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original research

Customized Noise-Stimulation Intensity for Bipedal Stability and Unipedal Balance Deficits Associated With Functional Ankle Instability

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Context: Stochastic resonance stimulation (SRS) administered at an optimal intensity could maximize the effects of treatment on balance.

Objective: To determine if a customized optimal SRS intensity is better than a traditional SRS protocol (applying the same percentage sensory threshold intensity for all participants) for improving double- and single-legged balance in participants with or without functional ankle instability (FAI).

Design: Case-control study with an embedded crossover design.

Setting: Laboratory.

Patients or Other Participants: Twelve healthy participants (6 men, 6 women; age = 22 ± 2 years, height = 170 ± 7 cm, mass = 64 ± 10 kg) and 12 participants (6 men, 6 women; age = 23 ± 3 years, height = 174 ± 8 cm, mass = 69 ± 10 kg) with FAI.

Intervention(s): The SRS optimal intensity level was determined by finding the intensity from 4 experimental intensities at the percentage sensory threshold (25% [SRS_{25}], 50% [SRS_{50}], 75% [SRS_{75}], 90% [SRS_{90}]) that produced the greatest improvement in resultant center-of-pressure velocity (R-COPV) over a control condition (SRS_0) during double-legged balance. We examined double- and single-legged balance tests, comparing optimal SRS (SRS_{opt1}) and SRS_0 using a battery of center-of-pressure measures in the frontal and sagittal planes.

Main Outcome Measure(s): Anterior-posterior (A-P) and medial-lateral (M-L) center-of-pressure velocity (COPV) and center-of-pressure excursion (COPE), R-COPV, and 95th percentile center-of-pressure area ellipse (COPA-95).

Results: Data were organized into bins that represented optimal (SRS_{opt1}), second (SRS_{opt2}), third (SRS_{opt3}), and fourth (SRS_{opt4}) improvement over SRS_0. The SRS_{opt1} enhanced R-COPV ($P \leq .05$) over SRS_0 and other SRS conditions ($SRS_0 = 0.94 \pm 0.32$ cm/s, $SRS_{opt1} = 0.80 \pm 0.19$ cm/s, $SRS_{opt2} = 0.88 \pm 0.24$ cm/s, $SRS_{opt3} = 0.94 \pm 0.25$ cm/s, $SRS_{opt4} = 1.00 \pm 0.28$ cm/s). However, SRS did not improve R-COPV over SRS_0 when data were categorized by sensory threshold. Furthermore, SRS_{opt1} improved double-legged balance over SRS_0 from 11% to 25% in all participants for the center-of-pressure frontal- and sagittal-plane assessments ($P \leq .05$). The SRS_{opt1} also improved single-legged balance over SRS_0 from 10% to 17% in participants with FAI for the center-of-pressure frontal- and sagittal-plane assessments ($P \leq .05$). The SRS_{opt1} did not improve single-legged balance in participants with stable ankles.

Conclusions: The SRS_{opt1} improved double-legged balance and transfers to enhancing single-legged balance deficits associated with FAI.

Key Words: chronic ankle instability, noise, postural stability, therapy

Key Points

- Stochastic resonance stimulation can be considered an alternative treatment for balance impairments.
- Stochastic resonance stimulation may be an effective treatment in the early stages of rehabilitation to facilitate immediate balance improvements that may help patients transition to complex postural stability exercises or functional movements.
- A double-legged balance-optimization protocol may be an efficient method to determine a customized optimal stochastic resonance stimulation intensity that will transfer to improving single-legged balance for functional ankle instability.

Functional ankle instability (FAI) is a residual symptom of ankle sprains that often causes the sensation of "giving way" at the ankle and recurrent ankle sprains.[1] In addition, sensorimotor deficits associated with FAI are present as balance impairments.[2] Postural instabilities are important to identify because poor balance is a predisposing factor of ankle sprain injury.[3–5] Given that balance improvements associated with rehabilitation often take 6 weeks to occur,[6,7] a therapy, such as stochastic resonance stimulation (SRS), that facilitates balance improvements immediately[8] or more quickly than rehabilitation alone[9,10] would be beneficial for individuals with FAI. Stochastic resonance stimulation is a therapy that introduces subsensory mechanical noise through the skin to enhance the ability of mechanoreceptors to detect and transmit weak signals related to balance.[11–13]

Natural noise created in the body can promote signal detection by amplifying weak sensory signals.[14,15] This natural noise occurs from external stimuli, physiologic processes, and biomechanics.[14,15] However, this internally generated noise may not be at a high enough level in some individuals to improve signal detection.[14,15] Healthy and injured individuals may benefit from SRS therapy when the level of naturally occurring noise is too low to facilitate signal detection.[14,15] Most evidence has indicated that individuals with and without sensorimotor impairments react similarly to SRS,[9,10,16–20] suggesting that the level of natural noise in the body is low enough for SRS to have positive treatment effects.

