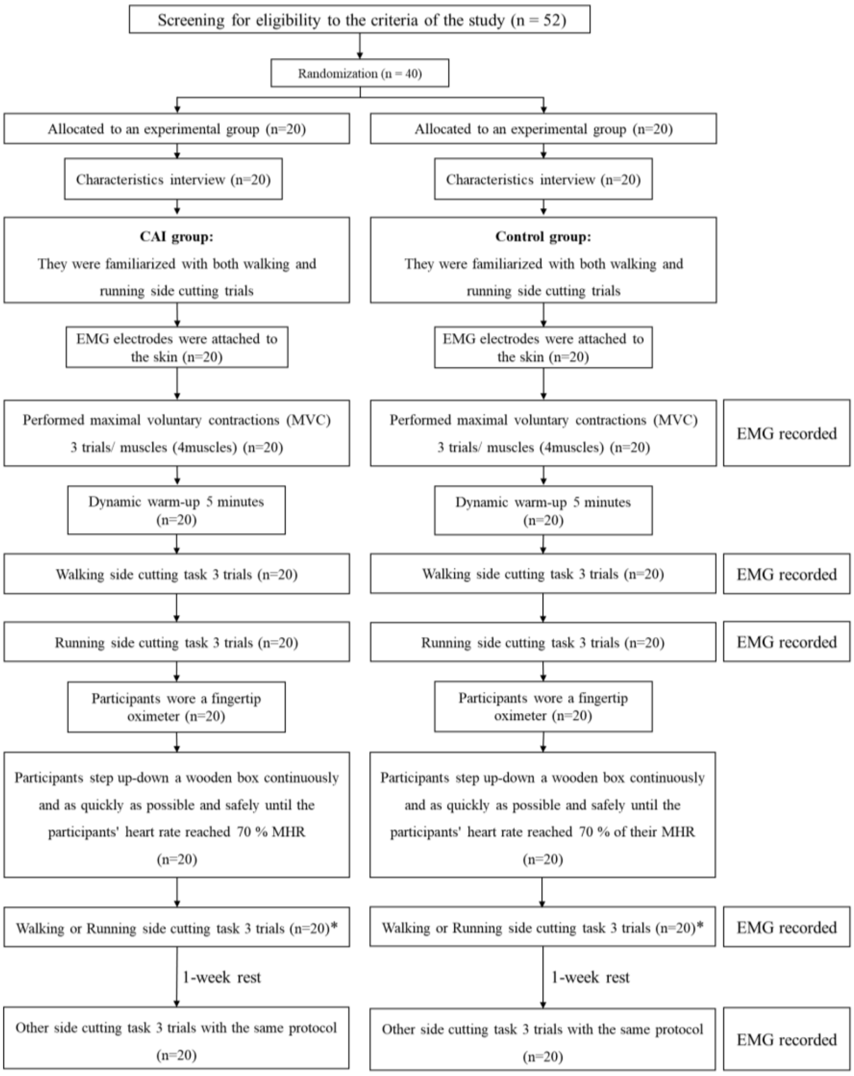

Figure 1. Participation flowchart (Abbreviations: *MVC:* Maximal voluntary contraction, *EMG:* Electromyography, *CAI:* chronic ankle instability, *n:* number, *MHR:* maximum heart rate) Note: *Maintain a heart rate of 70% MHR during trials and tests by stepping again.

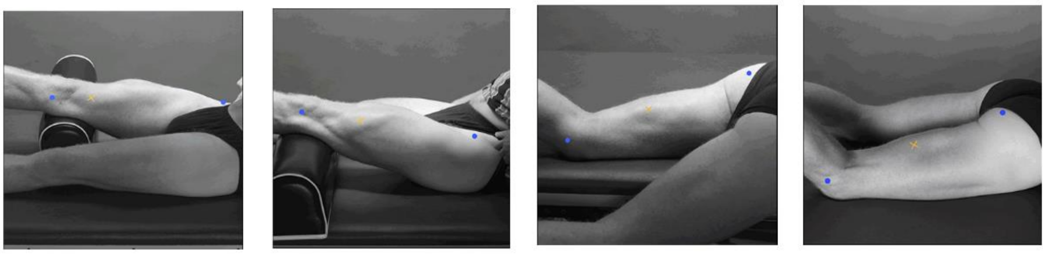
(a) (b) (c) (d)

