THE INFLUENCE OF SENSORIMOTOR TRAINING MODALITIES ON BALANCE, STRENGTH, JOINT FUNCTION, AND PLANTAR FOOT SENSITIVITY IN RECREATIONAL ATHLETES WITH A HISTORY OF ANKLE SPRAIN: A RANDOMIZED CONTROLLED PILOT STUDY

Sabine Deussen, PT, BSc¹

Martin Alfuth, PT, PhD, MA, BSc¹

ABSTRACT

Background: Ankle sprains frequently result in persistent sensorimotor deficits. Sufficient evidence of effects of sensorimotor training using unstable devices on physical functions is lacking. There is no insight as to whether simultaneous tactile stimulation of plantar foot mechanoreceptors using textured surfaces may influence outcomes in people with a history of ankle sprain.

Purpose: The purpose of this study was to investigate the potential effects of sensorimotor training using unstable textured surfaces on balance, strength, joint function, and plantar sensitivity in recreational athletes with a history of ankle sprain.

Participants: Nineteen recreational athletes (6 females, 13 males; mean age: 29 ± 7 years) with a history of ankle sprain and self-reported sensation of instability participated.

Methods: Self-reported function of the ankle joint, plantar cutaneous detection threshold to light touch, balance during single-leg stance as well as maximal isometric strength of the ankle joint in eversion and inversion were measured. Participants were randomly allocated to either a training group using unstable textured surfaces or a training group using unstable smooth surfaces or a control group. Outcome measurements were repeated after six weeks of training and at follow-up after 10 weeks. Within and between group differences were analyzed using ANOVA, Friedman tests, or Kruskal Wallis tests ($p < 0.05$) and post-hoc tests with Bonferroni correction. Correlations between outcome-parameters from baseline measurements were analyzed using Spearman's rho ($p < 0.05$).

Results: No significant between-group differences in all outcome measures were detected. However, a significant increase of strength in eversion was found for the training group using textured surfaces after 10 weeks ($p = 0.01$). A moderate correlation existed between plantar detection threshold of metatarsal head (MT) I and strength of inversion ($r = 0.51$, $p < 0.05$) before training across all groups. There were moderate negative correlations between balance parameters and strength in eversion ($r = -0.57$ – -0.64 , $p \leq 0.01$) as well as plantar detection thresholds at MT V ($r = -0.48$ – -0.62 , $p < 0.05$) at baseline across all groups.

Conclusion: A six-week sensorimotor training using unstable smooth and textured surfaces demonstrated no significant differences in balance, strength in eversion and inversion, plantar foot sensitivity, and self-reported ankle instability between training groups and the control group in recreational athletes with a history of ankle sprain. A better score on balance testing seems to correlate with an increase in eversion ankle strength and a decreased plantar sensitivity at MT V.

Keywords: ankle; balance training; movement system; sensorimotor deficits; textured surface

Level of Evidence: Level IIb

¹ Niederrhein University of Applied Sciences, Faculty of Health Care, Therapeutic Sciences, Reinarzstr. 49, 47805 Krefeld, Germany

Conflict of Interest Statement

The authors state that there are no known conflicts of interest associated with this publication and that there has been no financial support for this work that could have influenced its results.

CORRESPONDING AUTHOR

Prof. Dr. Martin Alfuth

Phone: + 49 (0)2151 822 6513

E-mail: martin.alfuth@hs-niederrhein.de

INTRODUCTION

In the United States of America, 628,000 ankle injuries, including sprains and fractures, occur each year¹ representing 20% of all treated joint injuries. Seventy-nine percent of these injuries are lateral ankle sprains, 4% are medial ankle sprains.² In 17% of all cases, the syndesmosis is damaged. About 74% of athletes suffer from at least one re-injury, and 22% sustain even five or more recurrent ankle sprains.³

Frequently, ankle sprains are considered to heal spontaneously.⁴ However, symptoms, such as pain, swelling, muscle weakness, or instability remain many years after the initial injury in 74% of athletes.⁵ Nineteen to seventy-two percent of individuals develop chronic instability.⁶ Chronic instability is categorized as either functional or mechanical instability.⁷ Mechanical instability is considered as a loss of mechanical support. Functional instability is characterized by subjective sensation of a weak, painful and lower functioning ankle joint.⁸ Furthermore, a feeling of “giving way” is representative of this kind of instability.^{9,10} Therefore, chronic instability incorporates recurrent injury including mechanical or functional instability and may lead to a number of deficits.⁸ However, why and how affected persons develop chronic instability remains incompletely understood.¹¹ Delayed stabilizing reflexes or prolonged reaction time of lower extremity muscles,^{12,13} deficits of kinesthesia and proprioception,¹⁴ or impaired postural control¹⁵ have been suggested as contributory factors.

Sefton et al.¹¹ considered variables of static balance, such as anterior-posterior and medial-lateral center of pressure (CoP) displacement as well as CoP velocity as those which clearly differentiate between persons with and without chronic ankle instability. Strength deficits of lower leg muscles seem to be associated with chronic instability, however, several studies do not support this assumption.¹⁶

Moreover, there are conflicting results with respect to eversion and inversion strength deficits as related to ankle instability.¹⁷⁻²¹ Altered myoelectric activity of lower extremity muscles is considered as a possible cause of those strength deficits.¹¹ In addition

to a loss of sensory input by articular mechanoreceptors,²² a reduction of plantar foot sensitivity has been discussed.^{23,24} This may be related to deficits in sensorimotor function as shown in a study on the effects of repetitive electrical stimulation on the control of force output at the ankle joint.²⁵

Balance training is effective in the prevention of recurrent ankle sprains.²⁶ However, based on the findings related to the functional adaptations, treatment of patients with chronic instability differs. David et al.²⁷ suggest a rehabilitation focused on control of eccentric muscle contraction of involved muscles. Kaminski et al.¹⁹ advise to additionally target joint proprioception in the treatment of chronic ankle instability. Sefton et al.,¹¹ postulated that static balance plays a major role in the rehabilitation of patients, however, they could not find an improvement after six weeks of balance training.²⁸ In contrast, Kidgell et al.²⁹ reported improved anterior-posterior and medial-lateral sway after six weeks of balance training using unstable devices. Overall, evidence regarding methods to improve postural control, perceived function of the ankle joint and other symptoms in patients with ankle instability is scant and further investigation is needed.^{26,28} Sensorimotor training seems to slightly influence components of muscle strength³⁰ and stimulation of the foot sole using textured insoles may assist in improving gait and balance in people with impairments of gait and balance.³¹ However, long-term effects of plantar cutaneous stimulation using unstable devices with textured surfaces during balance training on functions of the ankle joint in people with an ankle instability are unclear.

The purpose of this study was to investigate the potential effects of sensorimotor training using unstable textured surfaces on balance, strength, joint function, and plantar sensitivity in recreational athletes with a history of ankle sprain. Moreover, correlations between the outcome variables were examined across all groups before onset of intervention. It was hypothesized that outcome variables would significantly improve after balance training using unstable devices with a textured surface compared to balance training using unstable devices with a smooth surface and no treatment.

