doi:10.4085/1062-6050-0260.24

Pre- and Post-Surgical Cutaneous Reflexes and Perceived Instability During Gait in an Individual with Chronic Ankle Instability

Annalee M. H. Friedman, PhD, LAT, ATC*

Leif P. Madsen, PhD, LAT, ATC†

*Indiana State University, 567 N 5th St., Terre Haute, IN 47809, USA

†Indiana University, 1025 E 7th St, Bloomington, IN 47405, USA

Corresponding author: Annalee M.H. Friedman, PhD, LAT, ATC Indiana State University, 567 N 5th St., Terre Haute, IN 47809, USA

Tel: (614)747-1998, **E-mail**: annalee.friedman@indstate.edu

Pre- and Post-Surgical Cutaneous Reflexes and Perceived Instability During Gait in an Individual with Chronic Ankle Instability

Abstract

Context: Recent studies exploring chronic ankle instability (CAI) have found alterations in cutaneous reflexes of musculature surrounding the ankle which may contribute to perceived instability and recurrent LAS seen in this population. CAI is considered a multifaceted condition, making it difficult to determine the underlying cause of these altered reflexes.

Objective: To observe how mechanical laxity of the ankle affects lower limb cutaneous reflexes and perceived instability during gait and how surgical intervention to correct laxity affects these measures.

Design: Clinical Case Report

Setting: Research Laboratory

Patient: A physically active 25-year-old female (64in;130lbs) with 7 previous lateral ankle sprains (LAS) and met CAI diagnostic criteria based on CAI questionnaire scores. The patient underwent a Broström reconstruction of the CFL via allograft and partial synovectomy.

Main Outcome Measures: CAI questionnaire scores, middle latency lower limb cutaneous reflexes, and perceived instability following sural nerve stimulation during gait.

Results: Post-surgery, the patient’s CAIT and FAAM questionnaire scores aligned with those of a healthy individual. PL reflexes were diminished or inhibitory during the stance phases of gait. Pronounced variability of PL reflexes may have contributed to this lack of facilitation. BF facilitation at midstance was absent during both testing sessions while BF and RF facilitation was generally reduced post-surgical intervention. The patient's average perceived instability following sural stimulation was markedly reduced from the pre-surgical (6.5±0.48) to post-surgical (1.9±0.24) session.

Conclusions: Mechanical instability likely contributed to the reflex variations seen in this patient pre-surgically, while the enhanced static stability provided by the surgical procedure may have reduced the need for dynamic stability via lower limb cutaneous reflexes observed in the follow-up session. Identifying the specific limitations experienced by an individual with CAI will allow for a more effective monitoring and treatment and provide improved long-term health-related quality of life outcomes.

Key Words: chronic ankle instability; cutaneous reflexes; perceived instability; ligamentous stability

Key Points:

- Mechanical instability likely contributed to the cutaneous reflex alterations observed during gait, namely, a lack of protective PL and BF facilitation.
- The surgical intervention improved mechanical stability which likely improved perceptions of instability and reduced the need for dynamic stabilization via reflexive activity at the ankle and knee.
- Considering the multifaceted nature of CAI, specific symptoms should be identified on an individual basis to improve functional and patient-reported outcome measures.

Abstract Word Count: 295

Body of Manuscript Word Count: 3124

Pre- and Post-Surgical Cutaneous Reflexes and Perceived Instability During Gait in an Individual with Chronic Ankle Instability

Abstract

Context: Recent studies exploring chronic ankle instability (CAI) have found alterations in cutaneous reflexes of musculature surrounding the ankle which may contribute to perceived instability and recurrent LAS seen in this population. CAI is considered a multifaceted condition, making it difficult to determine the underlying cause of these altered reflexes.

Objective: To observe how mechanical laxity of the ankle affects lower limb cutaneous reflexes and perceived instability during gait and how surgical intervention to correct laxity affects these measures.

Design: Clinical Case Report

Setting: Research Laboratory

Patient: A physically active 25-year-old female (64in;130lbs) with 7 previous lateral ankle sprains (LAS) and met CAI diagnostic criteria based on CAI questionnaire scores. The patient underwent a Broström reconstruction of the calcaneofibular ligament via allograft and partial synovectomy.

