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Effect of stochastic resonance on proprioception and kinesthesia in anterior cruciate ligament reconstructed patients

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ABSTRACT

Low amplitude mechanical noise vibration has been shown to improve somatosensory acuity in various clinical groups with comparable deficiencies through a phenomenon known as Stochastic Resonance (SR). This technology showed promising outcomes in improving somatosensory acuity in other clinical patients (e.g., Parkinson's disease and osteoarthritis). Some degree of chronic somatosensory deficiency in the knee has been reported following anterior cruciate ligament (ACL) reconstruction surgery. In this study, the effect of the SR phenomenon on improving knee somatosensory acuity (proprioception and kinesthesia) in female ACL reconstructed (ACLR) participants (n = 19) was tested at three months post-surgery, and the results were compared to healthy controls (n = 28). Proprioception was quantified by the measure of joint position sense (JPS) and kinesthesia with the threshold to detection of passive movement (TDPM).

The results based on the statistical analysis demonstrated an overall difference between the somatosensory acuity in the ACLR limb compared to healthy controls ($p = 0.007$). A larger TDPM was observed in the ACLR limb compared to the healthy controls ($p = 0.002$). However, the JPS between the ACLR and healthy limbs were not statistically significantly different ($p = 0.365$). SR significantly improved JPS ($p = 0.006$) while the effect was more pronounced in the ACLR cohort. The effect on the TDPM did not reach statistical significance ($p = 0.681$) in either group.

In conclusion, deficient kinesthesia in the ACLR limb was observed at three months post-surgery. Also, the positive effects of SR on somatosensory acuity in the ACL reconstructed group warrant further investigation into the use of this phenomenon to improve proprioception in ACLR and healthy groups.

1. Introduction

Stochastic resonance (SR) is a phenomenon observed in a non-linear system where adding a certain level of noise improves signal transition/detection (Aihara et al., 2010). SR has been shown to improve somatosensory acuity (proprioception and kinesthesia)[1] in patients with osteoarthritis (Collins et al., 2011a; Collins et al., 2011b), postural stability in the elderly (Dhruv et al., 2002; Gravelle et al., 2002; Priplata et al., 2002; Costa et al., 2007; Rogan et al., 2012), individuals with Parkinson's disease (Turbanski et al., 2005; Ghoseiri et al., 2009; Kauta et al., 2011; Kaut et al., 2016), and patients with diabetes or following stroke (Liu et al., 2002).

The anterior cruciate ligament (ACL) is thought to play an important role in providing somatosensory feedback to the central nervous system (CNS) from the knee joint (Frank and Jackson, 1997). After the loss of this joint structure, an ACL reconstruction (ACLR) surgery is often performed. Experimental evidence related to changes in joint somatosensory acuity following ACLR remain inconclusive to date (Risberg et al., 1999; Gokeler et al., 2012). However, some degree of somatosensory deficiency is commonly reported in the knee following ACLR surgery (Relph, Herrington and Tyson, 2014).

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[1] Proprioception acuity can be defined as the awareness of the CNS to the relative positions of body segments in space while kinesthesia refers to the awareness of the CNS to the movements of these segments (Beynnon et al., 1999; Ashton-Miller et al., 2001; Stillman, 2002; Stillman, Tully and McMeeken, 2002; Goble, 2010).

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Somatosensory deficiency in the knee is particularly important since good somatosensory function following ACLR surgery was found to be highly correlated to satisfactory functional stability (84%) and patient satisfaction (90%) following reconstruction surgery (Barrett, 1991; Bali, Prabhakar and Dhillon, 2011). Due to somatosensory improvements with SR seen in previous works, it can be hypothesized that this phenomenon might be a potential modality to enhance somatosensory acuity in ACLR patients by recruiting other somatosensory elements (e.g. intact collateral ligaments and capsular receptors (Barrett, 1991), muscle spindles (Cordo et al., 1996), and cutaneous receptors (Lugo, Doti and Faubert, 2008; Magalhães and Kohn, 2011; Kimura et al., 2012; Mendez-Balbuena et al., 2012)).