METHODS

Participants

Twenty-one recreationally active participants between the ages 18 to 50 years volunteered for the study. They were recruited from the local university and local sport clubs. Further inclusion criteria predominantly followed the recommendations of the International Ankle Consortium¹⁰ and were:

- At least one ankle sprain with the initial injury at least 12 months prior to study enrollment related with inflammatory symptoms (pain, swelling etc.)
- At least one interrupted day of preferred physical activity
- The most recent sprain happened more than three months prior to study enrollment
- At least two episodes of “giving way” of the previously injured ankle joint within six months prior to study enrollment and/or at least two sprains to the same ankle
- Self-reported feeling of ankle joint instability

Prior to enrollment participants completed the German version of the Cumberland Ankle Instability Tool (CAIT)³² as previously recommended.¹⁰ The CAIT is a reliable and valid questionnaire that detects the severity of ankle instability.³³ The CAIT can also be used to detect ankle instability after ankle fracture. In the present study a cutoff-score of ≤ 27 was used. For bilaterally affected participants the ankle with the lower CAIT score was considered in the final data analysis.³⁴

Exclusion criteria were an ankle injury and/or other injuries of the lower extremity within the three months prior to enrollment, a CAIT score > 27 in both ankles as well as neurological and rheumatological diseases and disorders that could have influenced outcomes. People with a history of fracture of the foot, ankle or leg are often excluded in studies dealing with chronic ankle instability,¹⁰ however, these participants were included in the present study, because they also can show functional instability involving “giving way”.³³ Therefore, the term “history of ankle sprain with a self-reported feeling of instability” was used for the description of included participants rather than the term “chronic

ankle instability.” Furthermore, the study was a pilot study to replicate, in miniature, a planned full-sized RCT.³⁵ All of the participants provided written informed consent prior to participation and were able to withdraw from the study at any time. The study was approved by the “Ethikkommission an der Physio-Akademie des Deutschen Verbands für Physiotherapie” (2014 – 04). This study was not registered as a clinical trial.

PROCEDURES

In each participant the sensitivity of the sole of the foot, balance in single-leg stance, the maximal voluntary isometric strength of ankle eversion and inversion as well as self-reported function of both ankles using the CAIT score were measured before and after six weeks of sensorimotor training as well as after 10 weeks (follow-up). The tested foot, the sites of the foot sole and the direction of strength measurement were selected at random using concealed envelopes at baseline to avoid systematic effects of learning. All measurements during the study were completed by the same tester (SD) who was blinded to the group allocation. After baseline measurements, participants were allocated at random to one of three groups: training group textured surface (TS), training group smooth surface (SMS) and a control group (CG that received no training) (Figure 1). For randomization, a computer-generated table of random numbers was created using MS-Excel. The assessor (SD) kept the assignment order and provided the assignment to the treating physical therapist (MA) in a sequence of consecutively numbered opaque envelopes. Allocation was concealed from the tester at all times and from the participants and the treating physical therapist (MA) until the start of treatment.

Sensorimotor training began at least one week after baseline measurements. The participants of the training groups completed a six-week progressive exercise program two days per week that lasted 20 to 30 minutes. The program was supervised and intervention adherence documented by a physical therapist (MA) with 12 years of experience in the arena of sports physical therapy. Exercises included double- and single-leg stance (both legs) on unstable devices [wobble board, rocker board, and a soft balance

Figure 1. Flow diagram (CONSORT).

Figure 2. Participant balancing on the wobble board with the smooth surface (diameter: 37 cm; material: beechwood). The small picture in the top left-hand corner of the figure illustrates the textured surface (small pyramids) of the wobble board.

pad] with a textured surface (Thera-Band®, ARTZT vitality, Dornburg, Germany) for the TS group or a smooth surface for the group SMS (Figure 2). The textured surface of the wobble board (diameter: 41 cm; height: 8.8 cm; material: plastic) and the rocker

board (length: 33.4 cm, width: 35.6 cm; height: 9.5 cm; material: plastic) consisted of small pyramids (height: 3 mm). The wobble board with smooth surface (Therapy Balancing Tops, Sport-Thieme GmbH, Graslleben, Germany) was made of beechwood and had a diameter of 37 cm and a height of 9.5 cm. The rocker board with smooth surface (Pedalo® Rocking Board, Sport-Thieme GmbH, Graslleben, Germany) consisted of beechwood with a length of 45 cm, a width of 30 cm and a height of 9.5 cm. One side of the foam surface of the balance pad (Thera-Band®, ARTZT vitality, Dornburg, Germany; dimension: 40 x 50 x 6 cm; material: polyethylene) had broad horizontal grooves and this was used with the TS group. The SMS group used the same balance pad, however, it was turned over such that the smooth surface was on the top (under the surface of the foot).

During the first two weeks, exercises were carried out three times for 20 seconds with a resting period of 30 seconds between the sets and one minute between the exercises. Balance on the rocker board was performed in double-leg stance, while balance on the wobble board and the balance pad was carried out in single-leg stance. During the weeks three

to six all exercises were performed in single-leg stance. Sets were progressively increased to four during the weeks three and four, and to five sets during weeks five and six. The number of training sessions (12),^{36,37} the training frequency (two days per week),³⁸ the duration of training sessions (about 20 minutes),^{36,37} and the duration of each balance task (20 seconds)³⁶⁻³⁸ was based on previous studies. The control group received no sensorimotor training; however, participants were allowed to continue their usual sport activities.

Outcome measurements

Plantar foot sensitivity

Plantar cutaneous detection thresholds to light touch were measured at four locations of the foot sole of both feet using a set of 20 Semmes-Weinstein Monofilaments (SWM; Rehaforum MEDICAL GmbH, Elmshorn), which were considered reliable by Snyder et al.³⁹ with ICC values ranging from 0.61 to 0.85 for the intrarater reliability and 0.62 to 0.92 for the interrater reliability. The following locations were tested in a random order:

- Center of the big toe
- Head of the metatarsal I (MT I)
- Head of the metatarsal V (MT V)
- Center of the heel

Participants were tested in a well-lit quiet laboratory within the university. They were assessed in a prone position on a treatment bench with their feet off the end of the bench and were blinded to measurements. Locations were determined using the procedure reported by Perry⁴⁰ (Figure 3) at each measurement (baseline, post 6 weeks, follow-up) to ensure testing of the same points at the different measurements. Additionally, they were marked with a waterproof pen to avoid deviations from the test localization during testing. The calibrated monofilaments vary in diameter and provide a known target force [filament size = $\log(10 \times \text{force in milligrams})$]. They were applied perpendicular to the skin surface and pressed until bending to a C-shape. Plantar detection threshold to light touch at each location was determined using the 4-2-1 stepping algorithm.⁴¹ It was started with an intermediate

Figure 3. Determination of foot sole locations using the procedure described by Perry.⁴⁰

level (4.17 ± 1.48 g). Either the level was increased if the stimulus was not felt or decreased if the stimulus was felt by four steps until a turnaround point was reached. A level was considered valid when the participant detected at least two out of three trials. Then the level was increased or decreased by two steps until the next turnaround point was attained. Finally, the filaments were applied in single steps. If a level was not detected correctly for three times, then the next detected level above was accepted as the detection threshold for the tested localization. Randomized null-stimuli were included in the test to increase accuracy. Foot sole temperature was measured at each location using a calibrated infrared thermometer (Braun NTF 3000, no touch + forehead thermometer, Lausanne, Switzerland) before and after sensory testing. Furthermore, room temperature was controlled using a calibrated commercial thermometer.

