Physical Therapy in Sport 40 (2019) 71–77

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original Research

The effects of patellar tendon vibration on quadriceps strength in anterior cruciate ligament reconstructed knees

John Goetschius [a, *], Jay Hertel [b], Susan Saliba [b], Stephen F. Brockmeier [b], Joseph M. Hart [b]

[a] Adrian College, Adrian, MI, USA
[b] University of Virginia, Charlottesville, VA, USA

ARTICLE INFO

Article history:
Received 2 July 2019
Received in revised form
29 August 2019
Accepted 30 August 2019

Keywords:
Disinhibitory
Weakness
Graft
Gamma loop

ABSTRACT

Objectives: To examine the immediate effects of prolonged patellar tendon vibration on quadriceps strength in anterior cruciate ligament reconstructed (ACLR) knees with bone-patellar tendon-bone (BTB) grafts and non-BTB grafts, and healthy control knees.
Design: Pretest-posttest design.
Setting: Laboratory.
Participants: Young adult participants were stratified into one of three groups: non-BTB graft (n = 25), BTB graft (n = 26), and controls without ACLR (n = 21).
Main outcome measures: Maximum voluntary isometric contraction (MVIC) knee extension torque was measured at baseline and following a 20-min vibration intervention applied locally to the patellar tendon.
Results: Our findings suggest there was no difference in the effects of vibration on knee extension torque between the three groups. Knee extension torque significantly increased (effect size = 0.52 [0.18 to 0.81]) from baseline to post-vibration across all three groups (0.30 ± 0.26 Nm/kg, 21.8 ± 20.0%). Both ACLR groups demonstrated significantly lower knee extension torque compared the control group.
Conclusions: The vibration intervention had a net excitatory effect on quadriceps strength in all three groups and there were no differences in the magnitude of change between the three groups. Vibration could become a useful tool for enhancing quadriceps strength in ACLR and healthy knees.

1. Introduction

Anterior cruciate ligament reconstruction (ACLR) is a common elective treatment option for physically active individuals that suffer an anterior cruciate ligament (ACL) injury and wish to restore joint stability and return to physical activity. Despite post-surgical rehabilitation, evidence suggest that impairments in quadriceps strength are commonly present in patients with ACLR when attempting to return back to physical activity,(L. K. Lepley, 2015) and that these impairments may persist for up to 20-years after ACLR surgery.(Tengman, Brax Olofsson, Stensdotter, Nilsson, & Hager, 2014) Additionally, lower quadriceps muscle strength in patients with ACLR has been associated with poorer self-reported knee function(Goetschius & Hart, 2016; B G; Pietrosimone, Lepley, Ericksen, Gribble, & Levine, 2013), altered knee biomechanics during gait (Lewek, Rudolph, Axe, & Snyder-Mackler, 2002) that may expose the joint to abnormal tissue stresses(Andriacchi & Mundermann, 2006), and early signs of knee joint osteoarthritis such as tibiofemoral joint space narrowing(Tourville et al., 2014).

Researchers have theorized that the immediate and persistent impairments in quadriceps muscle function following ACLR may be due to adaptations in the neural pathways that regulate neuromuscular function(Ingersoll, Grindstaff, Pietrosimone, & Hart, 2008; Brian G Pietrosimone, McLeod, & Lepley, 2012; David Andrew Rice & McNair, 2010). Post-traumatic adaptations in afferent signals from peripheral receptors in the muscles and/or articular tissues are theorized to present secondary to ACLR and alter sensorimotor integration of excitatory and inhibitory neural pathways (Johansson, Sjolander, & Sojka, 1990; Y. Konishi, Fukubayashi, & Takeshita, 2002a; David Andrew Rice & McNair, 2010). Adaptations in peripheral, spinal, and supraspinal levels of quadriceps neuromuscular function have been observed in patients with a history of ACLR (A. S. Lepley et al., 2019; Luc-Harkey et al.,

* Corresponding author. 110. S. Madison Street Adrian, MI 49221, USA
E-mail address: jgoetschius@adrian.edu (J. Goetschius).

https://doi.org/10.1016/j.ptsp.2019.08.014
1466-853X/© 2019 Elsevier Ltd. All rights reserved.

2017; Norte, Hertel, Saliba, Diduch, & Hart, 2018). The presence of these neuromuscular adaptations may limit the effectiveness of conventional strengthening exercises during rehabilitation and account for the persistent impairments in quadriceps strength for years after ACLR surgery.