Interestingly, however, Priplata et al[18] reported that elderly participants had a better response to SRS than young healthy participants because the former used SRS to facilitate sensory signal detection to reduce sway. In addition, SRS improved balance in the elderly participants to within the normal range for young, healthy participants.[18] Sensorimotor impairments are associated with age, and the naturally occurring noise in the elderly participants might not have contributed to signal detection.[18] Thus, SRS corrected these sensorimotor deficits to facilitate balance improvements.[18] Given the findings in the elderly participants,[18] we postulate that the balance response to SRS might be better in individuals with FAI than in healthy individuals because FAI also is associated with sensorimotor deficits. Currently, no evidence exists to demonstrate that SRS produces better balance for FAI than stable ankles. Demonstrating that SRS improves balance more in FAI than stable ankles lends credence to the notion that this therapy enhances sensorimotor function.

Recent evidence[21] has indicated that the sensorimotor dysfunction with FAI may be due to reflex depressions, which can cause excessive sway with single-legged balance. These poor postural reflexes can result from an inability to integrate afferent input and efferent output.[22] That is, diminished sensation from the foot and ankle may not detect signals related to postural control, leading to inappropriate muscle contractions that maintain stability. The inability to sense signals to generate adequate postural reflexes suggests that the naturally occurring internal noise is at a level too low to facilitate signal detection. To correct this sensorimotor impairment, SRS can serve as a pedestal to predispose mechanoreceptors to fire in the presence of real sensory signals, especially signals that otherwise would be undetectable.[11–13]

The traditional method for examining the effects of SRS on balance improvements is to apply the same subsensory intensity to all participants within a research study.[16–20] Subsensory intensities from 25% to 90% have enhanced balance in patients who are healthy, have diabetes, or have had a stroke.[16–20] Researchers[17] also have presented preliminary data indicating that 75% of sensory threshold could be the optimal SRS intensity to affect the degree of balance improvements. This finding was confirmed in a second experiment[17] when this specific SRS intensity was applied to all participants to optimize balance enhancements.

Two research groups recently have proposed customizing the intensity of SRS applied to an individual to maximize treatment effects in lieu of applying the same intensity to all participants.[8,23] The rationale for this customized design was deduced from the early work of Collins et al,[24] who demonstrated that performance increased to a peak with increasing levels of SRS intensity and then decreased; however, the SRS intensity associated with this optimal intensity was slightly different for participants. In other words, the levels of SRS intensity for improving sensorimotor function must be fine tuned because subsensory intensities that are too low may not improve balance and those that are too high can diminish function.[8,11,17,23,24] Furthermore, a customized SRS intensity is proposed for minimizing random error in datasets, potentially decreasing washout effects in a group analysis.[8] Specifically related to FAI, researchers[8] using 1 of 2 input SRS intensities have demonstrated that 92% of participants with FAI improved their single-legged balance with at least 1 input intensity, whereas 55% of them had impaired balance at the other input intensity. This finding suggests that using 1 intensity for all participants may have masked the treatment effects of SRS if the intensity that impaired balance was used for analysis.[8] More recently, Mulavara et al[23] found that customizing the SRS intensity applied to an individual was crucial for maximizing balance improvements in healthy participants. These researchers defined an *optimal intensity* as the stimulus amplitude emitted from the SRS device that best improved balance over a control (no-SRS) condition.[23] By determining this customized optimal intensity for each individual, we speculate that treatment effects associated with SRS will increase compared with the same intensity for all participants.

Double-legged balance tests are recommended for determining the treatment effects of SRS on stability.[16–20,23] These bipedal assessments allow individuals to maximize their stability with a wide base of support, providing a reliable means of determining the optimal SRS intensity. This recommended double-legged SRS protocol has not been tested in participants with FAI. Clinically, this protocol may be important to examine with FAI because balance can be assessed quickly when optimizing SRS intensity. Single-legged balance protocols may not be efficient for optimizing SRS intensity because of the number of unsuccessful trials associated with FAI. However, most researchers do not use single-legged balance as a criterion standard for assessing balance deficits associated with FAI[2] or quantifying treatment effects of SRS on FAI.[8–10] Therefore, for clinical applications, we propose using a double-legged balance protocol to quickly and efficiently optimize SRS intensity and then using this intensity to enhance single-legged balance. This optimization protocol may be more clinically relevant if the intensity for enhancing double-legged balance transfers to improving single-legged balance.