Balance (single-leg stance)

Participants balanced in single-leg stance on their involved and uninvolved leg for 30 seconds on a force plate [Bertec Force Plate, Version 1.0.0. Bertec Corporation Columbus, Ohio (USA)]. Three-Dimensional ground reactions forces were sampled at 1000 Hz including an anti-aliasing filter of 500 Hz. Participants' eyes were open focusing on a spot on the wall that was about five meters in front of them. Their knee was slightly bent and their hands were resting on their iliac crests. They were not allowed to touch the ground with their contralateral foot or to touch the supporting lower extremity with any part of their contralateral lower extremity. Balance was measured by mean amplitudes of center of pressure (CoP), i.e. the average value over all data points recorded in a trial.⁴² Thereby, CoP displacements in anterior-posterior and medial-lateral directions were determined by summing the actual distance (m) between consecutive CoP locations in the respective direction.⁴³ Total CoP displacements (m) were determined by means of the Pythagorean theorem. Furthermore, the mean of center of pressure excursion velocity (CoPV) was calculated by dividing total CoP displacement by the total time of trial duration.⁴² CoP measurements were completed using the software Bertec Digital Acquire 4, (Version 4.0.11. Bertec Corporation Columbus, Ohio, USA). For each participant, data from second five to second 25 (20 seconds) out of one trial were used for further analysis.

Maximal isometric inversion and eversion muscle strength

Maximal isometric foot inversion and eversion forces of both feet were assessed using a belt-stabilized hand-held dynamometer (HHD; Commander™ Muscle Tester, JTECH Medical, Salt Lake City, USA) with participants lying on their side, with the measured foot off the end of the treatment bench and with the tibia of the tested leg secured with a non-elastic belt.⁴⁴ The participant's head and neck were supported by a foam therapy half roll. The knee was supported by a rolled towel at the medial side when measuring eversion force. The assessor stood close to the participant's tested foot. The treatment bench was adjusted to be level with the assessor's anterior iliac spine. The HHD was stabilized using a non-elastic belt that was vertically applied around

the forefoot of the participant and the foot of the tester. The belt was used for stabilization because of the probability that the forces produced by participants' would surpass the resisting force of the assessor, which is required to perform "make" tests accurately.⁴⁵

The foot was positioned at 10° of plantarflexion.⁴⁶ For testing foot eversion strength, the transducer of the hand-held dynamometer was placed at the lateral border of the forefoot directly below the fifth metatarsal head. For measuring foot inversion strength, the transducer of the hand-held dynamometer was positioned at the medial border of the forefoot directly below the first metatarsal head. The recorded force in Newton (N) was converted to torque and expressed as Newton-meters (Nm) by multiplying it by the corresponding lever arm (in meters).⁴⁷ The functional axis of rotation for eversion and inversion enters the front superior part of the talus on the medial side and crosses downwards to the lateral rearfoot.^{48,49} For testing inversion strength, the lever arm was defined as the distance between the first metatarsal head (dynamometer location) and the superior part of the sustentaculum tali, and for eversion strength between the fifth metatarsal head (dynamometer location) and the superior part of the cuboid.

Isometric "make" tests were performed.⁵⁰ During the make test, the participant exerts a maximal force against the HHD, that is stabilized by the examiner or a belt. In contrast, the break test is performed by the examiner pushing the HHD against the participant's limb until the participant's maximal muscular exertion is exceeded and the joint gives way. The participant held the contraction for three seconds.⁵¹ After one trial of a submaximal contraction was used to familiarize the participant with the task, three consecutive maximal contractions were completed by the participant and recorded by the assessor. The resting period between trials was about 10 sec. The participant was blinded to the results from all measurements. The mean of the three trials was used for further analysis.⁴⁷ The assessor and the participant were blinded to the results from previous measurements when performing the retests. All participants were measured barefoot. The foot (right/left) of the participant and the foot movement (inversion/

eversion) were assessed in a random order to avoid any effects of fatigue and learning. This testing procedure was preserved for the retests.

Functional instability of the ankle joint

Additionally to the CAIT score that was described before, the German version of the Foot and Ankle Outcome Score (FAOS) was used to assess the functional status of the ankle joint,⁵² according to the recommendations of the International Ankle Consortium.¹⁰

Statistical analysis

Data were examined for normal distribution using Shapiro-Wilk-tests and using histograms. The parametric distribution of data was confirmed. For continuous variables, within [pre vs. post 6 weeks vs. post 10 weeks] and between group differences [group TS vs. group SMS vs. control] were analyzed using repeated measures analysis of variance (ANOVA, $p < 0.05$). Greenhouse-Geisser correction was used, if the assumption of sphericity assessed by Mauchly's test was violated. For discrete variables, Friedman tests ($p < 0.05$) were used to test for differences within groups and Kruskal Wallis tests ($p < 0.05$) were performed to test for differences between groups. Post-hoc tests (t-tests for continuous variables and Wilcoxon signed-rank tests for discrete variables, $p < 0.05$) with Bonferroni correction were used for pairwise comparisons, respectively. The effect size was calculated using eta squared (η^2) and interpreted according to Cohen's approach, where $\eta^2 = 0.01$ represents a small effect, $\eta^2 = 0.06$ a moderate effect and $\eta^2 = 0.12$ a large effect.⁵³ Correlations between outcome-parameters from baseline measurements were analyzed using Spearman's rho ($p < 0.05$). Statistical analysis was conducted with commercial software (IBM SPSS Statistics 23.0).

Results

Participants included in the study

Nineteen participants (six females and 13 males) met the inclusion criteria and were included. Their mean age was 29 ($\pm$ SD 7) years, their mean height was 174 ($\pm$ SD 12) cm, their mean body mass was 76 ($\pm$ SD 12) kg, and their mean body mass index was 24 ($\pm$ SD 3) kg/m². Moreover, they regularly performed at least one session of sport per week at

study enrollment. Sport activities they carried out before initial injury and/or continued after initial injury are presented in Table 1.

Group characteristics

There were no differences between groups with respect to age, height, body mass and BMI at baseline measurement ($p \geq 0.05$). The distribution of females and males differed between groups (Table 1). The mean CAIT score in the control group was increased compared to the training groups, however, this was not statistically significant ($p \geq 0.05$).

Training effects

All participants in both training groups completed the intervention as planned. No significant between-group differences in all outcome measures were detected. However, a significant increase of strength in eversion was found for the training group using textured surfaces after 10 weeks ($p = 0.01$, $\eta^2 = 0.46$) (Figure 4).

Correlations between outcome measurements at baseline

A moderate correlation existed between plantar detection threshold of metatarsal head (MT) I and strength in inversion ($r = 0.51$, $p < 0.05$) before training across all groups. There were moderate negative correlations between balance parameters and strength in eversion [r_s (range) = -0.57 to -0.64 (anterior-posterior displacement), $p \leq 0.01$] as well as plantar detection thresholds at MT V [r_s (range) = -0.48 to -0.62 (anterior-posterior displacement), $p < 0.05$]. Descriptive statistics are presented in Table 2.