Main Outcome Measures: CAI questionnaire scores, middle latency lower limb cutaneous reflexes, and perceived instability following sural nerve stimulation during gait.

Results: Post-surgery, the patient's CAIT and FAAM questionnaire scores aligned with those of a healthy individual. Peroneus longus (PL) reflexes were diminished or inhibitory during the stance phases of gait. Pronounced variability of PL reflexes may have contributed to this lack of facilitation. Biceps femoris (BF) facilitation at midstance was absent during both testing sessions while BF and rectus femoris (RF) facilitation was generally reduced post-surgical intervention. The patient's average perceived instability following sural stimulation was markedly reduced from the pre-surgical (6.5±0.48) to post-surgical (1.9±0.24) session.

Conclusions: Mechanical instability likely contributed to the reflex variations seen in this patient pre-surgically, while the enhanced static stability provided by the surgical procedure may have reduced the need for dynamic stability via lower limb cutaneous reflexes observed in the post-surgical session. Identifying the specific limitations experienced by an individual with CAI will allow for a more effective monitoring and treatment and provide improved long-term health-related quality of life outcomes.

Key Words: chronic ankle instability; cutaneous reflexes; perceived instability; ligamentous stability

Key Points:

- Mechanical instability likely contributed to the cutaneous reflex alterations observed during gait, namely, a lack of protective PL and BF facilitation.
- The surgical intervention improved mechanical stability which likely improved perceptions of instability and reduced the need for dynamic stabilization via reflexive activity at the ankle and knee.
- Considering the multifaceted nature of CAI, specific symptoms should be identified on an individual basis to improve functional and patient-reported outcome measures.

Abstract Word Count: 296

Body of Manuscript Word Count: 2988

Introduction

Over 2 million lateral ankle sprains (LAS) occur in the U.S. annually, accounting for approximately 15% of all athletic injuries.[1,2] Half of LAS occurrences seen in U.S. emergency rooms are not associated with athletics, indicating these injuries bear a significant impact on the general population as well.[1] Up to 70% of individuals experiencing acute LAS are estimated to develop chronic ankle instability (CAI), a condition characterized by perceptions of ankle weakness or giving way, diminished sensorimotor function, and recurrent LAS.[1,3] Those with CAI often report lower health-related quality of life, lower levels of physical activity, and are at a higher risk of developing early onset osteoarthritis, all of which contribute to this condition's significant public health impact.[4,5] While initially thought to stem from mechanical deficiencies such as pathologic laxity, research from the last few decades has informed the development of a new, more complex model of CAI, consisting of pathomechanical, sensory-perceptual, and motor-behavioral impairments.[3,6]

Recent studies have found alterations in cutaneous reflexes of musculature surrounding the ankle which may contribute to perceived instability, postural stability, and reinjury rates seen in those with the CAI.[7-11] Since CAI is considered a multifaceted condition, patients present with a collection of interrelated deficits making it difficult to determine the underlying cause of these altered reflexes.[3,12] This case study was conducted to explore lower limb cutaneous reflexes during gait and patient-reported outcome measures in a patient with known pathologic laxity of lateral ankle ligaments. Additionally, while current literature[13-16] provides substantial evidence for the pathomechanical and functional benefits of Bröstrom reconstruction, little is known regarding the direct sensorimotor changes which may take place following surgical intervention. Therefore, this case study also sought to identify alterations in cutaneous reflex characteristics and perceived instability from cutaneous stimulation following allograft reconstruction to assess the impact of mechanical instability on neuromuscular recovery of LAS. This is the only case study, to date, exploring these outcomes in an individual with CAI before and after surgical intervention.

Case Presentation

The patient was a physically active 25-year-old female (64in; 130lbs) presenting with mechanical ankle instability as diagnosed by her orthopedic physician, specifically, a grade 3 tear of the calcaneofibular ligament (CFL) and presence of an os trigonum. A Broström reconstruction of the CFL via allograft was scheduled including a partial synovectomy and debriding of the affected region. The patient informed the researchers of their upcoming procedure and consented to participate in this case study which was approved by the university's Institutional Review Board.