Along these lines of clinical effectiveness, we believe that clinicians need to focus on 1 balance outcome measure when optimizing SRS intensity to improve stability. Common balance outcome measures that have improved with SRS over control conditions include sway velocity, excursion, and area.[16–20] Specifically related to FAI, resultant center-of-pressure velocity (COPV) has been used to assess the immediate effects of SRS on single-legged balance.[8] Other balance measures also have been examined with SRS in participants with FAI, but all use center-of-pressure excursion (COPE) data points to compute the outcome measures (eg, COPV is computed by dividing excursion by time).[9,10] For clinical applicability, we have taken a minimalist approach in our study by selecting resultant COPV as our main outcome measure for the optimization protocol because it has detected balance improvements associated with SRS in participants with FAI.[8]

Therefore, the initial purpose of our study was to determine if a customized optimal SRS intensity was better than a traditional SRS protocol (applying the same percentage sensory threshold intensity for all participants) for improving double- and single-legged balance in participants with and without FAI. Using a customized optimal SRS intensity, we wanted to determine (1) if individuals with FAI and individuals with stable ankles responded at different rates, (2) if double-legged balance (as measured by additional center-of-pressure measures) improved more with the optimal intensity than a control condition, and (3) if the optimal intensity for double-legged balance could transfer to improving single-legged balance over a control condition. Our hypotheses included the following: (1) The customized optimal SRS intensity protocol would improve double-legged balance better than the traditional protocol; (2) the treatment response to optimal SRS would be greater in individuals with FAI than in individuals with stable ankles; (3) the optimal intensity would improve double-legged balance more than a control condition; and (4) the optimal intensity would transfer to improving single-legged balance more than a control condition. The results of our study may be clinically relevant because a customized optimal SRS intensity level that maximally improves balance may enhance rehabilitation outcome measures and lead to greater ankle stability.

METHODS

Design

This case-control study with an embedded crossover design included the independent variables of group (FAI, stable) and treatment (4 SRS intensity levels, control). The dependent variables for center-of-pressure included (1) anterior-posterior (A-P) measures of COPV and COPE, (2) medial-lateral (M-L) measures of COPV and COPE, (3) resultant COPV, and (4) 95th percentile center-of-pressure area ellipse (COPA-95). The units of measures for these variables were (1) centimeters per second for COPV, (2) centimeters for COPE, and (3) centimeters squared for COPA-95.

Participants

All participants provided written informed consent, and the Institutional Review Board at Virginia Commonwealth University approved the study. Twelve individuals with FAI (6 men, 6 women, age = 23 ± 3 years, height = 174 ± 8 cm, mass = 69 ± 10 kg) and 12 individuals with stable ankles (6 men, 6 women, age = 22 ± 2 years, height = 170 ± 7 cm, mass = 64 ± 10 kg) participated. Participants with stable ankles were matched to participants with FAI for sex, age, height, and mass. Age ($t_{22} = 0.70$, $P = .50$), height ($t_{22} = 1.25$, $P = .28$), and mass ($t_{22} = 1.12$, $P = .27$) were not different between groups. In addition, participants with stable ankles were assigned a matched test limb for this study.[25] Matching was done by *limb dominance*, which was defined as the limb used to kick a ball (9 dominant test limbs per group, 3 nondominant test limbs per group).[25] All participants exercised a minimum of 3 hours per week. Inclusion criteria for the stable ankle group were no history of ankle sprain injury or giving way and no lower extremity injury.[25] Inclusion criteria for the FAI group included a self-reported history of ankle sprains and at least 2 episodes of giving-way sensations within the year before enrollment in this study.[25] Mechanical instability was neither an inclusion or exclusion criterion because we could not accurately assess it with radiographs.[25] Potential participants with FAI were excluded if they reported an ankle sprain within 6 weeks of inquiring about their eligibility.[25]

Participants' perceptions of functional abilities and clinical mechanical instability were examined. We used the Ankle Joint Functional Assessment Tool to assess participants' functional abilities (FAI score = 32 ± 3, stable score = 22 ± 2; $t_{22} = 8.64$, $P < .001$). Greater scores indicated impaired function.[26] Clinical mechanical instability was present in 50% of participants with FAI (positive anterior drawer or talar tilt test). Finally, participants with FAI self-reported a history of 3.50 ± 2.65 (range, 1–10 sprains) sprains and 0.56 ± 0.58 (range, 0.04–2.0) episodes per week of giving way.

Instrumentation

A white-noise vibratory signal with a bandwidth limited from 0 to 100 Hz was generated using a custom LabVIEW program (National Instruments Corporation, Austin, TX) on a personal laptop computer. This signal was sent to a BNC-shielded connector block (BNC-2111; National Instruments Corporation) that included a universal serial bus data-acquisition box (USB-6225 M series; National Instruments Corporation) with a 16-bit resolution and 250-kS/s sample rate and a card (E series; National Instruments Corporation) with a 16-bit resolution and 200-kS/s sample rate. Two BNC cables then carried this signal to a custom-made portable SRS, which was sent to 4 vibrating elements called *tactors* (C2 Tactors; Engineering Acoustics, Winter Park, FL).