Two of the most commonly reported methods to measure somatosensory acuity are joint position sense (JPS), and threshold to detection of a passive movement (TDPM). The JPS measures the ability of an individual to repeatedly reproduce a desired and predetermined joint position. The TDPM measures the minimum amount of passive movement in degrees that can be introduced before an individual can sense the movement in a joint (e.g. knee). Poor proprioception and kinesthesia are seen as an increase in the JPS and TDPM, respectively (Ellenbecker, Davies and Bleacher, 2012).

The novelty of this work is to study the effect of SR on the somatosensory acuity of the knee in an ACLR group. The comparison to a control group will establish the state of somatosensory acuity in the ACLR group at base line, and provide context for the extent of potential improvements caused by SR. The main objectives of this study were therefore: (1) to compare somatosensory acuity in the ACLR limb at three months post-surgery with that of healthy using highly controlled confounding variables such as isolated ACL injury, age and sex, and surgeries performed by a single surgeon (N.G.H.M) and (2) to investigate the effect of SR vibration applied to the knee area on the somatosensory acuity in ACLR individuals and healthy controls. This study tested the hypothesis that somatosensory acuity would be significantly different between ACLR individuals and healthy control limbs [H1]. Specifically, TDPM would be larger in the ACLR limbs at three months post-surgery than in the healthy controls [H1a]. In addition, JPS error would be larger in the ACLR limbs at three months post-surgery than in the healthy controls [H1b]. The second hypothesis tested was that somatosensory acuity would be improved by SR stimulation [H2]. Specifically, both TDPM [H2a] and JPS error [H2b] would be reduced in the presence of SR noise.

2. Methods

2.1. Participants

Twenty-eight healthy female participants [age 24 (4) (mean (SD)) years, height 166 (5) cm, body mass 59.2 (5.6) kg, self-reported training hours per week of 6 (3) hrs./wk., and BMI of 21.6 (1.8) kg/m^2]. Nineteen female participants with a unilateral ACLR (uninjured contralateral) at three months post-surgery were also recruited and tested [age 25(5) years, height 167 (8) cm, body mass 68.1 (11.8) kg, self-reported training hours per week 5 (3) hrs./wk., and BMI 24.4 (3.7) kg/m^2]. All ACLR participants were operated by one orthopedic surgeon (N.G.H.M.) with patellar tendon (n = 12) or hamstring graft (n = 7) ACL reconstruction techniques. Three months post-surgery is an important stage since some research suggests that ACL patients should return to light sporting activities (Scranton et al., 2002; Ejerhed et al., 2003; Kvist, 2004).

ACLR individuals were excluded by an orthopedic surgeon (N.G.H.M.) if they had: any major injury to any other knee structures except the ACL, any previous history of lower limb injury (joint required medical attention, treatment, or rehabilitation following the injury), needed assistive devices or showed abnormal effusion, range of movement or joint instabilities, been prescribed a knee brace prior to surgery, and/or surgical interventions performed on other joint structures during the surgery. Pregnant participants, or participants who had used any medication that might have altered their nervous and/or muscular performance were also excluded (Butler et al., 2006).

All participants provided written consent to participate in this Conjoint Health Research Ethics Board (University of Calgary) approved study.

2.2. Experimental setup

Participants were situated in the Biodex machine (Biodex Medical Systems, Inc., Shirley, New York) and the knee was passively flexed to 15°. All angles are reported compared to the average of three maximum knee extension angles with the participant's thigh on the seat. Mechanical noise was applied to the knee using an array of five C2 vibrotactile transducers (Engineering Acoustics Inc., Casselberry, FL, USA) (Fig. 1). The optimal location of the vibrators was determined through a pilot study prior to testing including the following arrangements: (1) All vibrators on Quadriceps, (2) All on Hamstring group, (3) Three vibrators on Hamstring two on calf muscles, (4) Three on quadriceps and two on Hamstring. The effect of placement didn't reach significance while the outcomes suggested that selected configuration (1) trended toward the smallest TDPM.

The vibrotactile transducers were controlled using ATC 3.0 software (Engineering Acoustics Inc., Casselberry, FL, USA) that included a "white noise" generator to administer a band-limited white noise (1–500 Hz). The stimulus intensity level of 90% of the vibration sensation threshold was selected according to (Priplata et al., 2002, 2006; Postema et al., 2009; Dettmer et al., 2015), ensuring that participants were unable to detect the vibration. To measure the vibration sensation threshold, the amplitude of stimulation was set to zero, then gradually increased. The lowest amplitude that the participant was able to feel the vibration was recorded. Two practice trials were performed to familiarize the participant with the protocol. The average of five measurements separated by 30 seconds of rest between trials was used as the vibration sensation threshold.