Methods

Two days prior to surgical intervention, the patient reported to the lab for testing where they completed the Identification of Functional Ankle Instability (IdFAI),[17] Cumberland Ankle Instability Tool (CAIT),[18] and the Foot and Ankle Ability Measure (FAAM)[19] which was modified to target instability (see Appendix). Muscle activity of the tibialis anterior (TA), medial (MG) and lateral (LG) gastrocnemius, peroneus longus (PL), biceps femoris (BF), and rectus femoris (RF) was measured via wired bipolar surface electrodes which communicated with a Delsys Bagnoli EMG system (Delsys Inc., Natick, MA). Sural nerve stimulations were administered via a stimulating bar electrode (Ambu, Inc., Columbia, MD) affixed over the sural nerve just posterior to the lateral malleolus on the affected limb. Stimulation intensity for testing was determined as 2x radiating threshold, ensuring the stimulation was non-noxious and did not produce a withdrawal reflex.

The patient walked for approximately 20 minutes at 4km/hr on a treadmill. A DS7A constant current stimulator (Digitimer North America, LLC, Ft. Lauderdale, FL) connected to a custom-built latency device was used to administer 5-train pulse stimulations during the 8 phases of gait. Heel-toe sensors inserted into both shoes collected heel strike data used for timing of each stimulation which was manually entered into the custom-built device. Eight phases of the gait cycle were divided equally across the patient's stride, from the initial heel strike of the affected limb to subsequent heel strike of the same limb. These phases represented heel strike (phase 1), stance (phases 2-4), toe-off (phase 5) and swing (phases 6-8). Stimulation trials were randomized to ensure 10 stimulations occurred at each of the 8 phases. Following each stimulation trial, the patient reported their feelings of instability on a scale of 0 to 10, defined as "no instability" or "feels normal" (0) to "severe instability" or "you feel you may stumble" (10). All EMG, stimulation, and heel strike data were recorded using a Biopac MP160 acquisition system and Acqknowledge 5.0 software (Biopac Systems, Inc., Goleta, CA). The patient returned approximately 5 months (148 days) later, having completed their prescribed rehabilitation program, received physician clearance for full return to activity, and underwent the same study protocol as described.

Data Processing

All data processing was completed using AcqKnowledge 5.0 software (Biopac Systems, Inc., Goleta, CA). Raw EMG data were filtered at a low frequency cutoff of 50Hz and high frequency cutoff of 500Hz. The root mean square (RMS) was then derived for the smoothed signals for each muscle. Stimulated trials were reviewed for step timing consistency and a minimum of 9 trials were averaged for each phase. Approximately 100 unstimulated trials were also ensemble averaged for comparison to stimulated trials. To compare values between testing sessions, all waveforms were normalized as a percentage of each muscle's maximum EMG amplitude during unstimulated trials (%MVC). Unstimulated waveforms were subtracted from stimulated waveforms to acquire the final reflex trace. For each muscle at each phase, middle latency reflex (MLR) values were identified as the mean amplitude of the reflex waveform 80-120ms after the first pulse in the stimulation train. A postive MLR is indicative of a faciliatory reflex while and a negative MLR is indicative of an inhibitory reflex. Unstimulated amplitudes during this time window for each of the 6 muscles at all 8 phases were extracted for analysis of background muscle activity. Additionally, normalized stimulated trials were extracted for analysis of reflex variability.

Comparative Outcomes

Patient Reported Outcome Measures

According to the International Ankle Consortium recommendations, the patient met CAI diagnostic criteria based on responses to presurgical questionnaires (see Table 1).[20] During their initial session, the patient reported 7 previous sprains in their left ankle, and met CAI thresholds for the IdFAI, CAIT, and FAAM subscales; Activities of Daily Living (ADL) and Sport. Chief complaints included pain and instability during sport, and recurrent feelings of instability during ADLs, especially when walking downstairs or on uneven surfaces. Upon returning post-surgical intervention and rehabilitation, the patient no longer met CAI diagnostic criteria based on their responses on the CAIT or FAAM questionnaires. Their IdFAI score was reduced by 14 points, however, it remained above the threshold for CAI diagnosis due to their extensive LAS history prior to surgical intervention.

During the walking task pre-surgical intervention, the patient reported a 4 out of 10 for perceived instability during unstimulated gait (prior to stimulated trials) and an average of 6.5±0.48 out of 10 perceived instability following sural nerve stimulation. Following surgery and recovery, the patient's perceived instability during the walking task was reduced to 0 out of 10 at baseline and 1.9±0.24 out of 10 when stimulated.