An AccuSwayPlus (AMTI, Inc, Watertown, MA) balance platform was used to assess balance. This platform was connected to a personal laptop computer via an RS-232 serial port. Data were sampled at 50 Hz and filtered with a fourth-order, zero lag, low-pass filter that had a cutoff frequency of 5 Hz.[27]

Sensory Threshold

Sensory threshold was determined using published protocols.[16,18,19] The portable SRS unit was strapped to the participants' waists. A standardized neoprene sleeve was placed on the lower leg, and a customized cloth sleeve was worn atop it. This cloth sheath had pockets that held tactors over the bellies of the ankle muscles of the test leg (gastrocnemius, peroneus longus, tibialis anterior, tibialis posterior). We stimulated these muscles to potentially target their respective muscle spindles, which are used to generate postural reflexive muscle contractions. The neoprene sleeve served to dampen mechanical vibrations so the participants did not feel the metal oscillating on their skin. Participants then stood quietly on both feet, and the tactors began to vibrate by receiving a noise signal from the SRS. The noise intensity was increased until participants barely felt the stimulation. This intensity level represented sensory threshold. Four SRS noise intensity levels of 25%, 50%, 75%, and 90% of sensory threshold were calculated and used for our optimization procedure.

Optimization Balance Protocol

We used an optimization protocol recommended by Priplata et al[17] that included 4 SRS noise-intensity levels to determine the therapeutic intensity that maximally improved balance in healthy and elderly participants. Participants performed all tests with the portable stimulator strapped to their waists, and tactors were positioned in the cloth sheath atop the neoprene sleeve over the aforementioned ankle muscles. Quiet double-legged balance was performed under 5 conditions that were a percentage of sensory threshold for each participant: 0% (SRS_0), 25% (SRS_{25}), 50% (SRS_{50}), 75% (SRS_{75}), and 90% (SRS_{90}). Three trials were performed for each condition, and the order of test conditions was counterbalanced to evenly distribute any potential learning or fatigue effects. Given that SRS is subsensory, participants were blinded to each test condition. During each balance test, participants stood barefoot atop a force plate with their hands on their hips, their eyes closed, and their feet in a neutral position. Participants' heels were separated by 8 cm while performing double-legged stance.[16] We instructed participants to remain as motionless as possible for each 20-second trial. They received 1 practice trial without SRS. For testing trials, force-plate recordings began immediately after participants stabilized their posture and closed their eyes. A 30-second rest period between trials and conditions was used for testing. During the rest periods, the intensity of SRS was adjusted, and participants were stimulated with the appropriate intensity just before beginning the balance test.

Balance Clinic Software (AMTI, Inc) computed resultant COPV as the absolute mean value of the instantaneous resultant velocity of the center of pressure. Percentage differences were calculated between the resultant COPV of SRS conditions and resultant COPV during the SRS_0 condition. Resultant COPV was used as the criterion for balance improvements because SRS has enhanced this variable in participants with FAI.[8] The *customized optimal SRS intensity* (SRS_{opt1}) was defined as the SRS noise intensity level that produced the greatest percentage change improvements in balance over the SRS_0 condition.

Single-Legged Balance Protocol

Quiet single-legged balance was performed under 2 conditions: SRS_0 and SRS_{opt1}. Participants were required to stand barefoot on the limb with FAI or the matched test limb atop a force plate for 20 seconds.[8] We instructed them to remain as motionless as possible while keeping their eyes closed and hands on their hips.[8] The weight-bearing limb was flexed slightly at the knee with the foot in a neutral toe in-out position, and the nonweight-bearing limb was flexed slightly at the hip and knee. Participants performed 1 practice trial without SRS, followed by 3 trials for each condition. Data collection was conducted in a randomized block design. Participants again were blinded to treatments because SRS_{opt1} was subsensory. For testing trials, force-plate recordings began immediately after participants stabilized their posture on a single leg and closed their eyes. A 30-second rest period between trials and conditions was used for testing. During the rest periods, the intensity of SRS was turned off and then turned on just before data collection for trials associated with SRS_{opt1}. Trials were discarded and repeated if participants hopped on the weight-bearing foot or touched the nonweight-bearing limb to the ground.

Data Analysis for Balance Protocols

The SRS_{opt1} and SRS_0 center-of-pressure vector components data (A-P, M-L) for double- and single-legged trials were exported to spreadsheets for analysis. A customized program in LabVIEW computed A-P COPV, M-L COPV, A-P COPE, M-L COPE, and COPA-95. The *COPV measures* were defined as the absolute mean value of the instantaneous velocity of the center of pressure in a given direction during a given period.[25,28] The *COPE measures* were defined as the absolute averaged distance between the instantaneous center of pressure and the average center-of-pressure position in a given direction during a given time.[25,28] The *COPA-95* was defined as the area of the 95th percentile ellipse, encompassing 95% of the center-of-pressure data points.[28] These center-of-pressure measures have been used to quantify treatment effects of SRS in participants with FAI and have been identified as measures that quantify balance impairments associated with FAI.[8,10] Greater values indicate poor stability.[25,28]

Statistical Analysis

Average values for each condition were computed in PASW (version 18.0; SPSS, IBM Corporation, Armonk, NY). The α level was set a priori at equal to or less than .05. We used double-legged balance data for analyses 1 through 3 and single-legged balance data for analysis 4.