Foot sole temperature

Mean foot sole temperature of each location and measurement is demonstrated in Table 3. Mean room temperature during measurements was 23.8 (± 1.1)°C at baseline, 23.9 (± 1.2)°C after six weeks and 23.4 (± 1.0)°C after 10 weeks. No significant differences were found between groups at each measurement for foot sole temperature as well as for room temperature ($p > 0.05$).

Post hoc power analysis

A post hoc power analysis (G*Power 3.1.9.2.) on the basis of $\alpha < 0.05$, the identified effect size for ankle

Table 1. Demographic data of the participants of the current study. Age, height, body mass and BMI are demonstrated as means ($\pm$ SD). CAIT-scores are presented as medians (1st quartile; 3rd quartile). Sport activities participants carried out before initial injury (pre) and/or continued after initial injury (post) are shown as numbers (n); multiple nominations were allowed.

Characteristics	Group SMS	Group TS	Control group	Total
N	7	6	6	19
Female	4	0	2	6
Male	3	6	4	13
Age (years)	30.0 (6.83)	29.83 (8.18)	26.67 (6.22)	28.89 (6.88)
Height (m)	1.70 (0.15)	1.79 (0.04)	1.75 (0.12)	1.74 (0.12)
Body mass (kg)	74.86 (17.02)	78.5 (9.29)	73.67 (9.27)	75.63 (12.19)
BMI (kg/m ²)	25.9 (4.49)	24.39 (2.59)	24.36 (3.98)	24.44 (3.0)
CAIT-score	19 (11; 21)	18 (15; 22)	22 (19; 24)	19 (16; 23)
Sport activities				
Badminton (pre/post)				n=9/ n=8
Football/soccer (pre/post)				n=4/ n=2
Fitness (pre/post)				n=4/ n=7
Running (pre/post)				n=2/ n=3
Volleyball (pre/post)				n=1/ n=1
Table tennis (pre/post)				n=1/ n=1

Figure 4. Differences ($p < 0.05$) in mean eversion muscle strength within- and between- groups pre, post 6 and post 10 weeks of sensorimotor training. Error bars represent standard deviations (SD). SMS: Smooth surface; TS: Textured surface

Table 2. Outcome measurements of different groups before intervention, after 6 weeks of sensorimotor training and at follow up after 10 weeks. Center of pressure excursions in different directions and eversion and inversion muscle strength are presented as mean ($\pm$ SD). Plantar sensitivity thresholds at different locations and joint function measured by the questionnaires CAIT and FAOS are presented as median (1st quartile; 3rd quartile).

Outcomes	SMS Group			TS Group			Control Group		
	Baseline	Post 6 weeks	Post 10 weeks	Baseline	Post 6 weeks	Post 10 weeks	Baseline	Post 6 weeks	Post 10 weeks
CoP total path (m)	1.5 (0.28)	1.41 (0.3)	1.43 (0.27)	1.5 (0.22)	1.42 (0.13)	1.4 (0.18)	1.65 (0.27)	1.59 (0.27)	1.6 (0.2)
CoP ant/post (m)	1.09 (0.21)	1.04 (0.23)	1.05 (0.22)	1.04 (0.14)	1.01 (0.11)	1.02 (0.12)	1.13 (0.19)	1.1 (0.18)	1.12 (0.16)
CoP med/lat (m)	0.81 (0.14)	0.76 (0.15)	0.77 (0.13)	0.84 (0.13)	0.79 (0.09)	0.77 (0.1)	0.9 (0.14)	0.86 (0.16)	0.86 (0.11)
CoPV (m/s)	0.08 (0.01)	0.07 (0.02)	0.07 (0.01)	0.08 (0.01)	0.07 (0.01)	0.07 (0.01)	0.08 (0.01)	0.08 (0.01)	0.08 (0.01)
Eversion muscle strength (Nm)	16.5 (4.4)	19.7 (4.5)	20.5 (5.5)	17.0 (5.5)	19.8 (4.7)	21.9 (4.6)*	15.5 (6.0)	15.8 (6.9)	18.9 (5.4)
Inversion muscle strength (Nm)	15.0 (4.9)	16.3 (6.4)	18.0 (7.4)	18.8 (3.6)	19.5 (3.0)	21.1 (3.8)	14.2 (6.0)	15.8 (7.8)	18.0 (7.2)
Plantar sensitivity (Heel)	3.61 (3.61; 4.08)	3.61 (3.42; 3.96)	3.61 (3.61; 4.09)	3.73 (3.61; 4.09)	3.61 (3.32; 4.32)	3.61 (3.32; 4.14)	3.61 (3.61; 3.61)	3.42 (3.22; 3.61)	3.61 (3.61; 3.61)
Plantar sensitivity (MT I)	3.61 (3.61; 4.31)	3.61 (3.22; 3.96)	3.61 (3.22; 4.44)	3.73 (3.61; 4.09)	3.61 (3.32; 3.61)	3.42 (3.22; 3.61)	3.61 (3.32; 3.61)	3.61 (3.32; 3.61)	3.61 (3.32; 3.61)
Plantar sensitivity (MT V)	3.61 (3.42; 4.09)	2.83 (2.83; 4.09)	3.61 (3.03; 4.09)	3.61 (3.61; 3.61)	3.61 (3.32; 4.32)	3.61 (3.61; 3.61)	3.22 (3.22; 3.51)	3.61 (3.61; 3.61)	3.61 (3.61; 3.61)
Plantar sensitivity (Great toe)	3.61 (3.61; 4.20)	3.61 (2.83; 3.61)	3.61 (3.22; 3.85)	3.61 (3.32; 3.78)	3.42 (3.22; 3.61)	3.22 (2.83; 3.61)	3.22 (2.93; 3.22)	3.42 (2.93; 3.61)	3.42 (2.93; 3.61)
CAIT	19 (11; 21)	19 (17; 25)	17 (15; 25)	18 (15; 22)	21 (19; 22)	24 (19; 27)	22 (19; 24)	22 (19; 24)	23 (19; 27)
FAOS symptoms	78.57 (66.07; 83.93)	82.14 (73.22; 89.20)	75.00 (67.86; 96.43)	87.50 (80.36; 97.23)	87.50 (79.46; 98.22)	89.29 (82.14; 96.43)	87.50 (80.36; 89.29)	89.29 (78.57; 94.65)	92.86 (76.79; 98.22)
FAOS pain	86.11 (84.03; 93.06)	97.22 (81.95; 98.61)	80.56 (80.56; 100.00)	95.83 (90.28; 97.22)	93.06 (86.81; 99.31)	98.61 (88.89; 100.00)	95.83 (94.44; 99.31)	93.10 (89.61; 94.44)	98.61 (95.41; 100.00)
FAOS ADL	89.71 (86.76; 96.33)	100.00 (89.71; 100.00)	98.53 (90.44; 100.00)	99.27 (97.43; 100.00)	99.27 (98.53; 100.00)	97.06 (93.75; 100.00)	97.80 (94.86; 99.63)	99.27 (95.22; 100.00)	100.00 (98.90; 100.00)
FAOS Sport	75.00 (65.00; 85.00)	90.00 (75.00; 97.50)	85.00 (70.00; 97.50)	97.50 (80.00; 100.00)	92.50 (82.50; 98.75)	95.00 (78.75; 100.00)	90.00 (82.50; 93.75)	90.00 (85.00; 95.00)	100.00 (96.25; 100.00)
FAOS QoL	68.75 (53.13; 78.13)	75.00 (59.38; 85.00)	75.00 (53.13; 93.75)	81.25 (60.94; 87.50)	78.13 (65.63; 95.31)	87.50 (71.88; 98.44)	75.00 (54.69; 90.36)	81.25 (62.50; 81.25)	78.13 (60.94; 95.31)

*Significant difference within the group TS between Post 6 weeks and Post 10 weeks ($p=0.017$).