Various forms of local vibration and whole-body vibration have been presented in the literature as interventions to both study and treat impairments in quadriceps strength in a variety of knee pathologies(Costantino, Bertuletti, & Romiti, 2018; Y.; Konishi, Fukubayashi, & Takeshita, 2002b; Y.; Konishi et al., 2002a; D N; Pamukoff et al., 2016a,b; D A; Rice, McNair, & Lewis, 2011). Theoretically, vibration can mechanically stimulate sensory mechanoreceptors, such as muscle spindles, and alter the sensory afferent signals that directly influence muscle excitation and alter peripheral, spinal, and supraspinal pathways (Derek N Pamukoff et al., 2016a,b; Roll, Vedel, & Ribot, 1989; Shinohara, 2005). Researchers have used prolonged patellar tendon vibration to study and identify potential neuromuscular adaptations underlying ACLR related quadriceps dysfunction(Y. Konishi, Aihara, Sakai, Ogawa, & Fukubayashi, 2007; Y. Konishi et al., 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). Those studies all observed that 20-min of patellar tendon vibration induced an expected decline in quadriceps strength in healthy control knees but that vibration had no effect on quadriceps strength in knees with ACLR (Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). Researcher theorized that this abnormal response to vibration in knees with ACLR may be a sign of an underlying adaptation in the gamma-loop, a reflexive neural pathway important to neuromuscular function, which is facilitating impairments in quadriceps strength (Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006) Alternatively, other researchers have used of vibration as a possible disinhibitory intervention to treat quadriceps dysfunction. Researchers have examined the effects of various forms local and whole-body vibration to enhance measures of quadriceps force production, spinal-reflex excitability, and corticomotor excitability in patients with a history of ACLR (Costantino et al., 2018; D N; Pamukoff et al., 2016a,b; Derek N; Pamukoff et al., 2017).

A collection of studies suggest that prolonged patellar tendon vibration may provide a technique to identify the presence of underlying adaptations in quadriceps neuromuscular function in patients with ACLR. This vibration technique could assist in further study of neural pathways of muscle dysfunction and possibly provide an opportunity to develop more targeted clinical intervention; however, additional research is still needed. Previous studies examining this vibration technique did not include patients with a history bone-patellar tendon-bone (BTB) autograft in an effort to limit the potential effects that harvesting the middle-third of patellar tendon could have on the technique, so we do not know whether their findings are actually applicable to an important population of patients with ACLR (Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). BTB is one of the most commonly utilized ACLR grafts in clinical practice and some evidence suggests that patients with BTB may experience greater impairments in quadriceps strength compared to hamstring grafts (Dempsey et al., 2019; Mohtadi, Chan, Dainty, & Whelan, 2011). In order to substantiate this vibration technique we need to confirm whether the findings previously observed in patients with non-BTB grafts are also present in patients with BTB grafts. Therefore, purpose of this study was to compare the effects of prolonged patellar tendon vibration on knee extension torque in ACLR knees with BTB grafts, ACLR knees with non-BTB grafts, and control knees without ACLR. Based on the findings of previous studies (Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006), we hypothesized that the patellar tendon vibration intervention would have no effect the ACLR groups but cause a significant decline in knee extension torque in the control group.

2. Methods

Our study was completed in a controlled laboratory setting. We had two independent variables: three groups, ACLR with a BTB graft (BTB), ACLR with a non-BTB graft (non-BTB) and healthy controls (control), and two times, baseline and post-vibration. Our primary dependent variable was knee extension torque during a maximal voluntary isometric contraction (MVIC). All participants completed a baseline measure of knee extension torque, then a 20-min patellar tendon vibration intervention, followed by a post-vibration measure of knee extension torque. Data collection was performed on a single test limb, the ACLR limb or a randomly selected limb for healthy control participants. Our study was approved by our University's institutional review board for health sciences research and all participants provided written informed consent.

2.1. Participants

Eighty-three individuals were recruited using convenience sampling. A total of seventy-five participants were enrolled in this study; however, two participants dropped-out because they felt the vibration intervention was “uncomfortable” (one BTB, one control) and one participant (non-BTB) was excluded from the final analyses because their age and years post-surgery were outliers, resulting in seventy-two ($n = 72$) participants included in the final analyses. Participants with ACLR had a history of primary, unilateral ACLR 9-months or greater before testing and had returned back to exercise/sport with no physical activity restrictions by a healthcare provider (Table 1). Participants with ACLR were excluded if they had a history of multi-ligament knee surgery, surgical complications, or bilateral knee joint surgery. There were no restrictions on participation based on ACLR graft type or a history of meniscectomy or repair at the time of ACLR; however, participants with active meniscal symptoms (joint line pain, clicking) were not included. Twenty-six ($n = 26$) participants with ACLR were stratified into the BTB group if their ACLR was performed with a BTB autograft, and twenty-five ($n = 25$) participants with ACLR were stratified into the non-BTB group if their ACLR was performed with a hamstring autograft ($n = 17$) or cadaver allograft ($n = 8$). Twenty individuals ($n = 20$) with no history of lower extremity injury or surgery, and no current symptoms of lower extremity pain or neuropathy participated as controls without ACLR (Table 1). All participants were between the ages of 18–35 and were recruited from our local community and University-based Sports Medicine sub-specialty orthopaedic surgery practice. All participants completed the international knee documentation committee subjective knee evaluation form (IKDC)(Irrgang et al., 2001), and Godin Leisure-Time Activity Scale (Godin)(Godin & Shephard, 1985) for descriptive purposes.