The first analysis for resultant COPV values for the 4 SRS intensities of the optimization protocol were organized into bins. Participants' lowest resultant COPV values represented SRS_{opt1}. Resultant COPV values belonging to the last 3 ranks were labeled second optimal SRS intensity (SRS_{opt2}), third optimal SRS intensity (SRS_{opt3}), and fourth optimal SRS intensity (SRS_{opt4}). Next, a mixed-model, repeated-measures analysis of variance (ANOVA) with 1 within factor with 5 levels (treatment: SRS_0, SRS_{opt1}, SRS_{opt2}, SRS_{opt3}, SRS_{opt4}) and 1 between factor with 2 levels (group: FAI, stable) was used for this first analysis.

For our second analysis for resultant COPV, we also used a mixed-model, repeated-measures ANOVA with 1 within factor with 5 levels (treatment: SRS_0, SRS_{25}, SRS_{50}, SRS_{75}, SRS_{90}) and 1 between factor with 2 levels (group: FAI, stable). This analysis was conducted to determine if the traditional protocol of applying the same intensity to all participants produced SRS treatment effects.

In the third analysis of double-legged balance, we examined 5 center-of-pressure measures using a multivariate ANOVA with 1 within factor with 2 levels (treatment: SRS_0, SRS_{opt1}) and 1 between factor with 2 levels (group: FAI, stable). Similarly, we conducted the fourth analysis on single-legged balance using the same 5 center-of-pressure measures and a multivariate ANOVA with 1 within factor with 2 levels (treatment: SRS_0, SRS_{opt1}) and 1 between factor with 2 levels (group: FAI, stable).

Cohen[29] effect size f and observed power (OP) values were calculated for all multivariate analyses. Effect size values of 0.10, 0.25, and 0.40 were considered low,

Table 1. Number of Participants for Each Stochastic Resonance Stimulation Bin

Group	Sensory Threshold, %	Stochastic Resonance Stimulation Bin: Optimal Intensity	Second Optimal Intensity	Third Optimal Intensity	Fourth Optimal Intensity
Functional ankle instability	25	2	6	1	3
	50	4	2	2	4
	75	1	2	6	3
	90	5	2	3	2
Stable ankle	25	2	3	0	7
	50	6	2	3	1
	75	2	6	3	1
	90	2	1	6	3

moderate, and high, respectively.[29] We performed post hoc tests with the Fisher least significant difference (LSD) for findings that were different.

RESULTS

Optimization

The number of participants and percentage sensory threshold SRS intensity belonging to each SRS category for the first analysis are displayed in Table 1. A main effect for treatment was found for resultant COPV ($F_{4,88} = 12.41$, $P < .001$; Cohen f = 0.73, OP = 0.91), indicating that SRS affected balance (Table 2). Post hoc Fisher LSD tests showed that SRS_{opt1} improved balance over SRS_0, SRS_{opt2}, SRS_{opt3}, and SRS_{opt4}. We found no differences among SRS_0, SRS_{opt2}, and SRS_{opt3}. However, SRS_{opt4} impaired balance compared with control and all SRS conditions. We did not find a treatment-by-group interaction ($F_{4,88} = 0.89$, $P = .48$; Cohen f = 0.16, OP = 0.10; Table 2) or a main effect for group ($F_{1,22} = 0.006$, $P = .94$; Cohen f = 0.02, OP = 0.05; Table 2).

Categorizing the second analysis for resultant COPV data by percentage sensory threshold did not yield findings that were different. We did not find a treatment-by-group interaction ($F_{4,88} = 0.826$, $P = .51$; Cohen f = 0.19, OP = 0.15; Table 3). We did not find a main effect for treatment ($F_{4,88} = 0.459$, $P = .77$; Cohen f = 0.14, OP = 0.10; Table 3) or a main effect for group. The main effect for group combines all resultant COPV for each treatment into 1 mean for each group. Thus, the lack of a main effect for group is the same finding for the first and second analyses.

Double-Legged Center-of-Pressure Measures

For the third analysis, we found a main effect for treatment (Wilks' $\lambda = 0.57$, $F_{5,18} = 2.77$, $P = .05$; Cohen f = 0.83, OP = 0.97), indicating that SRS_{opt1} improved double-legged balance. Post hoc Fisher LSD tests revealed that all measures were enhanced with SRS_{opt1} (Table 4). We did not find a treatment-by-group interaction (Wilks' $\lambda = 0.82$, $F_{5,18} = 0.82$, $P = .55$; Cohen f = 0.45, OP = 0.66). Finally, we did not find a main effect for group (Wilks' $\lambda = 0.76$, $F_{5,18} = 1.13$, $P = .38$; Cohen f = 0.53, OP = 0.66).