SMS: Smooth surface; TS: Textured surface; CoP: Center of pressure; MT I: Metatarsal head I; MT V: Metatarsal head V; CAIT: Cumberland Ankle Instability Tool;

FAOS: Foot and ankle outcome score; ADL: Activities of daily living; QoL: Quality of life

Table 3. Mean ($\pm$ SD) foot sole temperature ($^{\circ}$ C) at each location and time point ($n = 19$).

Foot sole location	Baseline	After 6 weeks	After 10 weeks
Heel	27.7 (2.8)	28.1 (3.3)	27.0 (3.5)
Metatarsal Head I	27.6 (3.0)	28.3 (3.5)	27.5 (3.5)
Metatarsal Head V	27.4 (2.8)	28.4 (3.3)	27.0 (3.6)
Great toe	26.3 (4.1)	27.1 (4.3)	26.0 (4.3)

eversion strength ($\eta^2 = 0.46$, i.e., $f = 0.92$) from repeated measures ANOVA (within factors), and a sample size of $n = 19$, revealed a test power of 100%.

DISCUSSION

To the best of the authors' knowledge, this was the first study exploring the influence of sensorimotor training on unstable textured surfaces on balance, strength, joint function and plantar foot sensitivity in participants with a history of ankle sprain and a self-reported feeling of ankle instability. The main finding was that no significant between-group differences in all outcome measures existed after

six weeks of training. However, eversion muscle strength significantly increased after sensorimotor training using unstable textured surfaces at the 10-week follow-up. Furthermore, increased eversion muscle strength was related to a better score on balance testing and decreased plantar cutaneous sensation to light touch before intervention.

Muscle strength

Authors have noted that balance training might have immediate effects on eversion and inversion muscle strength.⁵⁴ In the present study, eversion and inversion muscle strength did not differ between groups after the intervention and at follow-up, which was consistent with previously reported findings.³⁰ However, the significant increase of eversion muscle strength at the 10-week follow-up, but not at six weeks, in the group TS might indicate that a sensorimotor training on unstable textured surfaces potentially leads to a prolonged neuromuscular adaptation resulting in increased peroneal muscle strength. Accordingly,

it has been shown that cutaneous touch/pressure sensation is important for isometric ankle force control.²⁵ Furthermore, an acute local pressure at the lateral border of the foot using a sensorimotor insole increased muscle activity of the peroneus longus in loading response and mid-stance phases of walking.⁵⁵ A textured insert decreased muscular activation of the soleus and tibialis anterior during locomotion.⁵⁶ Therefore, pressures applied to the foot sole may alter sensory feedback⁵⁶ or even increase afferent information.⁵⁵ Thereby, firing of the most sensitive fast adapting receptors is responsible for the transmission of afferent information during balance and locomotor tasks.⁵⁷ A slight non-significant improvement was also detected for the other groups that might have been explained by a learning effect due to the repetition of the strength measurements after six and 10 weeks. However, previous authors have not reported significantly different values of eversion and inversion muscle strength using an HHD when measurements were repeated at the following day.^{44,58} Moreover, participants in the control group may have been increasingly motivated to achieve high force values.

Eversion and inversion isometric muscle strength values found in the subjects of the present study are comparable to those from patients with chronic ankle instability reported by Hall et al.⁵⁹ They measured 157.2 to 187.5 N for inversion as well as 141.2 to 175.5 N for eversion using an HHD with participants lying on their side. The original values of the present study without consideration of the lever arm in the calculation ranged from 155 to 219 N for eversion and from 142 N to 211 N for inversion. The higher values above 210 N compared to those from Hall et al.⁵⁹ may be explained by the belt-stabilization of the HHD. Hall et al.⁵⁹ provided manual resistance to the ankle. In HHD measurements, the strength of the assessor to withstand the force generated by the tested person is a decisive factor. When forces above 120 N are applied, the tester's strength seems to regulate the extent of the forces assessed with the HHD.⁶⁰ This may lead to an underestimation of muscle strength.

Postural control

No statistically significant differences were found within and between groups for all balance outcomes.

However, the SMS and TS groups showed a slight non-significant improvement of the total CoP displacement, the medial-lateral and anterior-posterior displacement as well as the mean CoP velocity after six and after 10 weeks. As the control group demonstrated a slight improvement as well and the changes were within the range of measurement error, a causal relationship between intervention and these improvements could not be concluded. Moreover, a learning effect rather than a training effect was more likely here.³⁰ It was previously hypothesized, that wearing textured insoles during single-leg stance results in a reduced ability of the sensorimotor system to reweight sensory feedback available to keep single-leg stance.⁶¹ This is potentially caused by changed information from cutaneous receptors of the foot sole due to the textured surface. Furthermore, individuals with chronic ankle instability seem to increasingly rely on sensory information, i.e. plantar cutaneous receptors, during single-leg stance. Although not assessed within the current study, it may be possible, that weekly repetitions of plantar stimulation during sensorimotor training in those with a feeling of ankle instability using a textured surface may lead to an increase of the ability of the sensorimotor system to reweight sensory input available to maintain balance.

The results of the present study are difficult to compare with previous study results, because different study designs, training regimes and parameters of CoP measurements were used. Sefton et al.²⁸ found no significant changes in total CoP path length and average CoP displacement after a six-week sensorimotor training, where participants with chronic ankle instability completed three sessions per week. Furthermore, they did not find a significant difference in these outcomes compared with healthy controls. Mettler et al.⁶² demonstrated that the CoP location under the foot shifted posteriorly after four weeks of balance training, that was performed three times per week, in those with chronic ankle instability compared to affected controls. They concluded that there is a recovery of impaired sensorimotor pathways that is induced by the balance training.

In the study by Freyler et al.⁶³ mean medial-lateral CoP displacements ranged from 94.6 (± 25.6) cm to 118.6 (± 24.4) cm compared to 0.76 $\pm$ 0.15 m (76 $\pm$ 15

cm) to 0.9 ± 0.14 m (90 ± 14 cm) in the present study. Freyler et al.⁶³ reported mean anterior-posterior CoP displacements ranging from $82.5 (\pm 11.7)$ cm to $102.1 (\pm 21.4)$ cm compared to 1.01 ± 0.11 m (101 ± 11 cm) to 1.13 ± 0.19 m (113 ± 19 cm) in the present study. The values for anterior-posterior CoP displacement were remarkably higher in the present study compared with those of Freyler et al.,⁶³ although the time of single-leg stance was 10 seconds less. However, it was not reported by the authors, from where healthy participants were recruited. Furthermore, no information about the participants' level of performance (e.g. elite, non-elite) was provided. Linens et al.⁶⁴ investigated the mean CoP excursions in medial-lateral and anterior-posterior directions as well as the mean CoP anterior-posterior and medial-lateral velocity using a force plate in people with chronic ankle instability and healthy controls. Their values were considerably decreased compared with the values found in the present study, although the time of single-leg stance was the same. Reasons for these differences might have been, that in the present study one trial was used for analysis compared to Linens et al.,⁶⁴ who used the mean out of three trials for their analysis. A learning effect between trials and previous balance tests performed in their study might have led to significantly reduced excursions. Additionally, settings at which force data were collected might have differed.