Reflex Patterns

During the pre-surgical session, late stance facilitatory reflexes were observed in the TA which were markedly reduced or absent during the post-surgical session, specifically, at phase 4 (20.6% to -0.93%) and phase 5 (53.3% to 22.1%). TA inhibition was observed at mid- and end-swing pre-surgically which were subsequently enhanced post-surgically, from -11.8% to -21.0% at phase 7 and from -22.1% to -34.6% at phase 8. In the MG and LG, pronounced inhibition was observed throughout stance in the pre-surgical session which was enhanced post-surgically at phase 2 (MG: -19.7% to -23.9%, LG: -4.79% to -7.22%). However, gastrocnemius inhibitory reflexes were reduced from the pre-surgical session at phase 3 (MG: -48.9% to -26.9%, LG: -53.1% to -45.3%) and phase 4 (MG: -5.06% to -0.44%, LG: -17.1% to -

6.21%). Notable gastrocnemius facilitation was also observed pre-surgically at the swing to stance transition (phase 8) which was then reduced post-surgically (MG: 10.6% to 7.23%, LG: 7.23% to 5.64%).

Pre-surgical facilitation of the PL was reduced during the stance to swing transition post-surgically, specifically, at phase 5 (35.4% to 17.8%) and phase 6 (22.1% to 14.5%). PL reflexes which were faciliatory during the swing to stance transition at the pre-surgical session became inhibitory post-surgically, namely at phase 1 (34.3% to -4.39%), and phase 8 (15.4% to -8.90%). Considerable BF and RF facilitation was noted for most of the gait cycle during the pre-surgical session except for the BF at phase 3 (3.22%) and in the RF at phase 6 (0.85%). Faciliatory reflexes were then markedly reduced for both muscles post-surgically, other than the BF at phase 7 and RF at phase 8 where facilitation was somewhat enhanced (BF: 8.72% to 13.5%, RF: 24.4% to 25.7%). Figure 1 provides a visual representation of reflex patterns across the gait cycle for all muscles measured.

Reflex Variability

In the TA, reflex variability was generally steady across the 8 phases of gait, peaking pre-surgically at phase 5 (±22.9%) and post-surgically at phase 6 (±22.3%). On average, TA reflex variability was reduced by ±5.47% from pre-surgical to post-surgical session. In MG and LG, reflex variability was almost identical pre- versus post-surgical intervention, increasing ±0.59% and ±0.90%, respectively. However, variability in phase 3 was considerably greater during the post-surgical session (MG ±13.3%, LG ±14.5%) compared to the pre-surgical session (MG ±10.5%, LG ±8.85%).

PL reflex variability was especially high pre-surgically, peaking at phase 8 (±36.6%) but was markedly reduced (by ±8.10%) during the post-surgical session, peaking at phase 5 (±25.4%). This reduction was especially notable during phase 2 where variability was lowered from 30.2% pre-surgically to ±8.38% post-surgically. In the BF, variability was also notably reduced from pre- to post-surgical session by ±5.1% on average. However, reflex variability at phase 7 was considerably elevated post-surgically, increasing from ±11.0% to ±40.3%. RF reflex variability was generally similar across both sessions, exhibiting only ±1.00% reduction pre- to post-surgically, on average. Table 2 provides average reflex variability and ranges across the gait cycle while Figure 2 provides visual representation of average reflex variability at each phase of gait for all muscles measured.

Discussion

Reflex Characteristics

Our method of dividing the gait cycle into 8 even time points when calculating reflex amplitudes was necessary to accurately align and compare muscle activity between stimulated and unstimulated trials. However, to discuss pertinent findings for clinical interpretation, subsequent discussion points regarding the location of reflex measurements across the gait cycle will be presented in two ways; 1) referencing the phase number(s) in which the reflex variable was calculated and 2) using clinically relevant descriptions to illustrate kinematics of the leg and foot at the time of the stimulation. For stance, phases 1-2 represent the *heel rocker* (heel contacts the ground and the foot is lowered by rotating around the heel), phases 2-4 represent the *ankle rocker* (foot is flat on ground and axis of rotation occurs at the talocrural joint), and phases 4-5 represent the *forefoot rocker* (rotation occurs at the metatarsophalangeal joints to lift the heel and mid-foot off the ground in preparation for swing).[21]