Single-Legged Center-of-Pressure Measures

We found a treatment-by-group interaction for the fourth analysis (Wilks' $\lambda = 0.55$, $F_{5,18} = 2.97$, $P = .04$; Cohen f = 0.85, OP = 0.99). Post hoc Fisher LSD results are presented in Table 5. The FAI group improved their balance with SRS_{opt1} compared with SRS_0 for all measures except COPA-95. However, the stable-ankle group did not improve their balance during SRS_{opt1} compared with SRS_0 for any measure. Furthermore, the FAI group had worse balance than the stable-ankle group during SRS_0 for all measures except A-P COPE and COPA-95. The SRS_{opt1} of the FAI group was not different from SRS_0 of the stable ankle group for A-P COPV, M-L COPV, M-L COPE, and COPA-95. The A-P COPE for the FAI group with SRS_{opt1} improved over SRS_0 of the stable-ankle group. We found a main effect for ankle (Wilks' $\lambda = 0.46$, $F_{5,18} = 4.19$, $P = .01$; Cohen f = 1.00, OP = 0.99; Table 5). This finding indicated that the FAI group had worse balance than the stable-ankle group. We did not find a main effect for treatment (Wilks' $\lambda = 0.71$, $F_{5,18} = 1.46$, $P = .25$; Cohen f = 0.60, OP = 0.81; Table 5).

DISCUSSION

The most important findings of this investigation were that SRS administered at a customized optimal intensity improved double-legged balance in individuals with or without FAI, and this intensity transferred to correcting single-legged balance impairments associated with FAI. Single-legged balance improvements ranged from 10% to 17% in our study, which is greater than the single-legged balance enhancements ranging from 3% to 8% reported by researchers[8,20] who did not customize SRS intensities to

Table 2. Double-Legged Balance Data Categorized by Optimal Intensity (Mean ± SD)

	Stochastic Resonance Stimulation, cm/s: Control	Optimal Intensity	Second Optimal Intensity	Third Optimal Intensity	Fourth Optimal Intensity
Functional ankle instability	0.90 ± 0.18	0.81 ± 0.10	0.88 ± 0.14	0.95 ± 0.18	1.00 ± 0.19
Stable ankle	0.98 ± 0.43	0.79 ± 0.26	0.88 ± 0.32	0.93 ± 0.32	1.00 ± 0.35
Main effect for treatment	0.94 ± 0.32	0.79 ± 0.20[a]	0.88 ± 0.24	0.94 ± 0.25	1.00 ± 0.28[b]

[a] Indicates stochastic resonance stimulation optimal intensity was improved over all other conditions.
[b] Indicates stochastic resonance stimulation fourth optimal intensity was greater than all other conditions.

Table 3. Double-Legged Balance Data Categorized by Percentage Sensory Threshold Intensity (Mean ± SD)

	Stochastic Resonance Stimulation, cm/s				
		Percentage of Sensory Threshold			
	Control	25%	50%	75%	90%
Functional ankle instability	0.90 ± 0.18	0.91 ± 0.15	0.91 ± 0.17	0.93 ± 0.19	0.89 ± 0.18
Stable ankle	0.98 ± 0.43	0.89 ± 0.28	0.88 ± 0.32	0.91 ± 0.34	0.93 ± 0.35
Main effect for treatment	0.94 ± 0.32	0.90 ± 0.22	0.90 ± 0.25	0.92 ± 0.27	0.91 ± 0.27

individuals. Our findings lend credence to previous reports demonstrating that single-legged balance improvements can be achieved with SRS in individuals with sensorimotor deficits (eg, elderly, FAI) and double-legged enhancements can be achieved in healthy individuals and those with FAI.[8,16–20,23] We speculate that balance improved with SRS because weak sensory signals related to postural stability became detectable with this therapy. Clinically, SRS devices may be used to improve balance immediately, which may allow individuals with FAI to perform rehabilitation exercises more effectively.

A specific input intensity is needed for SRS to work optimally in improving afferent signal detection.[11,24] In our study, we presented a group stochastic resonance behavior by categorizing data into bins (SRS_0, SRS_{opt1}, SRS_{opt2}, SRS_{opt3}, SRS_{opt4}). Balance improvements peaked at SRS_{opt1}, decreased toward baseline (SRS_0) with SRS_{opt2} and SRS_{opt3}, and finally became worse with SRS_{opt4}. Interestingly, we did not find a group stochastic resonance behavior when categorizing data by intensity (SRS_0, SRS_{25}, SRS_{50}, SRS_{75}, SRS_{90}). In this case, a washout effect occurred because not everyone improved balance optimally at the same intensity. Participants who improved the most at a specific intensity were grouped with others whose improvements were not optimal at the same intensity, creating the washout effect. These findings are critically important to future research with SRS because investigators[8,16–20] who did not optimize intensities may have found greater SRS treatment effects when data were subjected to group analyses.