2.2. Knee extension torque

We measured knee extension MVIC torque using a Biodex System III dynamometer (Biodex Medical Systems, Inc. Shirley, NY). Participants were seated with knees and hips flexed to 90° and 80°, respectively. We aligned the dynamometer axis with knee joint center and secured the torque arm to the test leg just superior to the malleoli. Participants sat upright with back flat against the seat and arms across the chest. We measured the average peak torque produced during three knee extension MVICs at baseline and post-vibration. Participants were instructed to gradually increase contraction intensity and to hold the contraction steady at maximal

Table 1
Demographic variables in ACL reconstruction groups and control group.

	Non-BTB(n = 25)	BTB(n = 26)	Control(n = 21)
Sex $_{F,M}$	19 female, 6 male	18 female, 8 male	13 female, 8 male
Age $_{years}$	21.7 ± 3.4	24.1 ± 5.4	22.2 ± 3.1
Mass $_{kg}$	64.3 ± 8.6	71.6 ± 12.5	70.54 ± 14.0
Height $_{m}$	1.7 ± .09	1.74 ± .09	1.71 ± .12
IKDC $_{0-100}$	86.0 ± 9.8[a]	87.4 ± 8.2[a]	99.3 ± 2.1
Godin	69.8 ± 18.6	63.5 ± 24.0	69.6 ± 19.9
Years Post-Surgery	4.2 ± 3.8 (0.8–13.5)	4.7 ± 3.2 (1.0–14.2)	NA

[a] Significantly lower than control group, b Significantly greater than the combined ACLR groups. BTB = bone-tendon-bone graft, IKDC = International Knee Documentation Committee Subjective Knee Evaluation Score, Godin = Godin Leisure-Time Activity Score.

contraction. Prior to baseline testing, participants completed four progressive warm-up contractions at 25, 50, 75, and 100% for testing familiarization. We performed post-vibration testing immediately following the conclusion of the vibration intervention. No warm-up contractions were completed prior to the post-vibrating testing in effort to avoid missing the potential effects of vibration.

2.3. Vibration intervention

We delivered the vibration intervention using a commercially available Deep-Tissue Percussion Therapeutic Massager (Wahl Clipper Corporation, Sterling, IL) with a modified applicator constructed from a rubber reflex-hammer head (Fig. 1). The vibration device was secured to stand made of metal framing strut. The device and stand were placed anterior to the test leg and positioned firmly against the anterior knee so that the applicator was aligned with the mid-substance of the patellar-tendon, central to the inferior patella and the tibial tuberosity(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). The vibration intervention was applied continuously for 20-min(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006), at a frequency of 50 Hz(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006), and an amplitude of 5.0 mm. Participants remained seated and secured in the dynamometer chair during the intervention and were instructed to sit still and to keep their leg muscles relaxed.

Figure 1. Patellar tendon vibration intervention set-up.

2.4. Data processing

Knee extension torque data were digitized at 125 Hz and smoothed using a moving median filter (10 samples) in AcqKnowledge 4.2 (Biopac Systems, Inc., Goleta, CA). We processed the average torque (Nm) over a 1.0-s epoch during peak MVIC for each trial, calculated the average of the 3 trials at baseline and post-vibration, and normalized the average knee extension torque by participants' body mass (Nm/kg).

2.5. Statistical analyses

We first performed Shapiro-Wilk and Levene's tests to examine normality and homogeneity of our data. We performed between group comparisons of participant's age, mass, height, IKDC, and Godin scores using separate one-way ANOVAs (LSD post-hoc) and comparisons of participant's sex using a Pearson's chi-square test. We also compared years post-surgery between the two groups with ACLR using an independent *t*-test. We compared knee extension torque between the three groups (non-BTB, BTB, Control) and times (baseline, post-vibration) using a 3×2 ANOVA with repeated measures. We calculated the post-vibration change (Nm/kg) and percent change (%) from baseline to post-vibration to describe the magnitude of change in knee extension torque. Significant time effects were further analyzed using Cohen's d effect sizes with 95% confidence intervals. Cohen's d effect size point estimates were interpreted as <0.2 = minimal, ≥ 0.2 = small, ≥ 0.5 moderate, ≥ 0.8 = large(Cohen, 1988). For exploratory purposes, we also examined whether the magnitude of impairment in quadriceps strength was associated with the magnitude of change in knee extension torque by calculating Pearson r correlation coefficients between the baseline knee extension torque and the post-vibration change in knee extension torque. Correlation coefficients (r) were interpreted as weak (0.0–0.4), moderate (0.4–0.7), or strong (0.7–1.0).(Goetschius & Hart, 2016).