A visual inspection of the reflex amplitudes across the gait cycle show that the patient's cutaneous reflex patterns pre- and post-surgical intervention in the TA, MG, and LG were generally well-aligned with those of healthy subjects in previous literature.[7,22,23] The patient exhibited phase-dependent reflex reversal of the TA across both testing sessions, specifically, a facilitation during the forefoot rocker (phase 5) and inhibition during the limb placement stage of swing (phases 7 and 8). Though TA reflex patterns are generally the same across sessions, post-surgically, facilitatory activity was somewhat reduced at the forefoot rocker, indicating a less effective response to dorsiflex the foot away from a potential obstacle. However, the subject demonstrated greater inhibitory activity in late swing compared to pre-surgical measures, which would provide for more rapid foot placing as the patient transitioned into double-leg stance to maintain better postural stability. Gastrocnemius inhibition during stance, a protective unloading mechanism commonly seen in healthy individuals,[7,22] was exhibited across the ankle rocker, with the most pronounced inhibition occurring at phase 3 and to a lesser degree at phases 2 and 4. The post-surgical reduction in gastrocnemius inhibition during the ankle rocker suggests a diminished preparedness to potentially shift weight to the contralateral limb should perturbation continue and compromise balance. Perhaps the increased reflex variability observed post-surgically in both the MG and LG contributed to this reduced inhibition throughout the ankle rocker rotation at midstance.

Reflex patterns of the BF and RF were somewhat variable from those of healthy individuals.[22,24,25] In both sessions at mid ankle rocker (phase 3), the patient lacked BF facilitation which typically occurs in tandem with RF facilitation to provide stabilization at the knee following an unexpected perturbation.[24-27] Co-facilitation of the BF and RF was exhibited throughout the other phases of stance (1, 2, and 4) during the pre-surgical session, however, this facilitation was reduced post-surgically which would diminish bracing at the knee during weight-bearing. As the limb advances into swing, facilitation of the BF is expected to surpass that of the RF to allow for knee flexion as a mechanism of obstacle avoidance.[22,24-26] This reflex was more prominently exhibited during the post-surgical testing session where RF activity decreased by 16.6% during the forefoot rocker (phase 5). While BF facilitation was somewhat reduced at phase 5, reflex variability was also reduced during this time implying a more consistent response was exhibited post-surgically. A lack of RF reflex at limb advancement (phase 6) was exhibited during both testing sessions which, in combination with prominent BF facilitation, likely acts to further withdraw the limb from a potential obstacle into the swing phase.[22,24,25]

The most unique cutaneous reflex patterns were observed in the PL, where both CAI and healthy individuals alike present with consistent facilitation throughout the gait cycle. PL facilitation during weight-bearing would increase dynamic stability of the lateral ankle following an unexpected perturbation.[7,8] The patient, however, exhibited facilitation only during the heel rocker (phase 1), forefoot rocker (phase 5), and limb advancement (phase 6) of the pre-surgical session. Post-surgically, PL facilitation at these phases was reduced or even reversed to inhibitory activity. During the pre-surgical session, the patient exhibited highly variable PL reflexes (1.31±32.56%) late into the heel rocker (phase 2), which then presented as inhibitory post-surgically (-15.4± 8.38%). PL reflexes throughout most of the gait cycle were highly variable, which likely contributed to the lack of net reflexes observed throughout most of the gait cycle. Following surgical intervention, PL facilitation was noted during the ankle rocker (phase 3) which indicates improved protective mechanism at the ankle following a lateral perturbation. Variability was also reduced at this phase post-surgical intervention which may have played a role in this net PL facilitation.