We also wanted to know the extent to which SRS_{opt1} improved traditional center-of-pressure double- and single-legged balance measures over SRS_0. These additional analyses provided an overall assessment of balance because we captured how quickly individuals controlled posture, displacement of pressure, and movement area. Center-of-pressure measure values decreased with SRS_{opt1}, indicating more stable double-legged balance over SRS_0 for all participants. However, our treatment-by-group interaction indicated that SRS_{opt1} enhanced single-legged balance only in participants with FAI. This finding demonstrates that the FAI group responded better to SRS_{opt1} than did the stable-ankle group and suggests that SRS_{opt1} improved single-legged balance by enhancing sensorimotor function. An interesting outcome of our investigation was that when SRS_{opt1} of the FAI group and SRS_0 of the stable ankle group were compared, SRS enhanced balance to normal or greater-than-normal limits for all single-legged balance measures except COPA-95. This finding reinforces our premise that SRS can adjust balance to normal levels that may allow individuals with FAI to perform balance exercises more effectively during rehabilitation. We did not find therapeutic effects of SRS_{opt1} for single-legged balance in healthy young participants, and we can only speculate that our healthy participants could determine sensory signals vital to maintaining single-legged balance. Conversely, a different customized intensity may enhance single-legged balance associated with stable ankles.

Single-legged balance improvements associated with SRS may have implications in reducing the incidence of ankle sprains; balance training reduces ankle sprain injury.[6,30] Eils and Rosenbaum[6] reported 4% to 9% improvements in center-of-pressure measures and a 60% reduction in ankle sprains in participants with ankle instability after a 6-week, multistation, balance-training program. The SRS corrected single-legged balance from 10% to 17% in our study, and these improvements were immediate, perhaps indicating that SRS may produce enhancements equal to or greater than the values associated with decreasing the incidence of ankle sprain. Unfortunately, this therapeutic device is not designed for wear during rigorous physical activity for long periods, limiting its clinical relevance for potentially preventing injury. However, SRS has been used in conjunction with rehabilitation exercises to ameliorate balance more quickly and to a greater degree than rehabilitation alone.[9,10] Essentially, improvements associated with SRS as an

Table 4. Traditional Double-Legged Balance Center-of-Pressure Measures for Stochastic Resonance Stimulation at an Optimal Intensity Level and Control Condition (Mean ± SD)

	Stochastic Resonance Stimulation	
Measure	Control	Optimal Intensity Level
Anterior-posterior center-of-pressure velocity, cm/s		
Functional ankle instability	0.71 ± 0.16	0.65 ± 0.10
Stable ankle	0.75 ± 0.31	0.65 ± 0.21
Main effect for treatment	0.73 ± 0.24	0.65 ± 0.16[a]
Medial-lateral center-of-pressure velocity, cm/s		
Functional ankle instability	0.37 ± 0.08	0.31 ± 0.06
Stable ankle	0.43 ± 0.24	0.40 ± 0.18
Main effect for treatment	0.40 ± 0.18	0.35 ± 0.14[a]
Anterior-posterior center-of-pressure excursion, cm		
Functional ankle instability	0.34 ± 0.13	0.29 ± 0.06
Stable ankle	0.29 ± 0.10	0.27 ± 0.06
Main effect for treatment	0.31 ± 0.11	0.28 ± 0.06[a]
Medial-lateral center-of-pressure excursion, cm		
Functional ankle instability	0.16 ± 0.04	0.15 ± 0.04
Stable ankle	0.16 ± 0.05	0.14 ± 0.04
Main effect for treatment	0.16 ± 0.05	0.14 ± 0.04[a]
95th Percentile center-of-pressure area ellipse, cm^2		
Functional ankle instability	10.40 ± 5.07	7.74 ± 2.38
Stable ankle	8.45 ± 4.62	6.63 ± 3.63
Main effect for treatment	9.43 ± 4.88	7.15 ± 2.99[a]

[a] Indicates main effect for treatment, with stochastic resonance stimulation at an optimal intensity level improved over the control condition.

Table 5. Traditional Single-Legged Balance Center-of-Pressure Measures for Stochastic Resonance Stimulation at an Optimal Intensity Level and Control Condition (Mean ± SD)

Measure	Group			
	Functional Ankle Instability		Stable Ankle	
	Control Condition	Stochastic Resonance Stimulation at an Optimal Intensity Level	Control Condition	Stochastic Resonance Stimulation at an Optimal Intensity Level
Anterior-posterior center-of-pressure velocity, cm/s	4.07 ± 0.81	3.42 ± 0.41[a]	3.47 ± 0.75[b]	3.52 ± 0.88
Medial-lateral center-of-pressure velocity, cm/s	4.66 ± 1.06	4.21 ± 0.61[a]	3.92 ± 0.59[b]	3.85 ± 0.60
Anterior-posterior center-of-pressure excursion, cm	0.90 ± 0.22	0.75 ± 0.09[a]	1.00 ± 0.31[c]	0.88 ± 0.17
Medial-lateral center-of-pressure excursion, cm	0.91 ± 0.28	0.81 ± 0.13[a]	0.78 ± 0.16[b]	0.76 ± 0.11
95th percentile center-of-pressure area ellipse, cm^2	27.87 ± 11.89	20.14 ± 6.40	23.14 ± 12.74	19.23 ± 7.17