3. Results

We observed no significant differences in age ($P = 0.11$), sex ($P = 0.59$), mass, ($P = 0.08$), height ($P = 0.15$), or Godin scores ($P = 0.49$) between the three groups, and no difference in years post-surgery between the BTB and non-BTB groups ($P = 0.86$) (Table 1). The BTB and non-BTB groups reported lower IKDC scores than the control group (both $P < 0.001$), but there were no differences in IKDC scores between the BTB and non-BTB groups ($P = 0.51$) (Table 1).

We observed no group by time interaction ($P = 0.78$), suggesting that there was no difference in the effects of vibration on knee extension torque between the three groups. We observed a significant time main-effect ($P < 0.001$), suggesting that there was a significant increase in knee extension torque (0.30 ± 0.26 Nm/kg, 21.8 ± 20.0%) from baseline to post-vibration across all three groups (Fig. 2). This significant increase across all three groups was supported by a moderate effect-size (d = 0.52 [0.18 to 0.81]). We also observed a significant group main-effect ($P = 0.03$), with post-hoc tests suggesting that knee extension torque was significantly lower in the non-BTB ($P = 0.03$) and BTB groups ($P = 0.02$) compared to the control group across the two time-points.

We observed moderate, negative correlations between baseline knee extension torque and mean change in knee extension torque in the BTB (r = −0.40, $P = 0.04$) and control (r = −0.51, $P = 0.02$) groups, suggesting that participants with lower baseline knee extension torque demonstrated a greater mean change in knee extension torque after the vibration intervention, but we did not observe the same relationship in the non-BTB group (r = 0.27, $P = 0.20$) (Fig. 3).

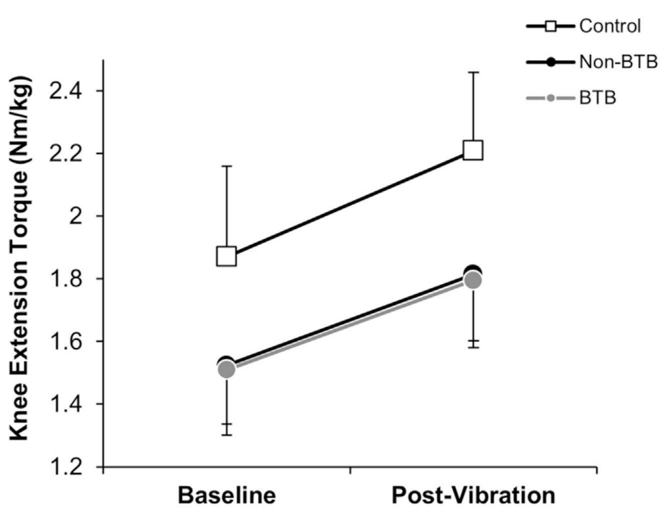

Fig. 2. Mean knee extension torque at baseline and post-vibration in the three groups with 95% confidence interval error bars. Knee extension increased from baseline to post-vibration in the three groups (P < 0.001).

4. Discussion

In contrast to our hypotheses, our primary findings were that 20-min of prolonged patellar tendon vibration caused an immediate increase in isometric knee extension torque production across all three groups, and that there were no differences in the effects of prolonged patellar tendon vibration on knee extension torque between the three groups, suggesting that neither a history of ACLR nor the patellar tendon graft harvesting affected the patellar tendon vibration intervention. Additionally, our exploratory correlational analyses suggest that the vibration intervention may have had a greater effect on increasing quadriceps strength in the participants with weaker baseline quadriceps strength in the BTB and control groups.

Contrary to our findings, previous studies that also examined the immediate effects of 20-min of prolonged patellar tendon vibration on isometric knee extension torque have reported declines in quadriceps strength in healthy knees and no changes in quadriceps strength in ACLR knees following vibration(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). Those researchers theorized that the decline in quadriceps strength observed in the healthy participants may be due to a reduction in excitatory Ia afferent feedback from the muscle spindles over the course of the prolonged 20-min of repeated vibration stimuli, possibly due to an increased discharge threshold of Ia afferents, presynaptic inhibition of the Ia afferents or neurotransmitter depletion at the Ia synapses(Roll et al., 1989; Shinohara, 2005), which results in a net decrease in alpha motor neuron excitation and quadriceps muscle activation(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). In ACLR knees, researchers theorized that the absence of this "normal" decline in quadriceps strength in response to prolonged patellar tendon vibration may be a sign of dysfunction in normal muscle spindle Ia afferents and regulation by the "gamma-loop"(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). In contrast to these previous studies, we observed increases in quadriceps strength following our 20-min patellar tendon vibration protocol in both ACLR and healthy knees.