Perceived Instability

While the cutaneous reflex patterns observed in this patient during gait are somewhat aligned with those of healthy individuals (namely in the TA and gastrocnemius), others varied from patterns previously seen in those with and without CAI. Considering the protective role cutaneous reflexes play during gait, deviation from normal motor responses to perturbation may result in inadequate defense from stumbling or injury and may manifest as a heightened perception of instability. A recent study[11] provides evidence of this potential relationship, finding greater reflex variability of the PL is correlated with higher levels of perceived instability following sural nerve stimulation. Mechanical instability resulting from torn lateral ankle ligaments may contribute to the reflex variations seen in this patient during the pre-surgical session. Post-surgically, the general reduction in reflex activity seen across most muscles and phases suggests that the improved static stability gained from the patient's allograft reconstruction reduces the patient's reliance on reflexive dynamic stabilization. For example, during pre-surgical testing we found that the muscles crossing the hip and knee (RF and BF) exhibited increased facilitation, and thus co-activation, when the sural nerve was stimulated during the stance phase. These cutaneous reflexes were likely present because there was reduced static stability at the ankle, and the lower limb compensated by stabilizing joints higher up the kinetic chain to maintain a steady gait cycle on the treadmill. Once surgical reconstruction was completed and the patient's mechanical ankle stability was improved, the co-facilitation of muscles crossing the hip and knee was reduced suggesting proximal joints were not assisting as substantially with lower limb dynamic stability.

While those with CAI are typically categorized based on symptoms of pain, instability, and recurrent sprain history, the CAI subjects included in earlier studies may not have had significant mechanical impairments. The addition of prominent mechanical limitations are unique features to this patient which provide further insight to the relationship between sensorimotor and pathomechanical deficits. Considering the inherent interconnectedness of pathologic laxity and sensorimotor deficits such as altered reflexes and perceived instability it is difficult to attribute the changes seen in this patient to surgical or rehabilitative intervention.[3,28,29] However, the outcomes explored in this study provide important insights into neuromuscular and sensory-perceptual plasticity following a surgical intervention aimed at improving pathomechanical function.

The post-surgical reduction in perceived instability observed in this patient may also be a result of their rehabilitation protocol which the patient reported was more specific to their limitations and performance-related goals than the conservative rehabilitations they underwent for previous ankle sprains. As a certified athletic trainer, the patient took agency over their rehabilitation after progression to full weight-bearing, designing and modifying therapeutic exercises to align with their changing goals and physical tolerance. The patient reported this autonomy, in addition to their knowledge of the improved mechanical stability in their affected ankle following surgery, enhanced their confidence and ultimately expedited their return to recreational exercise. In addition to patient-specificity, the patient also reported early implementation of proprioceptive interventions, namely, post-operative scar, soleus, and plantar massage which may have played a role in the reflexive or perceptual changes observed.[30-32]

Clinical Bottom Line

Considering the heterogeneity of CAI, patients with this condition should be treated based on their specific symptoms rather than a one-size-fits-all rehabilitation protocol.[33] Identifying the specific limitations experienced by an individual with CAI will allow for more effective treatment and provide improved long-term health-related quality of life outcomes. Establishing baselines for proprioceptive and perceptual measures will also help in identifying specific sensorimotor deficits which exist prior to rehabilitation so clinicians may accurately monitor training-induced adaptive changes.[34-36] The unique reflexive alterations observed in this case may act as another clinical marker for treating chronic symptoms among individuals with pathologic laxity in the ankle. Future research would benefit from measuring cutaneous reflexes before and after reconstruction or throughout conservative rehabilitation to determine how modulation patterns are affected by these interventions. As cutaneous reflexes may be linked to perceptions of instability and other sensorimotor outcomes, understanding the origin of reflexive changes following LAS may allow for more appropriate, patient-specific treatment and subsequent reduction of future injury.

References

1. Herzog MM, Kerr ZY, Marshall SW, Wikstrom EA. Epidemiology of ankle sprains and chronic ankle instability. *Journal of athletic training.* 2019;54(6):603-610.
2. Roos KG, Kerr ZY, Mauntel TC, Djoko A, Dompier TP, Wikstrom EA. The epidemiology of lateral ligament complex ankle sprains in National Collegiate Athletic Association sports. *The American journal of sports medicine.* 2017;45(1):201-209.
3. Hertel J, Corbett RO. An updated model of chronic ankle instability. *Journal of athletic training.* 2019;54(6):572-588.
4. Thompson C, Schabrun S, Romero R, Bialocerkowski A, van Dieen J, Marshall P. Factors contributing to chronic ankle instability: a systematic review and meta-analysis of systematic reviews. *Sports Medicine.* 2018;48(1):189-205.
5. Donovan L, Hetzel S, Laufenberg CR, McGuine TA. Prevalence and impact of chronic ankle instability in adolescent athletes. *Orthopaedic Journal of Sports Medicine.* 2020;8(2):2325967119900962.
6. Freeman M. Instability of the foot affer injuries to the lateral ligament of the ankle. *The Journal of bone and joint surgery British volume.* 1965;47(4):669-677.
7. Madsen LP, Kitano K, Koceja DM, Zehr EP, Docherty CL. Effects of chronic ankle instability on cutaneous reflex modulation during walking. *Experimental brain research.* 2019;237(8):1959-1971.
8. Heimark NE, Friedman AM, Kitano K, Madsen LP. The role of sural nerve reflexes during drop-landing in subjects with and without chronic ankle instability. *Experimental Brain Research.* 2023:1-15.
9. Futatsubashi G, Sasada S, Ohtsuka H, Suzuki S, Komiyama T. Misencoding of ankle joint angle control system via cutaneous afferents reflex pathway in chronic ankle instability. *Experimental Brain Research.* 2022:1-11.