2.2.1. The threshold to detection of a passive movement (TDPM)

During the kinesthesia tests (TDPM), participants wore earplugs (to block external audio stimuli) and were instructed to close their eyes (to block external visual stimuli) while paying close attention to the knee movement. Participants were instructed to press a stop-button as soon as a joint movement was perceived. The angular displacement was recorded at 0.1° precision. Participants were asked to determine the direction (flexion vs. extension) of the passive movement. If the direction was determined incorrectly, the trial was repeated (occurred <10 times during 62 data collection sessions with 10 trials/session).

An angular velocity of 0.25°/sec was used for the passive flexion/extension. This slow angular velocity was selected to maximize the stimulation of joint receptors while minimizing the stimulation of muscle receptors surrounding the joint (Lephart and Fu, 1995; Fridén et al., 2001). Three practice trials (not recorded) followed by five trials were measured for each SR condition (ON vs. OFF). The outcome was the average of absolute values of the difference between 15° and the angle at which the dynamometer was paused (in degrees). Participants were blinded to the SR status (ON vs. OFF).

2.2.2. Joint position sense (JPS) test

To determine the JPS, two sets of experiments were conducted. First, the knee was positioned at 15° and then flexed passively to

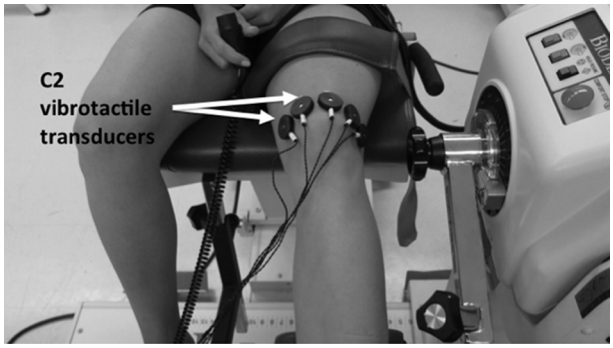

Fig. 1. Experimental setup on the Biodex machine (Biodex Medical Systems, Inc., Shirley, New York) with the five C2 vibrotactile transducers attached.

the target angle of 45°. Participants were instructed to memorize the new position (45° while held at that angle for three seconds. The knee was then extended back to the original position (15°). Next, the dynamometer passively flexed the joint at the rate of 10°/sec. Participants were asked to press the stop-button whenever the knee flexion reached the desired memorized target angle (45°). The test was passive to minimize pain and discomfort in the ACLR cohort during extension (reported by some participants during pilot studies). The JPS error was the absolute difference between the target angle (45°) and the angle reproduced by the participant. In the second set of experiments, the order of angles was reversed (i.e., knee positioned at 45° extended to a target angle of 15° and then flexed to 45°). Three practice trials (not recorded) followed by five trials of data collection were recorded for each SR condition (ON vs. OFF).

2.2.3. Summary

Each limb (ACLR or control) was tested in two conditions: once with SR ON and once with SR OFF. During each condition, ten trials of TDPM and ten trials of JPS were collected (in both cases, 5 flexions and 5 extensions = 10 trials total). The average of 10 trials for each condition was calculated leading to 4 values per limb used for the data analysis: (1) JPS when SR was ON (2) JPS when SR was OFF (3) TDPM when SR was ON, and (4) TDPM when SR was OFF. To exclude any potential residual effect of SR on somatosensory acuity, all SR OFF (baseline) trials were collected together and all SR ON trials were collected together. To control the effect of SR order (ON vs. OFF), a counterbalanced design was selected where, for half of the participants, the SR OFF trials were collected initially while for the remaining participants SR ON trials were collected first. In SR ON trials, the SR stimulation started approximately five seconds in advance and remained ON between these trials.