Plantar foot sensitivity

No significant changes of plantar cutaneous thresholds were found within and between groups after the intervention. The thresholds are mainly comparable to those of participants classified as copers and participants with chronic ankle instability, except for the measurement at the heel.⁶⁵ Copers are those who have sprained their ankle but have no perception of instability or repeated episodes of giving way and had continued activities without restriction for at least 12 months.^{65,66} Furthermore, copers are considered to demonstrate a CAIT score >24 .⁶⁷ The 4-2-1 stepping algorithm for sensation testing was also used by Burcal & Wikstrom,⁶⁵ however, a median threshold of 4.17 at the heel at baseline for those with chronic ankle instability was reported compared to 3.61/3.73 in the current study. Accordingly, two participants in the present study had a

CAIT score >24 (27 and 26) before intervention and may be classified as copers according to previously reported classifications.^{67,68} Powell et al.²⁴ found higher thresholds in participants with chronic ankle instability, ranging from a median of 4.08 for MT I to 4.56 for the heel. Interestingly, the thresholds of not affected participants in their study were similar to those of the participants in the present study. Furthermore, the thresholds in the current study were slightly lower as compared to those of healthy 20 to 30 year old people.⁴⁰ However, Perry⁴⁰ used a set of six monofilaments which is considered less sensitive compared to the set containing 20 monofilaments. There may have been other factors, such as time of day and gait activity⁶⁹ that could have influenced results of sensory testing. Although, Semmes-Weinstein monofilament testing is considered reliable and valid,⁷⁰ it may be questionable, whether it is sensitive enough to detect small differences and changes of plantar sensation in people with a history of ankle sprain and a feeling of instability.

Grade of severity of functional instability and foot function

No significant changes within and between groups were found for CAIT scores as well as for FAOS-scores. However, the greatest positive change of CAIT scores was observed in the group TS (three scores improved after six weeks and six scores after 10 weeks). As previously reported, four or six weeks of balance training resulted in improved CAIT scores, other activities of daily living related questionnaires and functional tests in people with chronic ankle instability.^{71,72} The sample size was considerably higher in both studies ($n=40^{72}$ and $n=70^{71}$). Wright et al.⁷² and Cruz-Diaz et al.⁷¹ performed the training sessions three times per week. Cruz-Diaz et al.⁷¹ used a multi-station program with a variety of exercises. This may indicate, that the number of sessions per week and the variety of exercises might have been too low in the present study.

Correlations between outcome parameters

Moderate correlations between plantar detection thresholds at MT I, MT V and the heel and muscle strength in eversion and inversion may indicate that a decreased sensitivity was related to an increased muscle strength. Usually it may be expected that

a higher sensitivity to light touch is correlated to a higher muscle strength. However, the findings here indicate the opposite or a negative correlation. A decreased sensitivity with a reduced feedback of cutaneous afferents may lead to an increased eversion and inversion muscle strength needed to compensate for the reduced cutaneous feedback in people with a history of ankle sprain and a feeling of instability in order to protect the ankle in situations of sudden ankle perturbations. However, reflex reaction to sudden inversion was not investigated in this study. Furthermore, reflex reaction to sudden ankle inversion is considered to be too slow to protect the ankle.⁷³ Therefore, the correlation between plantar sensory feedback and the change of motoneuron pool excitability²⁸ as well as rate of force development in a maximal voluntary muscle contraction⁷⁴ need to be explored more in a future study comparing the effects of sensorimotor training using different unstable surfaces in this population.

The moderate negative correlations between muscle strength in eversion and the CoP- parameters indicate that the higher eversion muscle strength the smaller the CoP displacement and velocity, i.e. the better balance ability. It appears, that participants with chronic ankle instability and copers use balance control strategies, where eversion muscle strength is primarily involved. Accordingly, the high relevance of eversion muscles in postural control has been confirmed previously.³⁴ Participants with chronic ankle instability and copers showed an increased muscle activation of the peroneus longus and tibialis anterior during the star excursion balance test compared with healthy controls. Thereby, muscle activation was even higher in copers than in participants with chronic ankle instability, indicating, that they use a fully developed strategy of increased muscle activation to compensate for loss of stability, usually provided by capsule and ligaments.

The negative correlation between plantar cutaneous threshold at MT V and balance parameters indicated that a decreased sensitivity was related to an increased balance ability. These findings were contrary to findings from the literature and difficult to explain.²⁴ However, the mean of time-to-boundary minima in anterior-posterior direction was measured and moderately correlated to plantar

cutaneous sensitivity. The results of the present study may suggest that decreased plantar sensitivity at MT V may lead to decreased CoP displacements as a result of increased muscle activation that may result in higher eversion and inversion strength.

Limitations of the study

There are limitations of the study that need to be addressed. As this was a pilot study, the sample was small and the group sizes were partially unequal. Therefore, the groups might not have been as comparable and generalizability of the results cannot be concluded. Furthermore, results should be considered with caution because two participants demonstrated a CAIT score >24, four participants had a history of ankle or foot fracture with surgery within two years and one participant had sustained a medial ankle sprain. The sensorimotor training might have led to adaptations of the central nervous system that could not be assessed with the measurement instruments used in the current study. In a previous study was found that balance training was able to restore the ability to modulate the excitability of motoneuron pools,⁷⁵ which is necessary to adjust to a changing environment.⁷⁶ The restoration process may need time and may become visible only after more than six weeks of training, because established control strategies have to change or new compensation strategies have to develop. Accordingly, it has been shown that CoP displacements in single-leg stance even slightly increased after six weeks of balance training.²⁸ Therefore, the period and intensity of sensorimotor training may have to be increased in future studies.

CONCLUSION

A six-week sensorimotor training using unstable smooth and textured surfaces demonstrated no significant differences in balance, strength in eversion and inversion, plantar foot sensitivity and self-reported ankle instability between training groups and the control group in recreational athletes with a history of ankle sprain. However, a better score on balance testing seems to correlate with an increase in eversion ankle strength and a decreased plantar sensitivity at MT V before a sensorimotor training. Future studies incorporating inclusion criteria of the CAIT score ≤24 used by Gribble et al,¹⁰ no fracture

with or without surgery, and only lateral ankle sprain should be considered for a robust controlled trial of homogenous participants.