10. Futatsubashi G, Sasada S, Tazoe T, Komiyama T. Gain modulation of the middle latency cutaneous reflex in patients with chronic joint instability after ankle sprain. *Clinical Neurophysiology.* 2013;124(7):1406-1413.
11. Friedman AMH, Madsen LP. Perceived ankle instability and cutaneous reflex modulation during gait. *Physiological Reports.* 2023;11(22):e15880.
12. Duysens J, Levin O. Ankle sprains: getting off on the wrong foot. *Exercise and sport sciences reviews.* 2010;38(3):143-149.
13. Hsu AR, Ardoin GT, Davis WH, Anderson RB. Intermediate and long-term outcomes of the modified Brostrom-Evans procedure for lateral ankle ligament reconstruction. *Foot & ankle specialist.* 2016;9(2):131-139.
14. Li X, Killie H, Guerrero P, Busconi BD. Anatomical reconstruction for chronic lateral ankle instability in the high-demand athlete: functional outcomes after the modified Broström repair using suture anchors. *The American journal of sports medicine.* 2009;37(3):488-494.
15. Lee JH, Lee SH, Jung HW, Jang WY. Modified Broström procedure in patients with chronic ankle instability is superior to conservative treatment in terms of muscle endurance and postural stability. *Knee Surgery, Sports Traumatology, Arthroscopy.* 2020;28:93-99.
16. Lee KT, Park YU, Kim JS, Kim JB, Kim KC, Kang SK. Long-term results after modified brostrom procedure without calcaneo-fibular ligament reconstruction. *Foot & ankle international.* 2011;32(2):153-157.
17. Simon J, Donahue M, Docherty C. Development of the identification of functional ankle instability (IdFAI). *Foot & Ankle International.* 2012;33(9):755-763.
18. Hiller CE, Refshauge KM, Bundy AC, Herbert RD, Kilbreath SL. The Cumberland ankle instability tool: a report of validity and reliability testing. *Archives of physical medicine and rehabilitation.* 2006;87(9):1235-1241.
19. Martin RL, Irrgang JJ, Burdett RG, Conti SF, Swearingen JMV. Evidence of validity for the Foot and Ankle Ability Measure (FAAM). *Foot & ankle international.* 2005;26(11):968-983.
20. Gribble PA, Delahunt E, Bleakley C, et al. Selection criteria for patients with chronic ankle instability in controlled research: a position statement of the International Ankle Consortium. *journal of orthopaedic & sports physical therapy.* 2013;43(8):585-591.
21. Medina McKeon JM, Hoch MC. The ankle-joint complex: a kinesiologic approach to lateral ankle sprains. *Journal of athletic training.* 2019;54(6):589-602.
22. Zehr EP, Komiyama T, Stein R. Cutaneous reflexes during human gait: electromyographic and kinematic responses to electrical stimulation. *Journal of neurophysiology.* 1997;77(6):3311-3325.
23. Yang JF, Stein RB. Phase-dependent reflex reversal in human leg muscles during walking. *Journal of Neurophysiology.* 1990;63(5):1109-1117.
24. Van Wezel BM, Ottenhoff FA, Duysens J. Dynamic control of location-specific information in tactile cutaneous reflexes from the foot during human walking. *Journal of Neuroscience.* 1997;17(10):3804-3814.
25. Tax A, Van Wezel B-l, Dietz V. Bipedal reflex coordination to tactile stimulation of the sural nerve during human running. *Journal of neurophysiology.* 1995;73(5):1947-1964.
26. Lamont EV, Zehr EP. Task-specific modulation of cutaneous reflexes expressed at functionally relevant gait cycle phases during level and incline walking and stair climbing. *Experimental brain research.* 2006;173(1):185-192.
27. Zehr EP, Stein RB. What functions do reflexes serve during human locomotion? *Progress in neurobiology.* 1999;58(2):185-205.
28. Wenning M, Gehring D, Mauch M, Schmal H, Ritzmann R, Paul J. Functional deficits in chronic mechanical ankle instability. *Journal of orthopaedic surgery and research.* 2020;15:1-8.
29. Ma T, Li Q, Song Y, Hua Y. Chronic ankle instability is associated with proprioception deficits: a systematic review and meta-analysis. *Journal of sport and health science.* 2021;10(2):182-191.