While our vibration protocol was similar in terms of vibration location (patellar tendon), duration (20-min), and frequency (50 Hz) as previous studies(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006), we theorize that the discrepancy in the effects of vibration on quadriceps strength may

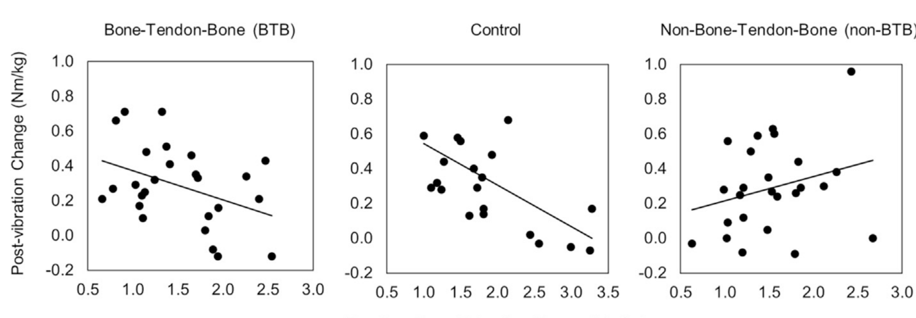

Fig. 3. Scatter-plots showing the relationship between baseline knee extension torque (Nm/kg) and the post-vibration change in knee extension torque (Nm/kg).

be due to the fact that vibration device used in our study had a much larger vibration amplitude of 5.0 mm compared the 1.5 mm vibration amplitude that had been used in previous studies(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). Our decision to use the 5.0 mm vibration amplitude was based on the manufacturer settings of the vibration device that we had available in our lab. Interestingly, our findings suggest that application of the larger amplitude patellar tendon vibration over 20-min had a net excitatory effect on quadriceps muscle activation rather than the inhibitory effects that have been observed in previous studies using prolonged, smaller amplitude vibrations(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006). It may be possible that the observed changes were the result of an alternative effect of the larger amplitude vibration on muscle spindle Ia afferents, or that the large amplitude vibration stimulation was able to stimulate alternative afferent fibers, possibly arising from the golgi tendon organs or mechanoreceptors in the skin and articular tissues. However, additional research is needed in order to substantiate these theories. Previous research suggests that like most therapeutic modalities, variations in vibration parameters such as the vibration type, duration, frequency, amplitudes, and acceleration can cause an alteration in neuromuscular responses to vibration(Lienhard et al., 2015; D N; Pamukoff, Ryan, & Blackburn, 2014; Ritzmann, Gollhofer, & Kramer, 2013). Since our findings did not align with the trends observed in previous studies examining the effects of prolonged patellar tendon vibration in ACLR knees(Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006), we cannot make conclusions regarding our initial research question as to whether the dysfunctional gamma-loop response that had been reported in those studies is detectable in ACLR knees with BTB graft.

Our combined sample demonstrated an average increase in quadriceps strength of 22% (0.30 Nm/kg) following the vibration intervention. This increase in quadriceps strength was supported by a moderate effect size with 95% confidence intervals that did not include zero. One previous study also observed immediate increases in quadriceps strength in ACLR knees following two different vibration interventions that were both dissimilar to the current study's vibration intervention. Pamukoff et al. observed average increases in quadriceps strength of approximately 6.6% (0.12 Nm/kg) and 8.5% (0.15 Nm/kg) following a local vibration intervention applied directly to the quadriceps muscle belly and a whole-body vibration intervention, respectively(D N Pamukoff et al., 2016a,b). Dissimilar to our study, their vibration protocols consisted of 6 x 1-min bouts of vibration with 2-min rest between each bout (16-min intervention), at a frequency of 30 Hz, and amplitude of 1.6 mm(D N Pamukoff et al., 2016a,b). While these findings of immediate improvements in quadriceps strength following single vibration interventions are promising, additional research is still needed before applying these interventions to clinical practice. Interestingly, both our vibration protocol and the Pamukoff et al. protocols have demonstrated immediate improvements in quadriceps function in participants with healthy, non-ACLR knees in addition to those with ACLR (Derek N Pamukoff et al., 2016a,b), suggesting that vibration may be able to induce an additional excitation of neuromuscular pathways in both the presence and absence of joint related inhibition.

Researchers have theorized that persistent post-traumatic neural muscle inhibition may limit the effectiveness of conventional quadriceps strengthening therapeutic exercises in patients with a history of ACLR, prompting efforts to identify and study “disinhibitory” interventions, such as vibration, to alter neuromuscular excitability for a “window of time” before or during traditional therapeutic exercises with the goal of enhancing muscle adaptations(B. Pietrosimone et al., 2015). Incorporating therapeutic exercises during this window of enhanced muscle activity may provide an opportunity to enhance the effectiveness of conventional therapeutic exercises in ACLR knees. In support of this theory, one study has examined the use of disinhibitory cryotherapy during 2-weeks of quadriceps strengthening rehabilitation in patients with ACLR and quadriceps inhibition. The study observed greater improvements in quadriceps strength in patients with ACLR who performed all rehabilitation exercises immediately after 20-min of cryotherapy compared to patients who performed conventional exercises without cryotherapy(Hart, Kuenze, Diduch, & Ingersoll, 2014).