2.3. Statistical analysis

The Shapiro-Wilk test was performed to verify normality prior to the parametric statistical tests. Potential differences in somatosensory acuity between healthy and ACLR groups (H1 and H2) were assessed using a Multivariate analysis of variance for the within-group factor of SR (noise vibration OFF vs. ON) and the between-group factor of health condition (healthy dominant vs. ACLR). To address H1a, H1b, H2a, and H2b (i.e., the changes in JPS and TDPM) for within factor of SR and between factor of health condition, a 2×2 mixed-model repeated measures analysis of variance (ANOVA) was performed. The significance level of $p < 0.05$ was selected for all statistical analyses with the Bonferroni correction applied to post-hoc comparisons. The p-values and the corresponding η^2 are reported, where η^2 is a measure of effect size in the ANOVA (Pierce, Block and Aguinis, 2004).

3. Results

A significant difference was observed between the ACLR and healthy control limbs for the grouped somatosensory measures (JPS error and TDPM) ($p = 0.007$; $\eta^2 = 0.201$). Therefore [H1] was supported. The somatosensory response in ACLR and healthy limbs was significantly altered with the SR treatment ($p = 0.012$; $\eta^2 = 0.181$) supporting [H2]. No significant interaction between SR and health condition was observed ($p = 0.321$; $\eta^2 = 0.05$) indicating that the findings were not confined to a certain participant group (i.e., ACLR or healthy controls).

The outcome of somatosensory acuity measures (JPS and TDPM) for the factors of limb side and SR are summarized graphically in Fig. 2. Specifically, TDPM for the study factors of SR and limb side are demonstrated in Fig. 2(b). The ACLR limb showed a larger TDPM by 0.3 ± 0.1° (mean ± SE) compared to the healthy controls ($p = 0.002$; $\eta^2 = 0.191$). However, although the outcome of JPS showed a trend toward larger values (poorer proprioception) in the ACLR limb compared to the healthy controls (Fig. 2(a)), the difference (0.1 ± 0.1°) was not significant ($p = 0.356$). The vibration

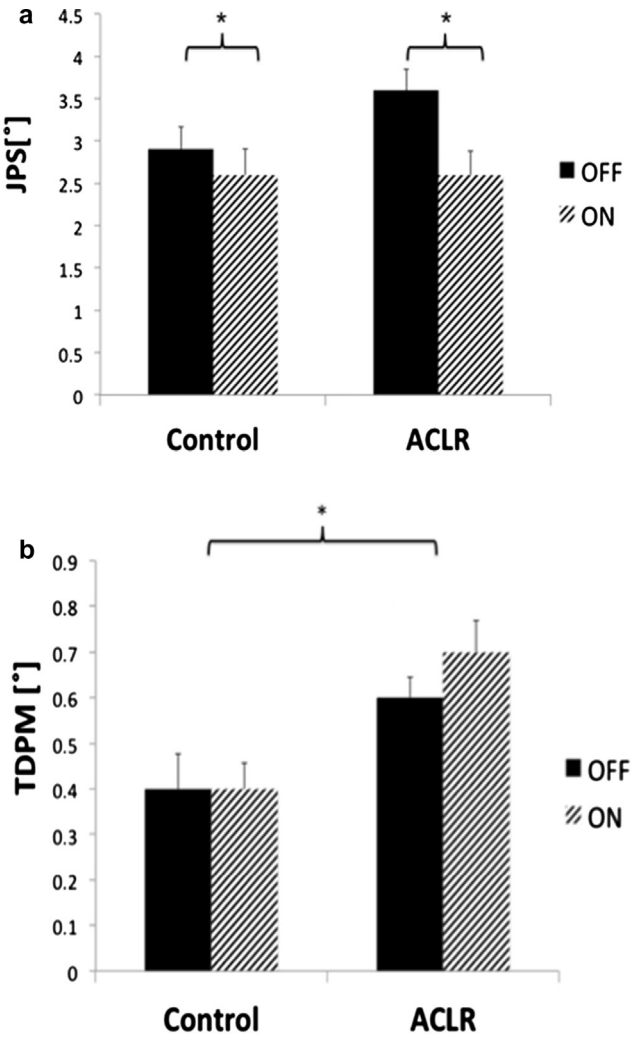

Fig. 2. Somatosensory function results for the control (n = 28) and ACLR (n = 19) groups: (a) results for the joint position repeatability (JPS) error. Significant JPS differences were observed between SR ON and OFF in each limb (b) Results for the threshold to detection of a passive movement (TDPM). Significant TDPM differences were observed between ACLR and control limbs. Error bars represent the standard error. The black and the hatched bars represent SR OFF and ON, respectively. The * shows presence of a significant difference at p = 0.05.