REFERENCES

1. Waterman BR, Owens BD, Davey S, Zacchilli MA, Belmont PJ, Jr. The epidemiology of ankle sprains in the United States. *J Bone Joint Surg Am*. 2010;92(13):2279-2284.
2. Gerber JP, Williams GN, Scoville CR, Arciero RA, Taylor DC. Persistent disability associated with ankle sprains: a prospective examination of an athletic population. *Foot Ankle Int*. 1998;19(10):653-660.
3. Yeung MS, Chan KM, So CH, Yuan WY. An epidemiological survey on ankle sprain. *Br J Sports Med*. 1994;28(2):112-116.
4. Graff GD. Ankle sprain. In: *Klippel J, Dieppe P. Rheumatology*. London: Mosby;1998.
5. Anandacoomarasamy A, Barnsley L. Long term outcomes of inversion ankle injuries. *Br J Sports Med*. 2005;39(3):e14; discussion e14.
6. Eechaute C, Vaes P, Van Aerschot L, Asman S, Duquet W. The clinimetric qualities of patient-assessed instruments for measuring chronic ankle instability: a systematic review. *BMC Musculoskelet Disord*. 2007;8:6.
7. Delahunt E, Coughlan GF, Caulfield B, Nightingale EJ, Lin CW, Hiller CE. Inclusion criteria when investigating insufficiencies in chronic ankle instability. *Med Sci Sports Exerc*. 2010;42(11):2106-2121.
8. Hertel J. Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. *J Athl Train*. 2002;37(4):364-375.
9. Arnold BL, Wright CJ, Ross SE. Functional ankle instability and health-related quality of life. *J Athl Train*. 2011;46(6):634-641.
10. 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. *J Orthop Sports Phys Ther*. 2013;43(8):585-591.
11. Sefton JM, Hicks-Little CA, Hubbard TJ, et al. Sensorimotor function as a predictor of chronic ankle instability. *Clin Biomech*. 2009;24(5):451-458.
12. Lofvenberg R, Karrholm J, Sundelin G, Ahlgren O. Prolonged reaction time in patients with chronic lateral instability of the ankle. *Am J Sports Med*. 1995;23(4):414-417.
13. Vaes P, Duquet W, Van Gheluwe B. Peroneal reaction times and eversion motor response in healthy and unstable ankles. *J Athl Train*. 2002;37(4):475-480.
14. Konradsen L. Factors contributing to chronic ankle instability: kinesthesia and joint position sense. *J Athl Train*. 2002;37(4):381-385.
15. Riemann BL. Is there a link between chronic ankle instability and postural instability? *J Athl Train*. 2002;37(4):386-393.
16. Kaminski TW, Hartsell HD. Factors contributing to chronic ankle instability: a strength perspective. *J Athl Train*. 2002;37(4):394-405.
17. Fox J, Docherty CL, Schrader J, Applegate T. Eccentric plantar-flexor torque deficits in participants with functional ankle instability. *J Athl Train*. 2008;43(1):51-54.
18. Hartsell HD, Spaulding SJ. Eccentric/concentric ratios at selected velocities for the invertor and evertor muscles of the chronically unstable ankle. *Br J Sports Med*. 1999;33(4):255-258.
19. Kaminski TW, Perrin DH, Gansneder BM. Eversion strength analysis of uninjured and functionally unstable ankles. *J Athl Train*. 1999;34(3):239-245.
20. Munn J, Beard DJ, Refshauge KM, Lee RY. Eccentric muscle strength in functional ankle instability. *Med Sci Sports Exerc*. 2003;35(2):245-250.
21. Ryan L. Mechanical stability, muscle strength and proprioception in the functionally unstable ankle. *Aust J Physiother*. 1994;40(1):41-47.
22. Freeman MA, Dean MR, Hanham IW. The etiology and prevention of functional instability of the foot. *J Bone Joint Surg Br*. 1965;47(4):678-685.
23. Hoch MC, McKeon PO, Andreatta RD. Plantar vibrotactile detection deficits in adults with chronic ankle instability. *Med Sci Sports Exerc*. 2012;44(4):666-672.
24. Powell MR, Powden CJ, Houston MN, Hoch MC. Plantar cutaneous sensitivity and balance in individuals with and without chronic ankle instability. *Clin J Sport Med*. 2014;24(6):490-496.
25. Choi JT, Lundbye-Jensen J, Leukel C, Nielsen JB. Cutaneous mechanisms of isometric ankle force control. *Exp Brain Res*. 2013;228(3):377-384.
26. McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part II: is balance training clinically effective? *J Athl Train*. 2008;43(3):305-315.
27. David P, Halimi M, Mora I, Doutrelot PL, Petitjean M. Isokinetic testing of evertor and invertor muscles in patients with chronic ankle instability. *J Appl Biomech*. 2013;29(6):696-704.
28. 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. *J Orthop Sports Phys Ther*. 2011;41(2):81-89.

-
29. Kidgell DJ, Horvath DM, Jackson BM, Seymour PJ. Effect of six weeks of dura disc and mini-trampoline balance training on postural sway in athletes with functional ankle instability. *J Strength Cond Res*. 2007;21(2):466-469.
 30. Hupperets MD, Verhagen EA, van Mechelen W. Effect of sensorimotor training on morphological, neurophysiological and functional characteristics of the ankle: a critical review. *Sports Med*. 2009;39(7):591-605.
 31. Alfuth M, Rosenbaum D. Effects of changes in plantar sensory feedback on human gait characteristics: a systematic review. *Footwear Science*. 2012;4(1):1-22.
 32. Gehring D, Faschian K, Lauber B, Lohrer H, Nauck T, Gollhofer A. Mechanical instability destabilises the ankle joint directly in the ankle-sprain mechanism. *Br J Sports Med*. 2014;48(5):377-382.
 33. Hiller CE, Refshauge KM, Bundy AC, Herbert RD, Kilbreath SL. The cumberland ankle instability tool: a report of validity and reliability testing. *Arch Phys Med Rehabil*. 2006;87(9):1235-1241.
 34. Pozzi F, Moffat M, Gutierrez G. Neuromuscular control during performance of a dynamic balance task in subjects with and without ankle instability. *Int J Sports Phys Ther*. 2015;10(4):520-529.
 35. Abbott JH. The distinction between randomized clinical trials (RCTs) and preliminary feasibility and pilot studies: what they are and are not. *J Orthop Sports Phys Ther*. 2014;44(8):555-558.
 36. Eils E, Schroter R, Schroder M, Gerss J, Rosenbaum D. Multistation proprioceptive exercise program prevents ankle injuries in basketball. *Med Sci Sports Exerc*. 2010;42(11):2098-2105.
 37. McKeon PO, Ingersoll CD, Kerrigan DC, Saliba E, Bennett BC, Hertel J. Balance training improves function and postural control in those with chronic ankle instability. *Med Sci Sports Exerc*. 2008;40(10):1810-1819.
 38. Gruber M, Gollhofer A. Impact of sensorimotor training on the rate of force development and neural activation. *Eur J Appl Physiol*. 2004;92(1-2):98-105.
 39. Snyder BA, Munter AD, Houston MN, Hoch JM, Hoch MC. Interrater and intrarater reliability of the semmes-weinstein monofilament 4-2-1 stepping algorithm. *Muscle Nerve*. 2016;53(6):918-924.
 40. Perry SD. Evaluation of age-related plantar-surface insensitivity and onset age of advanced insensitivity in older adults using vibratory and touch sensation tests. *Neurosci Lett*. 2006;392(1-2):62-67.
 41. Dyck PJ, O'Brien PC, Kosanke JL, Gillen DA, Karnes JL. A 4, 2, and 1 stepping algorithm for quick and accurate estimation of cutaneous sensation threshold. *Neurology*. 1993;43(8):1508-1512.
 42. Palmieri RM, Ingersoll CD, Stone MB, Krause BA. Center-of-pressure parameters used in the assessment of postural control. *J Sport Rehabil*. 2002;11:51-66.
 43. Hufschmidt A, Dichgans J, Mauritz KH, Hufschmidt M. Some methods and parameters of body sway quantification and their neurological applications. *Arch Psychiatr Nervenkr (1970)*. 1980;228(2):135-150.
 44. Alfuth M, Hahm MM. Reliability, comparability, and validity of foot inversion and eversion strength measurements using a hand-held dynamometer. *Int J Sports Phys Ther*. 2016;11(1):72-84.
 45. Koblbauer IF, Lambrecht Y, van der Hulst ML, et al. Reliability of maximal isometric knee strength testing with modified hand-held dynamometry in patients awaiting total knee arthroplasty: useful in research and individual patient settings? A reliability study. *BMC Musculoskelet Disord*. 2011;12:249.
 46. Cawthorn M, Cummings GS, Walker JR, Donatelli RA. Isokinetic measurement of foot invertor and evertor force in three positions of plantarflexion and dorsiflexion. *J Orthop Sports Phys Ther*. 1991;14(2):75-81.
 47. Hebert LJ, Remec JF, Saulnier J, Vial C, Puymirat J. The use of muscle strength assessed with handheld dynamometers as a non-invasive biological marker in myotonic dystrophy type 1 patients: a multicenter study. *BMC Musculoskelet Disord*. 2010;11:72.
 48. Oatis CA. Biomechanics of the foot and ankle under static conditions. *Phys Ther*. 1988;68(12):1815-1821.
 49. Pretterklieber ML. [Anatomy and kinematics of the human ankle joint]. *Radiologe*. 1999;39(1):1-7.
 50. Stratford PW, Balsor BE. A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. *J Orthop Sports Phys Ther*. 1994;19(1):28-32.
 51. Docherty CL, Moore JH, Arnold BL. Effects of strength training on strength development and joint position sense in functionally unstable ankles. *J Athl Train*. 1998;33(4):310-314.
 52. van Bergen CJ, Sierrevelt IN, Hoogervorst P, Waizy H, van Dijk CN, Becher C. Translation and validation of the German version of the foot and ankle outcome score. *Arch Orthop Trauma Surg*. 2014;134(7):897-901.
 53. Cohen J. Statistical power analysis for the behavioral sciences (2nd ed.). Lawrence Erlbaum: New Jersey. 1988.
 54. Kim KJ, Jun HJ, Heo M. Effects of Nintendo Wii Fit Plus training on ankle strength with functional ankle instability. *J Phys Ther Sci*. 2015;27(11):3381-3385.
 55. Ludwig O, Kelm J, Frohlich M. The influence of insoles with a peroneal pressure point on the electromyographic activity of tibialis anterior and peroneus longus during gait. *J Foot Ankle Res*. 2016;9(1):33.
-