There is currently some evidence suggesting that ACLR rehabilitation may be enhanced by incorporating whole-body vibration on a vibration platform(Costantino et al., 2018). A recent randomized control trial observed greater improvements in quadriceps and hamstring strength in young, adult, female patients with ACLR that added whole-body vibration exercises into weeks 13–20 of their standard post-surgical rehabilitation compared to those who did not add the whole-body vibration exercises(Costantino et al., 2018). While our current findings were unexpected, these findings do suggest that future research examining the use of patellar tendon vibration as a clinical disinhibitory intervention for quadriceps strengthening in patients with ACLR may be warranted. One clinical advantage of the vibration protocol used in the current study is that device used for the vibration intervention is currently commercially available and affordable ($27.99 at Amazon) for clinicians.

There are important limitations to consider when interpreting the findings of this study. Our decision to not include a control or placebo intervention was in alignment with study designs from prior investigations comparing patellar tendon vibration in participants with and without ACLR, (Y. Konishi et al., 2007, 2002a; Y. U. Konishi, 2011; Richardson et al., 2006); however, the absence of a comparison intervention in the current study limits the internal validity and suggests that these findings should be interpreted with caution. Fortunately, previous studies from our lab (Norte, Frye, & Hart, 2015) and other labs (Park & Hopkins, 2013) suggest that within-session knee extension MVIC torque measurements at 90-degrees flexion are highly reliability (ICC = 0.86–0.99) in participants with a history of knee injury and non-injured controls, suggesting that no change should be expected when performing repeated isometric knee extension torque measures. Our sample consisted of primarily chronic patients with ACLR with a wide range of times post-surgery, which limits the clinical applicability of these findings to patients earlier after ACLR surgery for whom clinical care is typically focused. Additionally, in our sample of participants with ACLR (1.5 Nm/kg) and controls (1.9 Nm/kg), average baseline quadriceps strength was relatively low when compared to ACLR and control participants in the literature (Lisee, Lepley, Birchmeier, O'Hagan, & Kuenze, 2019). Since we only examined the immediate effects of the vibration intervention within the initial 1-min post-vibration, we do not know the duration of the effects and for long this disinhibitory “window” may have lasted. In one prior study, Pamukoff et al. examined the effects of their vibration protocols (described above) on quadriceps function in healthy adults, and observed that improved quadriceps corticomotor function was present up to 10 and 20-min post-vibration (Derek N Pamukoff et al., 2016a,b).

In conclusion, all three groups experienced significant increases in knee extension torque following the 20-min patellar tendon vibration intervention, suggesting the prolonged patellar tendon vibration intervention had a net excitatory effect on quadriceps strength. There were no differences in the magnitude of improvement in quadriceps strength between the three groups, suggesting that neither ACLR nor the patellar tendon graft harvesting influenced the magnitude of the effects of vibration.

Conflicts of interest

The authors have no conflicts of interest to report that could inappropriately bias this work.

Ethical approval

This study was approved by the University of Virginia Institutional Review Board for Health Sciences Research (IRB-HSR), and all participants provided written informed consent.

Funding

This study was supported by funding from the Curry School of Education at the University of Virginia.

Declarations of interest

None.

References

Andriacchi, T. P., & Mundermann, A. (2006). The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Current Opinion in Rheumatology, 18*(5), 514–518. https://doi.org/10.1097/01.bor.0000240365.16842.4e.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale (NJ: L. Erlbaum Associates.

Costantino, C., Bertuletti, S., & Romiti, D. (2018). Efficacy of whole-body vibration board training on strength in athletes after anterior cruciate ligament reconstruction: A randomized controlled study. *Clinical Journal of Sport Medicine, 28*(4), 339–349. https://doi.org/10.1097/JSM.0000000000000466.

Dempsey, I. J., Norte, G. E., Hall, M., Goetschius, J., Slater, L. V., Cancienne, J. M., et al. (2019). Relationship between physical therapy characteristics, surgical procedure, and clinical outcomes in patients after ACL reconstruction. *Journal of Sport Rehabilitation, 28*(2), 171–179. https://doi.org/10.1123/jsr.2017-0176.

Godin, G., & Shephard, R. J. (1985). A simple method to assess exercise behavior in the community. *Canadian Journal of Applied Sport Sciences. Journal Canadien des Sciences Appliquees au Sport, 10*(3), 141–146.

Goetschius, J., & Hart, J. M. (2016). Knee-extension torque variability and subjective knee function in patients with a history of anterior cruciate ligament reconstruction. *Journal of Athletic Training, 51*(1), 22–27. https://doi.org/10.4085/1062-6050-51.1.12.