Figure 2. Illustrating the placement of the electrodes by x and depicting the original and insertion points by • in each muscle (Hermens *et al.*, 1999). (a) Vastus medialis (VM), (b) Vastus lateralis (VL), (c) Semitendinosus (SM), (d) Bicep femoris (BF)

In the CAI group, the testing limb was identified based on subjective reports from the CAIT questionnaire indicating the limb with the affected ankle. Conversely, in the control group, the testing limb was selected to match the participant in the CAI group as closely as possible in terms of sex, age, height, mass, and limb dominance. The dominant limb was determined by asking participants. If a participant's entire foot did not contact the force platform during the side cutting task, a trial was repeated. The cumulative total of the 3 successful trials from each participant was used in the statistical analysis (Koldenhoven *et al.*, 2022; Koshino *et al.*, 2014).

2.7 Statistical analysis

Demographic data were compared between the CAI and control groups using independent samples t-tests. Group comparisons were conducted with independent samples t-tests for normally distributed data and with Mann-Whitney tests for non-normally distributed data, with data distributions assessed using the Shapiro-Wilk test.

Means and standard deviations of the normalized percentage of average peak muscle activation were used for analysis. Dependent variables were amplitude of the VM, VL, SM, and BF muscles pre-side cutting and post-side cutting. For each dependent variable, effect sizes were calculated using the Cohen d with 95% confidence intervals (CIs) and interpreted as small (0.2), medium (0.5), or large (0.8) (Sullivan & Feinn, 2012). Data were analyzed using SPSS (version 15.0; SPSS Inc, Chicago, IL). The level of statistical significance was set to a p-value below 0.05.

3. Results and Discussion

The CAI and control groups exhibited similar age, height, and body weight. However, the CAI group had a significantly lower CAIT score compared to the control group. Additionally, the CAI group exhibited a history of lateral ankle sprains, a characteristic absent in the control group (Table 1). Muscle activation levels were assessed in four distinct muscles in both groups before and after inducing fatigue. After fatigue, significant increases in the activation of VM, VL, SM, and BF muscles were observed in the CAI group (Table 2). Conversely, the control group exhibited no significant change in muscle activation. These results suggest that individuals with CAI experience notable increases in muscle activation as a compensatory strategy for stability. Moreover, the results show that neither group displayed significant changes in muscle activation during walking or side-cutting activities post-fatigue, although some trends towards increased activation were observed (Table 3).

Previous studies indicated that individuals with CAI exhibited higher muscle activation during activities such as running and side cutting. This study supports a prior theory (Delahunt, Monaghan, & Caulfield, 2006) which proposed a centralized feed-forward mechanism as an adaptation following an ankle injury. The theory suggested that, post-injury, the typical muscle response patterns in healthy individuals were insufficiently fast to prevent further injuries in those with CAI. As a result, the body developed a feed-forward neural and muscle adaptation to protect the ankle from potential injuries, for both proximal and distal lower limb muscles by the injury site. While, in this study, participants were instructed to perform rapid running side cuts. It was likely to activate any protective neuromuscular mechanisms necessary for maintaining balance and stability, a scenario often associated with ankle sprains. The researchers believe that the muscles in the CAI group might have been activated more intensely to help stabilize the lower body in a safer position during these side cutting movements, especially when running side cutting while fatigued. This increased muscle activation could be the body's way of trying to protect the ankle from further injury.

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

Group	Leg test (Rt./Lt.)	Gender (n) (Male/Female)	Age (years)[*]	Height (cm)[*]	Mass (kg)[*]	CAIT score[*]
CAI	17/3	15/5	20.10 ± 1.03	171.63 ± 5.16	65.88 ± 10.49	21.13 ± 1.63
Control	15/5[a]	14/6	20.25 ± 0.86	171.50 ± 6.70	66.69 ± 8.55	26.56 ± 2.16

Abbreviations: The data are presented using *n:* number, *cm:* centimeters, *kg:* kilogram, *mean ± SD*, *CAIT:* Cumberland ankle instability Tool, *CAI:* chronic ankle instability, *Rt.*: right side, *Lt.*: left side

Note: [a] The superscripts presented are for dominant side leg, [*] The superscripts indicate significant differences with a *p-value* < 0.001 when comparing the characteristics data analyzed using the independent samples t-test.