[a] Indicates functional ankle instability stochastic resonance stimulation at an optimal intensity level was improved over the functional ankle instability control condition.
[b] Indicates the stable ankle control condition was less than the functional ankle instability control condition.
[c] Indicates the stable ankle control condition was greater than the functional ankle instability stochastic resonance stimulation at an optimal intensity level.

adjunct to exercise had long-term residual effects on balance because enhancements at post-testing occurred without stimulation.[9,10] Interestingly, though, SRS therapy was not administered at an optimal intensity in previous investigations,[9,10] and our results may indicate that long-term residual effects may be amplified with SRS_{opt1}. Thus, SRS_{opt1} may have future clinical implications for treating balance disorders associated with FAI, which may translate to reducing recurrent ankle sprains.

We speculate that SRS may have sensitized muscle spindles to enhance postural reflexive contractions and balance in our participants. Investigators[8,16–20] have suggested that balance improvements associated with SRS result from enhanced signal detection by afferent mechanoreceptors. Afferent mechanoreceptors detect signals that are vital for updating the central nervous system on the orientation of body parts to one another to maintain balance.[22] Proper feedback is needed from the somatosensory system to initiate reflexive postural responses and adjust motor programs responsible for stability.[22] Sensory signals, for example, can activate γ motor neurons to enhance the sensitivity of muscle spindles, which initiate postural reflexes crucial for postural stability.[22] Research models[11,13] have confirmed this mechanism by demonstrating that transcutaneous SRS activates muscle spindles to improve signal detection in humans and has increased muscle spindle output in cats. The SRS also can stimulate muscle spindles to enhance the preceding influential activity on γ motor neurons, in turn activating muscle spindles.[11] This enhanced feedback has been reported to globally affect the efferent output of the central nervous system by sensitizing individuals' abilities to report tactile signals[24] and increasing soleus H-reflex amplitudes in healthy individuals[31] and in patients who have had strokes and have sensorimotor deficits.[32] Based on this evidence, we believe that the SRS treatment effects on afferent input and efferent output have implications for balance rehabilitation associated with FAI.

Whereas our research questions focused on the group-by-treatment interaction, we believe that commenting on the main effects for group analyses is important. Balance deficits are associated with FAI when comparing stable- and unstable-ankle groups but mainly have been isolated to single-legged impairments.[2] One group[33] has reported double-legged balance deficits with a force-plate measure known as *time to stabilization*, but they have not found deficits with the traditional center-of-pressure measurements that we used in our study. Thus, the finding of no differences between groups for double-legged center-of-pressure measures agrees with the findings reported in the double-legged balance literature associated with FAI. When comparing groups for single-legged balance, however, we found worse balance associated with FAI during SRS_0. More specifically, balance was worse in participants with FAI than in participants with stable ankles under SRS_0 for A-P COPV, M-L COPV, and M-L COPE. These findings are consistent with a recent meta-analysis indicating that single-legged balance deficits exist with FAI.[2]

Although we used an established optimization protocol, a limitation of our study is that we only used 4 SRS intensity levels. Different percentages of sensory threshold may be better at improving balance. However, using more than 4 intensity levels to optimize may take too much time for this therapy to have clinical implications. A positive finding of our study was that the intensity for improving double-legged balance transferred to enhancing single-legged balance in participants with FAI. However, an alternative intensity associated with a single-legged optimization protocol may increase SRS treatment effects for single-legged balance. A reason we did not optimize to single-legged standing is the frequency of unsuccessful trials that can be associated with single-legged balance (touching down with the nonweight-bearing limb), particularly in participants with FAI. We were not certain if our results would be influenced by the potential increase in unsuccessful trials associated with performing 15 data-collection trials (3 trials for each condition). A double-legged optimization protocol allowed for quick and efficient assessments of SRS intensities on balance. An additional limitation may be related to only placing tactors over 4 lower limb muscles. Alternative sites may have affected the degree to which balance was improved. Lastly, our study may have been underpowered to detect SRS treatment effects in the double-legged traditional analysis in which we examined SRS between intensities. Balance improved for SRS_{25}, SRS_{50}, SRS_{75}, and SRS_{90} over SRS_0 from 3% to 4%. These percentage improvements have been reported as different by investigators using the traditional analysis.[18,20]

CONCLUSIONS

Clinicians may consider using SRS as an alternative treatment for balance impairments. In the early stages of rehabilitation, this therapy may effectively facilitate immediate balance improvements that may help patients transition to complex postural-stability exercises or functional movements. A double-legged balance optimization protocol may be an efficient method for determining a customized optimal SRS intensity that will transfer to improving single-legged balance for FAI. Balance is essential for executing movement, and researchers can examine the ability of SRS_{opt1} to transfer to ameliorating functional performance in physically active individuals with FAI.

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