Hart, J. M., Kuenze, C. M., Diduch, D. R., & Ingersoll, C. D. (2014). Quadriceps muscle function after rehabilitation with cryotherapy in patients with anterior cruciate ligament reconstruction. *Journal of Athletic Training, 49*(6), 733–739. https://doi.org/10.4085/1062-6050-49.3.39.

Ingersoll, C. D., Grindstaff, T. L., Pietrosimone, B. G., & Hart, J. M. (2008). Neuromuscular consequences of anterior cruciate ligament injury. *Clinics in Sports Medicine, 27*(3), 383–404. vii https://doi.org/10.1016/j.csm.2008.03.004.

Irrgang, J. J., Anderson, A. F., Boland, A. L., Harner, C. D., Kurosaka, M., Neyret, P., et al. (2001). Development and validation of the international knee documentation committee subjective knee form. *The American Journal of Sports Medicine, 29*(5), 600–613.

Johansson, H., Sjolander, P., & Sojka, P. (1990). Activity in receptor afferents from the anterior cruciate ligament evokes reflex effects on fusimotor neurones. *Neuroscience Research, 8*(1), 54–59.

Konishi, Y. U. (2011). ACL repair might induce further abnormality of gamma loop in the intact side of the quadriceps femoris. *Int J Sports Med, 32*(4), 292–296. https://doi.org/10.1055/s-0030-1270488.

Konishi, Y., Aihara, Y., Sakai, M., Ogawa, G., & Fukubayashi, T. (2007). Gamma loop dysfunction in the quadriceps femoris of patients who underwent anterior cruciate ligament reconstruction remains bilaterally. *Scandinavian Journal of Medicine & Science in Sports, 17*(4), 393–399. https://doi.org/10.1111/j.1600-0838.2006.00573.x.

Konishi, Y., Fukubayashi, T., & Takeshita, D. (2002a). Mechanism of quadriceps femoris muscle weakness in patients with anterior cruciate ligament reconstruction. *Scandinavian Journal of Medicine & Science in Sports, 12*(6), 371–375.

Konishi, Y., Fukubayashi, T., & Takeshita, D. (2002b). Possible mechanism of quadriceps femoris weakness in patients with ruptured anterior cruciate ligament. *Medicine & Science in Sports & Exercise, 34*(9), 1414–1418. https://doi.org/10.1249/01.mss.0000027628.04801.27.

Lepley, L. K. (2015). Deficits in quadriceps strength and patient-oriented outcomes at return to activity after ACL reconstruction: A review of the current literature. *Sport Health, 7*(3), 231–238. https://doi.org/10.1177/1941738115578112.

Lepley, A. S., Grooms, D. R., Burland, J. P., Davi, S. M., Kinsella-Shaw, J. M., & Lepley, L. K. (2019). Quadriceps muscle function following anterior cruciate ligament reconstruction: Systemic differences in neural and morphological characteristics. *Experimental Brain Research, 237*(5), 1267–1278. https://doi.org/10.1007/s00221-019-05499-x.

Lewek, M., Rudolph, K., Axe, M., & Snyder-Mackler, L. (2002). The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical Biomechanics, 17*(1), 56–63.

Lienhard, K., Vienneau, J., Nigg, S., Meste, O., Colson, S. S., & Nigg, B. M. (2015). Relationship between lower limb muscle activity and platform acceleration during whole-body vibration exercise. *The Journal of Strength & Conditioning Research, 29*(10), 2844–2853. https://doi.org/10.1519/JSC.0000000000000927.

Lisee, C., Lepley, A. S., Birchmeier, T., O'Hagan, K., & Kuenze, C. (2019). Quadriceps strength and volitional activation after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. *Sport Health, 11*(2), 163–179. https://doi.org/10.1177/1941738118822739.

Luc-Harkey, B. A., Harkey, M. S., Pamukoff, D. N., Kim, R. H., Royal, T. K., Blackburn, J. T., et al. (2017). Greater intracortical inhibition associates with lower quadriceps voluntary activation in individuals with ACL reconstruction. *Experimental Brain Research, 235*(4), 1129–1137. https://doi.org/10.1007/s00221-017-4877-8.

Mohtadi, N. G., Chan, D. S., Dainty, K. N., & Whelan, D. B. (2011). Patellar tendon versus hamstring tendon autograft for anterior cruciate ligament rupture in adults. *Cochrane Database of Systematic Reviews, 9*, CD005960. https://doi.org/10.1002/14651858.CD005960.pub2.

Norte, G. E., Frye, J. L., & Hart, J. M. (2015). Reliability of the superimposed-burst technique in patients with patellofemoral pain: A technical report. *Journal of Athletic Training, 50*(11), 1207–1211. https://doi.org/10.4085/1062-6050-50.10.03.

Norte, G. E., Hertel, J., Saliba, S. A., Diduch, D. R., & Hart, J. M. (2018). Quadriceps neuromuscular function in patients with anterior cruciate ligament reconstruction with or without knee osteoarthritis: A cross-sectional study. *Journal of Athletic Training, 53*(5), 475–485. https://doi.org/10.4085/1062-6050-102-17.