Table 2. Muscle activation in running side-cutting interaction results

Muscle	Group	Muscle activation %, mean ± SD		p-value	Mean difference (95% Confidence interval)
		Pre-fatigue	Post-fatigue		
Vastus medialis (VM)	CAI	30.42 ± 17.29	33.38 ± 19.57	0.04[*]	-2.63 (-3.01 - 10.04)
	Control	30.74 ± 15.08	31.90 ± 18.35	0.68	-0.09 (-0.04 - 0.51)
Vastus lateralis (VL)	CAI	33.48 ± 15.29	37.22 ± 19.48	0.01[*]	-3.14 (-4.67 - 10.04)[b]
	Control	30.75 ± 8.55	32.66 ± 4.40	0.74	-0.99 (-0.07 - 0.97)
Semitendinosus (SM)	CAI	46.28 ± 15.89	50.14 ±20.13	0.03[*]	-3.42 (-7.59 - 5.74)[b]
	Control	48.48 ± 15.44	51.66± 17.58	0.05[*]	-2.09 (-4.24 - 0.51)
Bicep femoris (BF)	CAI	51.63 ± 19.32	57.23 ± 24.52	0.02[*]	-5.35 (-8.11 - 5.86)[a]
	Control	50.88 ± 16.44	53.12 ± 20.66	0.09	-3.03 (-0.08 - 0.11)[b]

Abbreviation: *CAI:* chronic ankle instability

Note: [a] Indicates strong effect size, [b] Indicates moderate effect size

[*] The superscripts indicate significant differences with a *p-value* < 0.05 for the data analyzed using the dependent samples t-test.

Table 3. Muscle activation in walking side-cutting interaction results

Muscle	Group	Muscle activation %, mean ± SD		p-value	Mean Difference (95% Confidence Interval)
		Pre-fatigue	Post-fatigue		
Vastus medialis (VM)	CAI	30.42 ± 17.29	31.11 ± 12.88	0.69	-0.84 (-0.48 - 2.01)
	Control	30.74 ± 15.08	29.99 ± 18.49	0.24	0.05 (-0.03 - 0.04)
Vastus lateralis (VL)	CAI	33.48 ± 15.29	32.66± 19.52	0.62	1.23 (-2.16 - 1.15)
	Control	30.75 ± 8.55	30.99± 15.22	0.32	-0.04 (2.42 - 4.41)
Semitendinosus (SM)	CAI	46.28 ± 15.89	48.11± 13.36	0.07	-1.23 (1.77 - 5.24)
	Control	48.48 ± 15.44	50.08 ± 14.53	0.09	-1.27 (-0.92 - 2.74)
Bicep femoris (BF)	CAI	51.63 ± 19.32	52.42± 21.52	0.41	-1.04 (-0.98 - 4.62)
	Control	50.88 ± 16.44	52.33± 23.44	0.08	-1.28 (-0.75 - 5.66)

Abbreviation: *CAI:* chronic ankle instability
Note: [a] Indicates strong effect size, [b] Indicates moderate effect size
[*] The superscripts indicate significant differences with a *p-value* < 0.05 for the data analyzed using the dependent samples t-test.