-
56. Nurse MA, Hulliger M, Wakeling JM, Nigg BM, Stefanyshyn DJ. Changing the texture of footwear can alter gait patterns. *J Electromyogr Kinesiol.* 2005;15(5):496-506.
 57. Strzalkowski ND, Mildren RL, Bent LR. Thresholds of cutaneous afferents related to perceptual threshold across the human foot sole. *J Neurophysiol.* 2015;114(4):2144-2151.
 58. Kelln BM, McKeon PO, Gontkof LM, Hertel J. Hand-held dynamometry: reliability of lower extremity muscle testing in healthy, physically active, young adults. *J Sport Rehabil.* 2008;17(2):160-170.
 59. Hall EA, Docherty CL, Simon J, Kingma JJ, Klossner JC. Strength-training protocols to improve deficits in participants with chronic ankle instability: a randomized controlled trial. *J Athl Train.* 2015;50(1):36-44.
 60. Wikholm JB, Bohannon RW. Hand-held dynamometer measurements: tester strength makes a difference. *J Orthop Sports Phys Ther.* 1991;13(4):191-198.
 61. McKeon PO, Stein AJ, Ingersoll CD, Hertel J. Altered plantar-receptor stimulation impairs postural control in those with chronic ankle instability. *J Sport Rehabil.* 2012;21(1):1-6.
 62. Mettler A, Chinn L, Saliba SA, McKeon PO, Hertel J. Balance training and center-of-pressure location in participants with chronic ankle instability. *J Athl Train.* 2015;50(4):343-349.
 63. Freyler K, Krause A, Gollhofer A, Ritzmann R. Specific stimuli induce specific adaptations: sensorimotor training vs. reactive balance training. *PLoS One.* 2016;11(12):e0167557.
 64. 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.
 65. Burcal CJ, Wikstrom EA. Plantar cutaneous sensitivity with and without cognitive loading in people with chronic ankle instability, copers, and uninjured controls. *J Orthop Sports Phys Ther.* 2016;46(4):270-276.
 66. Wright CJ, Arnold BL, Ross SE. Altered kinematics and time to stabilization during drop-jump landings in individuals with or without functional ankle instability. *J Athl Train.* 2016;51(1):5-15.
 67. Doherty C, Bleakley C, Hertel J, Caulfield B, Ryan J, Delahunt E. Single-leg drop landing movement strategies in participants with chronic ankle instability compared with lateral ankle sprain 'copers'. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(4):1049-1059.
 68. Wright CJ, Arnold BL, Ross SE, Linens SW. Recalibration and validation of the cumberland ankle instability tool cutoff score for individuals with chronic ankle instability. *Arch Phys Med Rehabil.* 2014;95(10):1853-1859.
 69. Alfuth M, Rosenbaum D. Are diurnal changes in foot sole sensation dependent on gait activity? *Neurosci Lett.* 2011;504(3):247-251.
 70. Jerosch-Herold C. Assessment of sensibility after nerve injury and repair: a systematic review of evidence for validity, reliability and responsiveness of tests. *J Hand Surg Br.* 2005;30(3):252-264.
 71. Cruz-Diaz D, Lomas-Vega R, Osuna-Perez MC, Contreras FH, Martinez-Amat A. Effects of 6 weeks of balance training on chronic ankle instability in athletes: a randomized controlled trial. *Int J Sports Med.* 2015;36(9):754-760.
 72. Wright CJ, Linens SW, Cain MS. A randomized controlled trial comparing rehabilitation efficacy in chronic ankle instability. *J Sport Rehabil.* 2017;26(4):238-249.
 73. Konradsen L, Voigt M, Hojsgaard C. Ankle inversion injuries. The role of the dynamic defense mechanism. *Am J Sports Med.* 1997;25(1):54-58.
 74. Gruber M, Gruber SB, Taube W, Schubert M, Beck SC, Gollhofer A. Differential effects of ballistic versus sensorimotor training on rate of force development and neural activation in humans. *J Strength Cond Res.* 2007;21(1):274-282.
 75. Trimble MH, Koceja DM. Modulation of the triceps surae H-reflex with training. *Int J Neurosci.* 1994;76(3-4):293-303.
 76. Sefton JM, Hicks-Little CA, Koceja DM, Cordova ML. Modulation of soleus H-reflex by presynaptic spinal mechanisms during varying surface and ankle brace conditions. *Neurophysiol Clin.* 2007;37(1):15-21.