

# Noise-Enhanced Eversion Force Sense in Ankles With or Without Functional Instability

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**Context:** Force sense impairments are associated with functional ankle instability. Stochastic resonance stimulation (SRS) may have implications for correcting these force sense deficits.

**Objective:** To determine if SRS improved force sense.

**Design:** Case-control study.

**Setting:** Research laboratory.

**Patients or Other Participants:** Twelve people with functional ankle instability (age = 23 ± 3 years, height = 174 ± 8 cm, mass = 69 ± 10 kg) and 12 people with stable ankles (age = 22 ± 2 years, height = 170 ± 7 cm, mass = 64 ± 10 kg).

**Intervention(s):** The eversion force sense protocol required participants to reproduce a targeted muscle tension (10% of maximum voluntary isometric contraction). This protocol was assessed under SRS<sub>on</sub> and SRS<sub>off</sub> (control) conditions. During SRS<sub>on</sub>, random subsensory mechanical noise was applied to the lower leg at a customized optimal intensity for each participant.

**Main Outcome Measure(s):** Constant error, absolute error, and variable error measures quantified accuracy, overall performance, and consistency of force reproduction, respectively.

**Results:** With SRS, we observed main effects for force sense absolute error (SRS<sub>off</sub> = 1.01 ± 0.67 N, SRS<sub>on</sub> = 0.69 ± 0.42 N) and variable error (SRS<sub>off</sub> = 1.11 ± 0.64 N, SRS<sub>on</sub> = 0.78 ± 0.56 N) ( $P < .05$ ). No other main effects or treatment-by-group interactions were found ( $P > .05$ ).

**Conclusions:** Although SRS reduced the overall magnitude (absolute error) and variability (variable error) of force sense errors, it had no effect on the directionality (constant error). Clinically, SRS may enhance muscle tension ability, which could have treatment implications for ankle stability.

**Key Words:** chronic injuries, error, proprioception, sensorimotor system, stochastic resonance

## Key Points

- In both participants with functional ankle instability and those with normal ankles, stochastic resonance stimulation immediately reduced the overall magnitude (absolute error) and variability (variable error) of force sense errors.
- The treatment had no effect on error directionality (constant error).

Inversion ankle sprains are common in physically active individuals.<sup>1</sup> Sprains to the ankle are often thought to be innocuous, but prolonged symptoms occur frequently, and individuals may continue to sustain sprains because of joint instability.<sup>2–4</sup> The term used to describe this syndrome is *functional ankle instability* (FAI), which can be more specifically defined as ankles with repetitive bouts of “giving way” or instability that leads to recurring sprains.<sup>5,6</sup> Currently, a single source of this instability has not been established, but the causal factors range from mechanical to functional inadequacies.<sup>7</sup> Functional inadequacies associated with FAI include deficits in proprioception, kinesthesia, neuromuscular control, strength, and balance.<sup>7</sup> Certain functional factors may be enhanced through rehabilitation exercises, but the results of other studies are equivocal regarding the degree to which rehabilitation can improve these functional deficiencies associated with FAI.<sup>8–10</sup> Consequently, researchers and clinicians may not be treating the correct causal factor of FAI and may need to refocus rehabilitation on other functional inadequacies. Alternatively, a complementary

therapeutic intervention may be needed to amplify treatment effects.

Force sense is a functional deficiency that has been documented with ankle instability.<sup>11–15</sup> *Force sense* is defined as the ability to detect tension from a muscle contraction.<sup>11</sup> Evidence indicates that individuals with FAI do not sense low-load eversion forces when replicating a targeted eversion muscle tension.<sup>11–15</sup> This inability to adjust eversion tension adequately is also correlated with episodes of giving way at the ankle joint and perceived ankle instability.<sup>11,13</sup> Consequently, force sense is important to investigate because the ability of muscles, in particular foot evertors, to generate adequate tension may be the difference between maintaining joint stability and sustaining an inversion ankle sprain.<sup>11,13</sup>

Muscle strains to the foot evertors can occur with ankle sprains,<sup>3</sup> and accompanying damage to muscle mechanoreceptors from the strain is a likely source of force sense deficits associated with FAI. More specifically, injury to muscle spindle endings or Golgi tendon organs (or both) may be the root of force sense impairments.<sup>16,17</sup> When

compromised, these muscle mechanoreceptors may distort force sense by inhibiting the agonist muscle and facilitating activation of the antagonist, potentially leading to a muscle's inability to generate adequate tension.<sup>11</sup> In FAI, for example, the evertors may become inhibited, and the invertor muscles may be facilitated to generate a greater inversion moment, forcing the foot into a more vulnerable supinated position. Therapy to enhance force sense and prevent foot positions that predispose ankles to sprains is an obvious intervention, but we currently do not know if rehabilitation corrects force sense impairments.<sup>15</sup> Perhaps a therapy that sensitizes these muscle mechanoreceptors is necessary to attain clinically relevant treatment effects.