Pamukoff, D. N., Pietrosimone, B., Lewek, M. D., Ryan, E. D., Weinhold, P. S., Lee, D. R., et al. (2016a). Whole-body and local muscle vibration immediately improve quadriceps function in individuals with anterior cruciate ligament reconstruction. *Archives of Physical Medicine and Rehabilitation*. https://doi.org/10.1016/j.apmr.2016.01.021.

Pamukoff, D. N., Pietrosimone, B., Lewek, M. D., Ryan, E. D., Weinhold, P. S., Lee, D. R., et al. (2016b). Immediate effect of vibratory stimuli on quadriceps function in healthy adults. *Muscle & Nerve, 54*(3), 469–478. https://doi.org/10.1002/mus.25081.

Pamukoff, D. N., Pietrosimone, B., Ryan, E. D., Lee, D. R., Brown, L. E., & Blackburn, J. T. (2017). Whole-body vibration improves early rate of torque development in individuals with anterior cruciate ligament reconstruction. *The Journal of Strength & Conditioning Research, 31*(11), 2992–3000. https://doi.org/10.1519/JSC.0000000000001740.

Pamukoff, D. N., Ryan, E. D., & Blackburn, J. T. (2014). The acute effects of local muscle vibration frequency on peak torque, rate of torque development, and EMG activity. *Journal of Electromyography and Kinesiology, 24*(6), 888–894. https://doi.org/10.1016/j.jelekin.2014.07.014.

Park, J., & Hopkins, J. T. (2013). Within- and between-session reliability of the maximal voluntary knee extension torque and activation. *International Journal of Neuroscience, 123*(1), 55–59. https://doi.org/10.3109/00207454.2012.725117.

Pietrosimone, B., Blackburn, J. T., Harkey, M. S., Luc, B. A., Pamukoff, D. N., & Hart, J. M. (2015). Clinical strategies for addressing muscle weakness following knee injury. *Clinics in Sports Medicine, 34*(2), 285–300. https://doi.org/10.1016/j.csm.2014.12.003.

Pietrosimone, B. G., Lepley, A. S., Ericksen, H. M., Gribble, P. A., & Levine, J. (2013). Quadriceps strength and corticospinal excitability as predictors of disability after anterior cruciate ligament reconstruction. *Journal of Sport Rehabilitation, 22*(1), 1–6.

Pietrosimone, B. G., McLeod, M. M., & Lepley, A. S. (2012). A theoretical framework for understanding neuromuscular response to lower extremity joint injury. *Sport Health, 4*(1), 31–35. https://doi.org/10.1177/1941738111428251.

Rice, D. A., & McNair, P. J. (2010). Quadriceps arthrogenic muscle inhibition: Neural mechanisms and treatment perspectives. Seminars in arthritis and rheumatism. https://doi.org/10.1016/j.semarthrit.2009.10.001.

Rice, D. A., McNair, P. J., & Lewis, G. N. (2011). Mechanisms of quadriceps muscle weakness in knee joint osteoarthritis: The effects of prolonged vibration on torque and muscle activation in osteoarthritic and healthy control subjects. *Arthritis Research and Therapy, 13*(5), R151. https://doi.org/10.1186/ar3467.

Richardson, M. S., Cramer, J. T., Bemben, D. A., Shehab, R. L., Glover, J., & Bemben, M. G. (2006). Effects of age and ACL reconstruction on quadriceps gamma loop function. *Journal of Geriatric Physical Therapy, 29*(1), 28–34.

Ritzmann, R., Gollhofer, A., & Kramer, A. (2013). The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. *European Journal of Applied Physiology, 113*(1), 1–11. https://doi.org/10.1007/s00421-012-2402-0.

Roll, J. P., Vedel, J. P., & Ribot, E. (1989). Alteration of proprioceptive messages induced by tendon vibration in man: A microneurographic study. *Experimental Brain Research, 76*(1), 213–222.

Shinohara, M. (2005). Effects of prolonged vibration on motor unit activity and motor performance. *Medicine & Science in Sports & Exercise, 37*(12), 2120–2125.

Tengman, E., Brax Olofsson, L., Stensdotter, A. K., Nilsson, K. G., & Hager, C. K. (2014). Anterior cruciate ligament injury after more than 20 years. II. Concentric and eccentric knee muscle strength. *Scandinavian Journal of Medicine & Science in Sports, 24*(6), e501–e509. https://doi.org/10.1111/sms.12215.

Tourville, T. W., Jarrell, K. M., Naud, S., Slauterbeck, J. R., Johnson, R. J., & Beynnon, B. D. (2014). Relationship between isokinetic strength and tibiofemoral joint space width changes after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine, 42*(2), 302–311. https://doi.org/10.1177/0363546513510672.