30. Hu X, Liao J, Hu X, Zeng Z, Wang L. Effects of plantar-sensory treatments on postural control in chronic ankle instability: A systematic review and meta-analysis. *PloS one.* 2023;18(6):e0287689.
31. Park J, Shim J, Kim S, et al. Application of massage for ankle joint flexibility and balance. *Journal of physical therapy science.* 2017;29(5):789-792.
32. McKeon PO, Wikstrom EA. Sensory-targeted ankle rehabilitation strategies for chronic ankle instability. *Medicine and science in sports and exercise.* 2016;48(5):776.
33. Terada M, Bowker S, Hiller C, Thomas A, Pietrosimone B, Gribble P. Quantifying levels of function between different subgroups of chronic ankle instability. *Scandinavian journal of medicine & science in sports.* 2017;27(6):650-660.
34. Zehr EP. Training-induced adaptive plasticity in human somatosensory reflex pathways. *Journal of applied physiology.* 2006;101(6):1783-1794.
35. Sefton JM, Yarar C, Hicks-Little CA, Berry JW, Cordova ML. Six weeks of balance training improves sensorimotor function in individuals with chronic ankle instability. *Journal of orthopaedic & sports physical therapy.* 2011;41(2):81-89.
36. Tedeschi R, Ricci V, Tarantino D, Tarallo L, Catani F, Donati D. Rebuilding Stability: Exploring the Best Rehabilitation Methods for Chronic Ankle Instability. *Sports.* 2024;12(10):282.


Net Reflex Amplitude (%MVC)
Tibialis Anterior
Pre
Post
Medial Gastrocnemius
Pre
Post
Peroneus Longus
Pre
Post
Lateral Gastrocnemius
Pre
Post
Biceps Femoris
Pre
Post
Rectus Femoris
Pre
Post
1
2
3
4
5
6
7
8
Stance
Swing
Stance
Swing

Questionnaire	CAI Threshold Values	Pre-surgical	Post-surgical
IdFAI	≥ 11	31	17
CAIT	≤ 24	10	26
FAAM-ADL	< 90%	50%	97%
FAAM-Sport	< 80%	46%	90%
"Current Level of Instability" (FAAM)	N / A	Severely Abnormal (15%)	Normal (90%)
Average Perceived Instability (following sural stimulation)	N / A	6.5±0.48	1.9±0.24

Muscle	Pre-Surgical Variability	Post-Surgical Variability
Tibialis Anterior (TA)	**±14.1%** (±9.28 to ±22.9%)	**±8.63%** (±1.60 to ±22.3%)
Peroneus Longus (PL)	**±25.0%** (±5.49 to ±36.8%)	**±16.9%** (±8.38 to ±25.4%)
Medial Gastrocnemius (MG)	**±6.48%** (±0.43 to ±12.1%)	**±7.07%** (±0.98 to ±13.3%)
Lateral Gastrocnemius (LG)	**±4.39%** (±1.21 to ±9.29%)	**±5.29%** (±1.02 to ±14.5%)
Biceps Femoris (BF)	**±24.4%** (±2.79 to ±55.7%)	**±19.3%** (±2.55 to ±40.3%)
Rectus Femoris (RF)	**±17.2%** (±3.22 to ±26.9%)	**±16.2%** (±2.03 to ±26.6%)