Recently, stochastic resonance stimulation (SRS) has been used as a complementary therapy for FAI to potentially facilitate the activation of muscle mechanoreceptors.<sup>18-23</sup> This therapy introduces subsensory mechanical or electrical noise through the skin to enhance the ability of the mechanoreceptors to detect and transmit weak sensory signals.<sup>24-26</sup> This subsensory noise can stimulate the mechanoreceptors to bring membrane potentials closer to threshold by changing ion permeability.<sup>27</sup> Essentially, SRS can prime the mechanoreceptors to fire and transmit sensory information.<sup>27</sup> Interestingly, SRS has been reported to facilitate the efferent output of the central nervous system by sensitizing tactile response<sup>28</sup> and amplifying reflexive muscle contractions in patients with sensorimotor deficits.<sup>29,30</sup> Thus, SRS may be used to enhance sensorimotor function in individuals with FAI.

The use of SRS for treating FAI has mainly focused on improving static and dynamic balance, which can occur more quickly and to a greater extent than with rehabilitation alone.<sup>18-23</sup> Furthermore, when applied during static and dynamic balance, SRS has improved balance immediately.<sup>18,20,23</sup> Recent results<sup>23</sup> also indicate that customizing the stimulation intensity for individuals may enhance the treatment effects associated with SRS. In addition, customizing SRS intensity may improve balance to a greater degree in ankles with instability than in stable ankles.<sup>23</sup> This outcome supports the need to tailor the SRS intensity to achieve optimal balance enhancements.<sup>23</sup> Consequently, no single intensity has been identified to apply universally to all individuals to optimize SRS treatment effects. To improve balance, SRS may act on muscle mechanoreceptors to enhance the sensory feedback and reflexive contractions necessary for postural control.<sup>23</sup> Interestingly, the mechanoreceptors that may be affected by SRS to enhance balance are also responsible for improving force sense. Thus, SRS may sensitize mechanoreceptors to allow adequate adjustments in muscle tension.

Based on the aforementioned evidence, we speculated that SRS administered at an optimal intensity to improve balance would enhance force sense in ankles with functional instability and that improvements in these ankles would be greater than those seen in stable ankles. The capacity of SRS to improve force sense of the evertors has not been examined, and research is needed to demonstrate that this stimulation may be a viable intervention to enhance treatment effects. Thus, the purpose of our study was to examine the effects of SRS on force sense in foot-evertor muscles in ankles with functional instability and in stable ankles. If successful for improving force sense, then SRS could be used as a complementary therapy for FAI and

may have clinical relevance in allowing individuals with FAI to develop adequate muscle tension to prevent instability and sprains.

## METHODS

### Design

This study was a case-control study with an embedded crossover design. The independent variables were group (FAI, no FAI) and treatment (SRS<sub>on</sub>, SRS<sub>off</sub>). The dependent variables were force sense errors: (1) constant error (CE), (2) absolute error (AE), and (3) variable error (VE). These errors assess accuracy (CE), overall performance (AE), and consistency (VE) in reproducing a target force.

### Participants

The university's institutional review board granted approval for this project, and we obtained informed written consent from each participant before the study. Participants in this study were also involved in a related investigation.<sup>23</sup> Twelve individuals with FAI (age = 23 ± 3 years, height = 174 ± 8 cm, mass = 69 ± 10 kg; 6 men, 6 women) and 12 individuals with stable ankles (age = 22 ± 2 years, height = 170 ± 7 cm, mass = 64 ± 10 kg; 6 men, 6 women) participated. Participants with FAI were matched with those having stable ankles in age, height, mass, and sex, none of which were different between groups ( $P > .05$ ). All participants exercised a minimum of 3 hours per week. Inclusion criteria for FAI were self-reporting a history of ankle sprains and at least 2 occurrences of giving-way sensations within the year before the study. Inclusion criteria for stable ankles were no history of ankle sprains, no sensations of ankle instability (giving way), and no previous lower extremity injury. No participants with FAI had an acute ankle sprain injury during the study.