Koldenhoven *et al.* (2022) investigated lower limb joint kinetics during a side cutting task in participants with CAI compared to those without CAI. The study found a statistically significant 3-16% increase in the plantarflexion angle and a significant rise in hip joint angle among individuals with CAI. These changes likely indicate increased activation of proximal lower limb muscles to compensate for the ankle muscles. Additionally, this study showed significantly higher muscle engagement during running side cuts in the CAI group, supporting the theory that disruptions in muscle spindle activity post-injury contribute to neuromuscular control deficits in CAI (Khin-Myo-Hla, Ishii, Sakane, & Hayashi, 1999; Lephart, Riemann, & Fu, 2000). This theory suggests that fatigue raises the muscle spindle discharge threshold, disrupting afferent feedback and altering joint proprioception. Previous research observed impaired ankle muscle control in CAI individuals after induced fatigue (Hiemstra, Lo, & Fowler, 2001; Miura *et al.*, 2004). Furthermore, another study found that fatigue affecting knee and hip muscles significantly increased center-of-pressure velocity scores. It concluded that maintaining balance in a fatigued state relies more on proximal neuromuscular control rather than the traditional distal muscle recruitment strategy for postural control in younger individuals (Winter, Prince, Frank, Powell, & Zabjek, 1996). Moreover, the theory of anatomy trains, which explores the interconnection of muscles and fascia within the human body, has been instrumental in the comprehension of muscle fatigue (Myers, 2020; Ostiak, Kaczmarek-Maciejewska, & Kasprzak, 2011). Studies have indicated that the coordination of muscle activity is influenced by both anatomical and functional connections among muscles, with the modular structure of functional networks largely influenced by anatomical constraints of the musculoskeletal system. Moreover, muscle synergies aid in simplifying the control issue of the musculoskeletal system through network theory analysis, demonstrating extensive connectivity between muscles at various frequency bands and unique network structures across different conditions (Kerkman, Daffertshofer, Gollo, Breakspear, & Boonstra, 2018; Myers, 2020). Consequently, this aligns with the results of this study (Tables 2 and 3), which identified heightened muscle activation in the proximal lower limb muscles during both running and walking side cutting among individuals with CAI, compared to those without CAI. Moreover, notable statistically significant changes were observed with the onset of fatigue.

Nevertheless, this study has some limitations. The broad inclusion criteria did not differentiate between various sports, potentially overlooking sport-specific factors influencing lower limb muscle function in individuals with CAI during fatigue. Additionally, the study did not compare results between genders and groups. The cross-sectional design also limits the ability to infer long-term effects and treatment outcomes. Future research should differentiate between sport types and include gender and group comparisons to enhance generalizability. Longitudinal studies are needed to evaluate the effectiveness of training programs targeting CAI under fatigue conditions, focusing on treatment outcomes.

4. Conclusions

This study confirms that understanding these patterns highlights the importance of designing rehabilitation programs for individuals with chronic ankle instability (CAI). These programs should focus not only on the ankle but also on the proximal lower limb muscles to improve stability and reduce the risk of future injuries.

Acknowledgements

We would like to sincerely thank the funding support from Mae Fah Luang university (65A10010), school of integrative medicine and health science, Mae Fah Luang university for supporting laboratory testing tools. And last but not least to the research team.

References

Besomi, M., Hodges, P. W., Van Dieen, J., Carson, R. G., Clancy, E. A., Disselhorst-Klug, C., . . . Wrigley, T. (2019). Consensus for experimental design in electromyography (CEDE) project: Electrode selection matrix. *Journal of Electromyography and Kinesiology*, *48*, 128–144. doi:10.1016/j.jelekin.2019.07.008

Bragada, J. A., Bartolomeu, R. F., Rodrigues, P. M., Magalhaes, P. M., Bragada, J. P., & Morais, J. E. (2022). Validation of StepTest4all for assessing cardiovascular capacity in young adults. *International Journal of Environmental Research and Public Health, 19*(18), 11274. doi:10.3390/ijerph191811274

Caulfield, B. M., & Garrett, M. (2002). Functional instability of the ankle: Differences in patterns of ankle and knee movement prior to and post landing in a single leg jump. *International Journal of Sports Medicine, 23*(1), 64-68. doi:10.1055/s-2002-19272

Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., & Yu, B. (2005). Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *The American Journal of Sports Medicine, 33*(7), 1022–1029. doi:10.1177/0363546504273047

Darendeli, A., Ertan, H., & Enoka, R. M. (2023). Comparison of EMG activity in leg muscles between overground and treadmill running. *Medicine and Science in Sports and Exercise, 55*(3), 517. doi:10.1249/MSS.0000000000003055