(SR ON) reduced the JPS error ($p = 0.006$; $\eta^2 = 0.155$) by an average of 0.7 ± 0.2° with a more pronounced decrease in the JPS error with vibration (SR ON) in the ACLR (1.0 ± 0.1°) than the healthy cohort (0.3 ± 0.2°). This finding indicates that the SR phenomenon was observed and affected the ACLR cohort to a larger extent. However, the application of vibration (SR ON) did not significantly alter the TDPM ($p = 0.681$ with a difference of 0.0 ± 0.1°).

4. Discussion

The current study investigated the somatosensory effect of SR in ACL reconstructed patients at three months post ACL reconstruction surgery compared to healthy controls. The study findings demonstrated that SR stimulation improved somatosensory acuity in both the ACLR group and the healthy controls. This study supported the first hypothesis [H1] and determined a significant somatosensory difference between the ACLR limbs compared to the healthy controls (Fig. 2). The findings of a significantly larger TDPM in the ACLR limb compared to the healthy controls supported sub-hypothesis [H1a]. In agreement with the directionality of [H1b], the JPS error showed a trend towards larger values in the ACLR limb compared to healthy controls. However, the difference between the JPS in the ACLR and healthy controls was not statistically significant and [H1b] was not supported. A significant change in somatosensory acuity in the presence of SR supported the second hypothesis [H2] (Fig. 2). Specifically, SR reduced the JPS error and thus hypothesis [H2b] was supported. However, the TDPM was not statistically significantly altered by SR and [H2a] was not supported.

The TDPM was significantly larger in the ACLR group compared to healthy controls. The TDPM measures the amount of passive movement in the knee before the movement is detected by the CNS (Ellenbecker et al., 2012). A larger TDPM implies that a larger knee movement is required before CNS detection. This finding might be important from an injury risk perspective. A higher risk of ACL or secondary injuries to the knee in the ACLR population are generally reported (Mandelbaum et al., 2005; Ben-Amar and André, 2006), where poor kinesthesia was suggested to be a potential risk factor (Ben-Amar and André, 2006). Moreover, despite improving the JPS, SR stimulation was unable to improve the TDPM. This might suggest that the TDPM, although deficient in the ACLR limb, is functioning at its optimal level with a systematic deficiency that might not be improved by SR.

The difference in JPS error was absent between ACLR and healthy control groups although, a trend towards larger JPS error values was observed in the ACLR group. One explanation is that the proprioception measured by the passive JPS protocol may be fully restored in the injured knee after three months post-surgery as was also suggested previously (Fremerey et al., 2001; Reider et al., 2003; Angoules et al., 2011). Alternatively, given the observed power of 24%, a larger sample size might be needed to provide satisfactory statistical power to discriminate the JPS in two cohorts (e.g. n = 252 for a power of 80%, 2-sided test at p = 0.05).

Larger improvement in proprioception might be expected if the cohort was able to participate in an active JPS protocol. Muscle afferents are mostly inactive during passive movements (Han et al., 2016). Sensory receptors in muscles (muscle spindle primary and secondary endings) are one of the major contributors to somatosensory acuity of the knee (Ageberg, 2002). These ending have shown improved sensory signal quality in the presence of SR stimulation (Fallon, 2004). It is likely that the small magnitude of changes observed in JPS by SR in the current paper is attributed to the inactivity of these afferents due to the passive JPS protocol. In an active JPS protocol it is likely that additional aspects of motor control will be tested along with the sensory system (Elangovan et al., 2014). As SR was shown to improve function in the motor system (Martinez et al., 2007) and sensory system (in the current study), it is likely that a larger improvement in the active JPS might be observed with SR whenever the health status of the cohort allows for such a protocol. Furthermore, the active method may more appropriately represent the lower limb muscle activities during functional tasks.

The current study was not designed to identify the underlying mechanism of SR and its related effects on the somatosensory feedback system. SR stimulation was previously shown to improve signal transmission from tactile (Collins et al., 1996; Wells et al., 2001; Dhruv et al., 2002; Liu et al., 2002; Well et al., 2005) and Golgi-tendon afferents (Fallon, 2004). It can be theorized that combined signal improvement in the discharge from the cutaneous and ligamentous receptors might have led to improved somatosensory signal transmission. Future research might provide further insights regarding the underlying mechanisms.