We assessed participants' functional perceptions, mechanical instability, history of ankle sprains, and giving-way episodes per month. However, these items were not inclusion or exclusion criteria; rather, they were used only as descriptors. Those with FAI had a greater perception of functional instability as assessed by the Ankle Joint Functional Assessment Tool (maximum score = 48, higher scores indicate more symptoms; FAI = 32 ± 3, stable = 22 ± 2). Clinical mechanical instability was present in half of our participants with FAI. Those with FAI self-reported greater than 3 sprains (3.50 ± 2.65) before the study and on average had 2 giving-way episodes per month (2.42 ± 2.51) within the year before the study.

### Instrumentation

The equipment used in this investigation generated a white noise vibratory signal, assessed balance, and examined force sense. A customized SRS device generated mechanical white noise via vibrating elements known as *tactors* (model C-2; Engineering Acoustics, Inc, Winter, FL). An AccuSwayPlus balance platform (Advanced Mechanical Technology, Inc, Watertown, MA) assessed balance. Finally, a 500-N load cell (Sensotec, Inc, Columbus, OH) attached to a wall-mounted frame assessed force sense.

## Sensory Threshold

Our sensory threshold protocol is outlined in a previous report.<sup>23</sup> The portable SRS unit was worn around the participant's waist and tactors were held in place atop a neoprene sleeve on the lower leg. Tactors were positioned midway between the origins and insertions of each of the following muscles: gastrocnemius, peroneus longus, tibialis anterior, and tibialis posterior. The participant stood quietly on both feet without shoes or socks, and we increased the intensity on the SRS device so that the tactors began vibrating at a sensory level that was just barely felt. This intensity level represented the *sensory threshold*. The 4 SRS noise intensity levels of 25%, 50%, 75%, and 90% of sensory threshold were then computed.<sup>31</sup>

## Optimization Protocol

We were interested in examining if our protocol for determining the SRS treatment intensity transferred to improving force sense. Thus, we used an optimization balance protocol from a previous study.<sup>23</sup> Our optimization setup was identical to our sensory threshold protocol, but participants stood on a force platform for balance testing. Quiet double-legged balance was performed under a control condition (SRS<sub>off</sub>) and 4 intensities were set at a percentage of the sensory threshold for each participant (25%, 50%, 75%, and 90%).<sup>23,31</sup> Each condition was performed 3 times, and the order of test conditions was counterbalanced. The participant stood with hands on the hips, eyes closed, and feet in neutral position. Each test condition lasted 20 seconds, during which the participant was instructed to remain as motionless as possible. The optimal SRS intensity was computed as the SRS intensity level that produced the greatest percentage change improvement in balance during the SRS<sub>off</sub> condition; these values were published in a previous report.<sup>23</sup>

## Maximal Voluntary Isometric Contraction

The participant was supine, and the foot was fastened to a load cell. The testing position for the ankle was 0° of plantar flexion and subtalar neutral.<sup>11</sup> The hips and knees were slightly flexed, to approximately 30° and 60°, respectively.<sup>11</sup> Excessive hip motion was eliminated with a bolster to block internal rotation and a belt that secured the proximal knee joint. The participant was then instructed to evert the foot with maximal force 3 times for 5 seconds each.<sup>11</sup> The average peak force of these 3 trials was recorded as the maximal voluntary isometric contraction (MVIC).

## Eversion Force Sense Test

During the force sense test, the participant was barefoot and in the same test position as described for the MVIC test. We used published force sense test methods for this assessment.<sup>11</sup> The target force was 10% of the MVIC,<sup>11</sup> which was established using the digital display connected to the load cell. The participant was then asked to evert the foot to produce the target force and maintain this force for 5 seconds while receiving feedback from the digital display.<sup>11</sup> The display was removed, and the participant was asked to reproduce the target force and hold it for 5 seconds. Once

the target force was reproduced, the participant depressed a switch to electronically mark the data file.<sup>11</sup>

Each participant performed 2 practice trials and 6 test trials under 2 conditions: (1) control condition (SRS<sub>off</sub>) and (2) the optimal SRS (SRS<sub>on</sub>). The order of test conditions was a randomized block design to prevent contamination of the data. The participant had a 60-second rest period between trials. All conditions were performed with the tactors on the participant. Because SRS was subsensory, the participant was blinded to each test condition.

## Data Collection and Processing

The AccuSway platform was interfaced with a laptop computer. Data were collected at a sampling frequency of 50 Hz and filtered with a fourth-order, zero-lag, low-pass filter with a cutoff frequency of 5 Hz.<sup>23</sup> Balance Clinic software (version 1.1; Advanced Mechanical Technology, Inc) computed resultant center-of-pressure velocity.