Delahunt, E., Monaghan, K., & Caulfield, B. (2006). Altered neuromuscular control and ankle joint kinematics during walking in subjects with functional instability of the ankle joint. *The American Journal of Sports Medicine, 34*(12), 1970-1976. doi:10.1177/0363546506290989

Feger, M. A., Donovan, L., Hart, J. M., & Hertel, J. (2015). Lower extremity muscle activation in patients with or without chronic ankle instability during walking. *Journal of Athletic Training, 50*(4), 350–357. doi:10.4085/1062-6050-50.2.06

Fong, D., Hong, Y., Chan, L. K., Yung, P., & Chan, K. C. (2007). A systematic review on ankle injury and ankle sprain in sports. *Sports Medicine* (*Auckland, N.Z.*), *37*, 73–94. doi:10.2165/00007256-200737010-00006

Gribble, P. A., Delahunt, E., Bleakley, C. M., Caulfield, B., Docherty, C. L., Fong, D. T.-P., . . . Wikstrom, E. A. (2014). Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the international ankle consortium. *Journal of Athletic Training, 49*(1), 121–127. doi:10.4085/1062-6050-49.1.14

Francis, K. T. (1987). Fitness assessment using step tests. *Comprehensive Therapy*, *13*(4), 36–41.

Gwinn, N., Leman, R., Kratz, J., White, J. K., Zile, M. R., & Gillette, P. (1992). Chronotropic incompetence: A common and progressive finding in pacemaker patients. *American Heart Journal*, *123*(5), 1216–1219. doi:10.1016/s0002-8703(10)80001-8

Hermens, H. J., Freriks, B., Merletti, R., Hagg, G. G., Stegeman, D., Blok, J., . . . Disselhorst-Klug, C. (1999). *European recommendations for surface electromyography: Deliverable of the SENIAM project*. Enschede, The Netherlands: Roessingh Research and Development.

Hiemstra, L. A., Lo, I. K., & Fowler, P. J. (2001). Effect of fatigue on knee proprioception: implications for dynamic stabilization. *The Journal of Orthopaedic and Sports Physical Therapy, 31*(10), 598–605. doi:10.2519/jospt.2001.31.10.598

Houston, M. N., Van Lunen, B. L., & Hoch, M. C. (2014). Health-related quality of life in individuals with chronic ankle instability. *Journal of Athletic Training, 49*(6), 758–763. doi:10.4085/1062-6050-49.3.54

Kerkman, J. N., Daffertshofer, A., Gollo, L. L., Breakspear, M., & Boonstra, T. W. (2018). Network structure of the human musculoskeletal system shapes neural interactions on multiple time scales. *Science Advances*, *4*(6), eaat0497. doi:10.1126/sciadv.aat0497

Khin-Myo-Hla, Null, Ishii, T., Sakane, M., & Hayashi, K. (1999). Effect of anesthesia of the sinus tarsi on peroneal reaction time in patients with functional instability of the ankle. *Foot and Ankle International*, *20*(9), 554–559. doi:10.1177/107110079902000903

Koldenhoven, R., Simpson, J. D., Forsyth, L., Donovan, L., & Torp, D. M. (2022). Utility of gait biofeedback training to improve walking biomechanics in patients with chronic ankle instability: A critically appraised topic. *Journal of Sport Rehabilitation, 31*(6), 819–825. doi:10.1123/jsr.2021-0395

Koshino, Y., Ishida, T., Yamanaka, M., Ezawa, Y., Okunuki, T., Kobayashi, T., . . . Tohyama, H. (2016). Kinematics and muscle activities of the lower limb during a side-cutting task in subjects with chronic ankle instability. *Knee Surgery, Sports Traumatology, Arthroscopy: Official Journal of the ESSKA*, *24*(4), 1071–1080. doi:10.1007/s00167-015-3745-y

Koshino, Y., Yamanaka, M., Ezawa, Y., Ishida, T., Kobayashi, T., Samukawa, M., . . . Takeda, N. (2014). Lower limb joint motion during a cross cutting movement differs in individuals with and without chronic ankle instability. *Physical Therapy in Sport: Official Journal of the Association of Chartered Physiotherapists in Sports Medicine*, *15*(4), 242–248. doi:10.1016/j.ptsp.2013.12.001

Lephart, S. M., Riemann, B. L., & Fu, F. H. (2000). Introduction to the sensorimotor system. In S. M. Lephart & F. H. Fu (Eds.), *Proprioception and neuromuscular control in joint stability* (pp. 37–51). Champaign, IL: Human Kinetics.