To date, only a few studies have directly measured changes in somatosensory acuity through SR using a locally applied electrical noise stimulation (Collins et al., 2009; Collins, 2010; Collins et al., 2011b). The amplitude of the changes in JPS and TDPM through SR in the current study is comparable to these findings. For example, the JPS error was reduced (improved) by 0.1° to 0.2° when a knee sleeve and noise stimulation was applied during partial and full load-bearing tasks in healthy young adults (Collins et al., 2009). Similarly, in osteoarthritis patients, an improvement of 0.7in JPS error was reported under partial weight bearing with noise stimulation and a sleeve (Collins et al., 2011b). However, comparisons to the current study are limited due to the differences in the clinical population, type of noise, the presence of knee sleeves, and slightly different experimental setup.

SR stimulation has promising clinical and research potential. Ross and colleagues showed that coordination training accompanied by SR stimulation in participants with ankle instability led to better postural balance (Ross et al., 2007) and single leg jump-landing outcomes (Ross and Guskiewicz, 2006). Training with SR might help reduce the likelihood of recurrent ankle sprain (Ross et al., 2007) and rehabilitate/improve postural stability more quickly and to a greater extent (Ross and Guskiewicz, 2006). Future studies in the knee might determine if SR stimulation reduces the risk of re-injury in the ACLR cohort, and if rehabilitation outcomes will be more promising in the presence of this treatment. Furthermore, the effect of repeated exposure on somatosensory function can be explored. Since some research has correlated the risk of knee injury to somatosensory deficiency in the joint (Barrett, 1991; Bali, Prabhakar and Dhillon, 2011), the effect of SR stimulation on reducing the risk of ACL injury can be investigated during physical activities with a high risk of knee injury (e.g. soccer, hockey, football). Lastly, the positive effect of SR may be explored in the healthy cohort in its potential to reduce the risk of knee problems including ACL injury.

5. Limitations

Female participants with limited and minimal injuries to structures of the knee other than ACL were recruited and tested to limit the confounding study variables and isolate the role of the ACL in providing somatosensory feedback. This may limit the scope of this work to groups of similar demographics. If patients with more extensive knee injuries had been recruited and tested, a more pronounced somatosensory deficiency might have been observed. Further, improvements in proprioception with SR might become more pronounced with more extensive joint impairment (Dettmer et al., 2015). A two-tailed Pearson correlation analysis was performed to

study the correlation between somatosensory improvements with SR with respect to the corresponding values at baseline. Significant positive correlations between changes against baseline in the JPS ($r = 0.523$; $p < 0.001$) and the TDPM ($r = 0.628$; $p < 0.001$) were observed in the current study. Moreover, SR stimulation may have a lower impact on the somatosensory function of healthy individuals due to a floor effect (i.e., when all participants show small error in their TDPM or JPS scores). This limitation might be resolved by comparing to a control group of ACLR participants through cross-over design.

The ACLR cohort displayed larger BMI compared to the healthy cohort. The BMI in three ACLR participants fell within the 25–30 kg/m^2 margin that might be categorized as overweight. Since in females the subcutaneous body fat shows a tendency to be stored in the lower limb, the larger BMI in the ACLR cohort can be speculated to have negatively affected the SR stimulation. However, a two-tailed Pearson correlations analysis between BMI and improvements in TDPM and JPS due to SR did not support this speculation (TDPM ($r = -0.081$; $p = 0.56$) and JPS ($r = -0.066$; $p = 0.66$)) supporting that the current findings are not likely biased by the effect of subcutaneous fat.

The current study did not specifically screen individuals to determine if they possessed somatosensory deficiency. As suggested by previous literature, some ACLR patients may present with these deficits, while others may not. As the potential exists for ceiling effects of the SR stimulation, only evaluating the effects in patients who possess these deficits may yield a stronger effect and different results.

6. Conclusions

The current findings contribute new insights into somatosensory deficiencies in individuals with ACLR. The effect of SR on the somatosensory acuity of the knee has been evaluated for the first time in an ACLR group by applying mechanical vibration to the knee area. SR was shown to improve JPS in healthy and ACLR cohorts.

Conflict of interest

The authors have no conflict of interest.

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