The load cell was calibrated to convert voltage to Newtons (1 volt = 100 Newtons) and interfaced with a laptop computer. We used Data Pac 2000 (version 2.40 Lab Applications Systems software; Run Technologies, Laguna Hills, CA) to acquire, process (using a 200-Hz low-pass filter), and analyze force sense data.<sup>11</sup>

## Statistical Analysis

For data analysis, SPSS statistical software (version 20.0; IBM Corporation, Armonk, NY) was used. The  $\alpha$  level was set a priori at  $P \leq .05$  to indicate statistical significance. The difference between the target force and reproduction force was used to compute the average of trial errors (CE) and the average of the absolute values of each trial error (AE). The standard deviation of the 3 reproduction forces defined the VE. We calculated a mixed-model repeated-measures analysis of variance with 1 within-subject factor with 2 levels (treatment: SRS<sub>on</sub>, SRS<sub>off</sub>) and 1 between-subjects factor with 2 levels (group: FAI, no FAI). The 95% confidence intervals for the difference between means (CI<sub>D</sub>95%) were computed for our main-effect analyses. The Cohen<sup>30</sup> effect-size  $f$  values were computed from the analysis-of-variance tables in SPSS. Effect-size values of 0.10, 0.25, and 0.40 were considered *low*, *moderate*, and *high*, respectively.<sup>32</sup>

## RESULTS

Means and standard deviations for groups and treatments are reported in the Table with the corresponding Cohen  $f$  values for their main effects and interactions. We found no significant group-by-treatment interactions for any of the variables (all  $P$  values  $> .40$ ). Main effects for treatment were noted for AE ( $P = .013$ , CI<sub>D</sub> 95% = 0.11, 1.29) and VE ( $P = .013$ , CI<sub>D</sub> 95% = 0.11, 1.43); however, no main effect for treatment was observed for CE ( $P = .60$ ; Figure 1). No group main effects were demonstrated for any of the variables (all  $P$  values  $> .15$ ; Figure 2).

## DISCUSSION

Our study had several important findings, with the most significant being that SRS enhanced participants' ability to adequately adjust evector muscle tension. In other words,

**Table. Force Sense Results**

Error Group	Stochastic Resonance Stimulation, N (Mean ± SD)		Cohen <i>f</i> Value		
	Off	On	Group	Treatment	Group by Treatment
Constant					
FAI	0.27 ± 0.68	0.31 ± 0.45	0.27	0.27	0.40
Stable	0.53 ± 1.05	0.31 ± 0.53			
Absolute					
FAI	0.84 ± 0.40	0.60 ± 0.37	0.70	1.25 <sup>a</sup>	0.28
Stable	1.18 ± 0.85	0.80 ± 0.47			
Variable					
FAI	0.97 ± 0.48	0.68 ± 0.52	0.56	1.35 <sup>a</sup>	0.05
Stable	1.24 ± 0.76	0.89 ± 0.60			

Abbreviation: FAI, functional ankle instability.

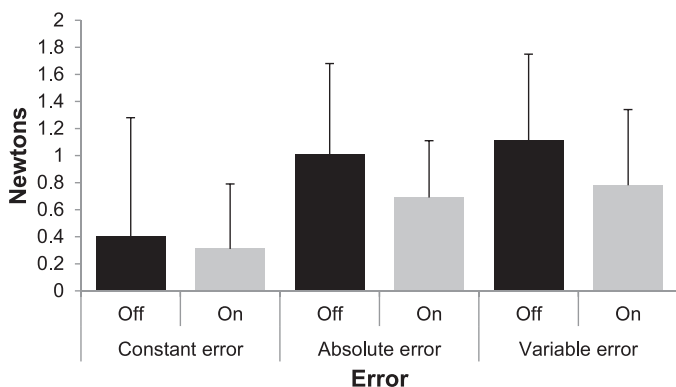
<sup>a</sup> Significant treatment main effect regardless of group.

they replicated the target muscle tension better with SRS. We also hypothesized that force sense in those with FAI would be affected more by SRS than in those with stable ankles. Interestingly, however, no difference existed between ankle groups for the rate at which SRS improved force sense. Thus, SRS was effective for enhancing neurologic mechanisms in both the presence and absence of a musculoskeletal injury. This effect of SRS on both injured and uninjured individuals is consistent with the majority of the evidence reported in the literature.<sup>23,33-35</sup> Although our findings indicate that SRS affected neurologic mechanisms responsible for adjusting muscle tension, we cannot definitely conclude which mechanisms were affected by this stimulation.