Lin, J.-Z., Lin, Y.-A., & Lee, H.-J. (2019). Are landing biomechanics altered in elite athletes with chronic ankle instability. *Journal of Sports Science and Medicine*, *18*(4), 653–662.

Miura, K., Ishibashi, Y., Tsuda, E., Okamura, Y., Otsuka, H., & Toh, S. (2004). The effect of local and general fatigue on knee proprioception. *Arthroscopy: The Journal of Arthroscopic and Related Surgery*, *20*(4), 414–418. doi:10.1016/j.arthro.2004.01.007

Myers, T. W. (2020). *Anatomy trains: Myofascial meridians for manual therapists and movement professionals* (4th ed.). Amsterdam, The Netherlands: Elsevier.

Ostiak, W., Kaczmarek-maciejewska, M., & Kasprzak, P. (2011). Foot and shin in terms of anatomy trains. *The Journal of Orthopaedics Trauma Surgery and Related Research*, *5* (25) 36-44.

Perotto, A. O. (2011). *Anatomical guide for the electro myographer: The limbs and trunk* (5th ed). Springfield, IL: Charles C Thomas.

Poitras, I., Bielmann, M., Campeau-Lecours, A., Mercier, C., Bouyer, L. J., & Roy, J.-S. (2019). Validity of wearable sensors at the shoulder joint: combining wireless electromyography sensors and inertial measurement units to perform physical workplace assessments. *Sensors* (*Basel, Switzerland*), *19*(8), 1885. doi:10.3390/s19081885

Powden, C. J., Hoch, J. M., & Hoch, M. C. (2017). Rehabilitation and improvement of health-related quality of life detriments in individuals with chronic ankle instability: A meta-analysis. *Journal of Athletic Training*, *52*(8), 753–765. doi:10.4085/ 1062-6050-52.5.01

Roos, K. G., Kerr, Z. Y., Mauntel, T. C., Djoko, A., Dompier, T. P., & Wikstrom, E. A. (2017). The epidemiology of lateral ligament complex ankle sprains in national collegiate athletic association sports. *The American Journal of Sports Medicine*, *45*(1), 201–209. doi:10.1177/0363546516660980

Silva, M. G., Struber, L., Daniel, O., & Nougier, V. (2021). Effects of a lower limb muscular fatigue on posture-movement interaction during a lower limb pointing task. *European Journal of Applied Physiology*, *121*(1), 287–295. doi:10.1007/s00421-020-04529-9

Sullivan, G. M., & Feinn, R. (2012). Using effect size-or why the p value is not enough. *Journal of Graduate Medical Education*, *4*(3), 279. doi:10.4300/JGME-D-12-00156.1

Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., Cauraugh, J. H., Naugle, K. E., & Borsa, P. A. (2010). Dynamic postural control but not mechanical stability differs among those with and without chronic ankle instability. *Scandinavian Journal of Medicine and Science in Sports*, *20*(1), e137-144. doi:10.1111/j.1600-0838.2009. 00929.x

Winter, D. A., Prince, F., Frank, J. S., Powell, C., & Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology*, *75*(6), 2334–2343. doi:10.1152/jn.1996.75.6.2334

Xu, Y., Song, B., Ming, A., Zhang, C., & Ni, G. (2022). Chronic ankle instability modifies proximal lower extremity biomechanics during sports maneuvers that may increase the risk of ACL injury: a systematic review. *Frontiers in Physiology*, *13*, 1036267. doi:10.3389/fphys.2022.1036267

Zhang, L., Yan, Y., Liu, G., Han, B., Fei, J., & Zhang, Y. (2022). Effect of fatigue on kinematics, kinetics and muscle activities of lower limbs during gait. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine*, *236*(9), 1365–1374. doi:10.1177/09544 119221112516