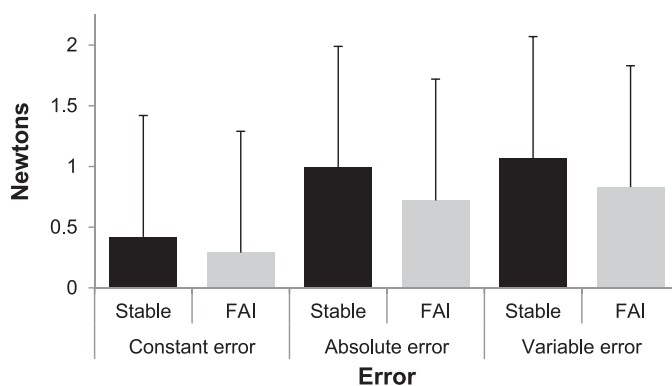
Previous reports<sup>24,25</sup> have indicated that the muscle spindles are sensitized by SRS applied either directly to the mechanoreceptors or over the skin of the mechanoreceptors. We speculate that these muscle mechanoreceptors may be responsible for adequate adjustment of the evertors. This contention is somewhat counterintuitive because spindles do not detect tension generated by the muscles. However, the spindles react to small and large vibrations applied over the muscle belly,<sup>36</sup> which is where we positioned our tactors. Clinically, therapists have used sensory vibration to stimulate spindles and recruit  $\alpha$  motoneurons in agonist muscles, which often become

inhibited by spasticity in antagonist muscles.<sup>37</sup> The difference between therapists' vibration techniques and SRS is that the former therapy is sensory and the latter therapy is subsensory. Interestingly, evidence<sup>24,29,30</sup> demonstrates that muscle spindle function improves with subsensory noise stimulation (ie, SRS). Thus, the SRS in our study might have served a similar function as sensory vibration therapy for evertor force adjustments. As force sense was regulated, our participants toggled the test foot into eversion and inversion to explore the amount of tension needed to achieve the target force. This motion requires the agonist and antagonist muscles to excite and inhibit, respectively, until the target force is reached. As the foot inverts, the evertor spindles are stretched to recruit  $\alpha$  motoneurons, and reflexive evertor contractions are produced to facilitate force generation. The SRS could have sensitized spindles to detect these small changes in length. During evertor force generation, spindles in the agonist are not stretched, but SRS might still have stimulated them to recruit the  $\alpha$  motoneurons responsible for generating adequate muscle tension. Signal transmission from spindles during contraction can occur because they are kept "tight" through  $\gamma$  motoneuron activation, and signal transmission may have been facilitated via subsensory mechanical vibration.

If SRS has the potential to increase  $\alpha$  motor-unit activity via muscle spindles, then muscle tension would inherently heighten and sensitize Golgi tendon organ activity. Golgi



**Figure 1. Stochastic resonance stimulation treatment main effects for constant error, absolute error, and variable error. Black bars represent the stochastic resonance stimulation off (control) condition, and gray bars, the stimulation on condition. The treatment reduced absolute and variable error over each respective control condition ( $P < .05$ ).**



**Figure 2. Stochastic resonance stimulation group main effects for constant error, absolute error, and variable error. No differences were found between groups ( $P > 0.05$ ). Abbreviation: FAI, functional ankle instability.**



tendon organs will be activated by the increased muscle tension that is generated from the muscle spindle signals that increase  $\alpha$  motoneuron activity.<sup>38</sup> This increased activity may allow the Golgi tendon organs to detect tension and accurately reproduce a force. Although this mechanism is an indirect pathway to increasing Golgi tendon organ activity, we cannot rule out that SRS might have directly affected Golgi tendon organ activity. Limited research<sup>39</sup> indicates that Golgi tendon organs are not reactive to subsensory mechanical vibration; however, our SRS might have been administered at a sufficient intensity to increase the sensitivity of these receptors. In addition, researchers<sup>11-14</sup> have speculated that damage to the Golgi tendon organs may be 1 source of force sense impairments in unstable ankles. Thus, any improvements made to Golgi tendon organ function through direct or indirect mechanisms should be evident in force sense outcome measures.

A final mechanism for improving force sense with SRS may be the cutaneous receptors. Although it appears counterintuitive because of the subsensory level of stimulation, SRS has enhanced the sensitivity of cutaneous receptors<sup>28</sup> by potentially bringing membrane potentials closer to threshold.<sup>27</sup> In 1 research investigation,<sup>28</sup> for example, SRS improved the ability to detect subthreshold tactile stimuli. In addition, researchers<sup>24</sup> found that SRS applied to the forearm increased muscle spindle signals during passive wrist rotation. They speculated that SRS could have activated the cutaneous receptors to influence the sensitivity of the spindles by preceding influential activity in the  $\gamma$  motoneurons.<sup>24</sup> This indirect pathway would then have a similar effect to the aforementioned spindle mechanism for achieving adequate muscle tension. Further research is needed to define the neurologic mechanisms for enhancing force sense with SRS.

Our results are promising, but we believe that future researchers should calibrate an optimal intensity if the goal of the therapy is to enhance force sense. We chose not to implement this type of protocol because our interest was in demonstrating that an optimization protocol for improving balance could transfer to improving force sense. In a related study,<sup>23</sup> an optimization protocol improved balance between 11% and 25% in participants with or without FAI. These percentage improvements were greater than the enhancements with SRS applied at intensities that were not customized.<sup>23</sup> Force sense enhancements in this study were evident in participants with or without FAI and thus showed that the optimal intensity for double-legged balance improvements transferred to decreasing errors in replicating the target force. However, our methods do not allow us to conclude that our treatment intensity was optimal for improving force sense.

Therapists may use SRS as a complementary rehabilitation tool for enhancing force sense. Our protocol had large treatment effects for improving force sense, both for performance enhancement and consistency of force reproduction. We do note that no effect was present for accuracy. However, this lack of a treatment effect was due to a washout effect occurring with the computation of CE, which combines both positive (overshoot) and negative (undershoot) errors. Therefore, we focused more on the AE and VE outcomes to interpret our results. The treatment effects from SRS were immediate, and as a result, we recommend using this therapy to improve sensorimotor

function in a single rehabilitation session. Furthermore, we demonstrated a treatment effect with a laboratory measure (ie, force sense), which may limit the clinical usefulness of our results. However, these outcomes are still clinically important because we detected a therapeutic treatment effect in a clinically meaningful group of participants. Future investigators might focus on recruiting FAI participants with greater force sense deficits than in our current sample to determine if the SRS treatment effect can be intensified, which may clarify the clinical usefulness of this therapy. Lastly, demonstrating a residual SRS treatment effect and an ability to translate to improved self-reported function in future studies is critical in determining the clinical importance of SRS.

Our results indicate that no force sense differences existed between the groups. The current literature displays 3 trends regarding force sense in ankles with functional instability. First, force sense deficits exist with FAI and are related to the degree of ankle instability.<sup>11,13,14</sup> Second, force sense impairments with FAI exist as measured by AE<sup>11,12,14</sup> and VE.<sup>12,13</sup> However, 1 research group<sup>13</sup> did not find AE impairments, and another<sup>11</sup> did not find VE deficits. Third, researchers have not demonstrated CE deficiencies in patients with FAI.<sup>11,13,14</sup> Our outcomes do not help to clarify discrepancies in the literature for AE and VE, but our CE results are consistent in demonstrating that CE impairments did not exist in participants with FAI. Based on our results and those reported in the literature, we speculate that our participants with FAI may not have had a high degree of ankle instability because their ability to reproduce forces was as good as that in participants without FAI. Future researchers should continue to explore force sense differences between ankle groups to definitively answer this question.

Our study had limitations that should be considered when interpreting and applying our results. Low-load force sense assessment is not functional but is necessary to increase the sensitivity of this assessment.<sup>11</sup> Thus, caution should be used in applying our results to functional movements. As described in our Methods, we took a number of steps to eliminate the contribution of leg rotation in computing MVIC values and target (reproduction) forces. We believe that our participants minimized this motion but lack the data to definitively determine the degree to which leg rotation might have contributed to our results. Furthermore, we did not screen for force sense errors. Perhaps a better research design would be to identify individuals with force sense impairments and then examine how SRS might correct these deficits. Lastly, the variations in our ankle groups may be a function of the small sample sizes. With larger sample sizes, the variation in groups should decrease.

## CONCLUSIONS

The SRS reduced the overall magnitude (AE) and variability (VE) of force sense errors but had no effect on the directionality (CE) of errors. Clinically, SRS may enhance muscle-tension-generation capabilities during a rehabilitation session. Future investigators might wish to focus on long-term effects of SRS on force sense and its ability to improve ankle stability.

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