Lumbopelvic Joint Manipulation and Quadriceps Activation of People With Patellofemoral Pain Syndrome

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Context: Quadriceps weakness and inhibition are impairments associated with patellofemoral pain syndrome (PFPS). Lumbopelvic joint manipulation has been shown to improve quadriceps force output and inhibition, but the duration of the effect is unknown.

Objective: To determine whether quadriceps strength and activation are increased and maintained for 1 hour after high-grade or low-grade joint mobilization or manipulation applied at the lumbopelvic region in people with PFPS.

Design: Randomized controlled clinical trial.

Setting: University laboratory.

Patients or Other Participants: Forty-eight people with PFPS (age=24.6±8.9 years, height=174.3±11.2 cm, mass=78.4±16.8 kg) participated.

Intervention(s): Participants were randomized to 1 of 3 groups: lumbopelvic joint manipulation (grade V), side-lying lumbar midrange flexion and extension passive range of motion (grade II) for 1 minute, or prone extension on the elbows for 3 minutes.

Main Outcome Measure(s): Quadriceps force and activation were measured using the burst superimposition technique during a seated isometric knee extension task. A 2-way re-

peated-measures analysis of variance was performed to compare changes in quadriceps force and activation among groups over time (before intervention and at 0, 20, 40, and 60 minutes after intervention).

Results: We found no differences in quadriceps force output ($F_{5,33,101.18}=0.65$, $P=.67$) or central activation ratio ($F_{4,84,92.03}=0.38$, $P=.86$) values among groups after intervention. When groups were pooled, we found differences across time for quadriceps force ($F_{2,66,101.18}=5.03$, $P=.004$) and activation ($F_{2,42,92.03}=3.85$, $P=.02$). Quadriceps force was not different at 0 minutes after intervention ($t_{40}=1.68$, $P=.10$), but it decreased at 20 ($t_{40}=2.16$, $P=.04$), 40 ($t_{40}=2.87$, $P=.01$) and 60 ($t_{40}=3.04$, $P=.004$) minutes after intervention. All groups demonstrated decreased quadriceps activation at 0 minutes after intervention ($t_{40}=4.17$, $P<.001$), but subsequent measures were not different from preintervention levels (t_{40} range, 1.53–1.83, $P>.09$).

Conclusions: Interventions directed at the lumbopelvic region did not have immediate effects on quadriceps force output or activation. Muscle fatigue might have contributed to decreased force output and activation over 1 hour of testing.

Key Words: force output, knee pain, manual therapy, muscle activation

Key Points

- Interventions applied to the lumbopelvic region did not immediately affect quadriceps force output or activation.
- Local muscle fatigue might have resulted in decreased force output and activation over the 1-hour testing session.
- Changes in quadriceps force output and activation were not present in the 1 hour after high-grade or low-grade joint mobilization or manipulation directed at the lumbopelvic region.

Patellofemoral pain syndrome (PFPS) is a complex musculoskeletal occurrence that affects up to 30% of the population.^{1–3} People with PFPS have been shown to demonstrate quadriceps weakness^{2,4–6} and inhibition.^{7–10} Pain

is thought to be the underlying cause of muscle weakness and inhibition,^{11–15} but researchers have found little relationship between perceived pain and muscle inhibition.^{16–19} Even when pain has subsided, inhibition might be present for years after

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injury.^{20–24} The persistent muscle inhibition is thought to be an underlying cause and risk factor for osteoarthritis.^{25,26}

Interventions for PFPS usually focus on strengthening the quadriceps^{4,27–31} and hip muscles.^{32–36} Traditional strengthening interventions might not fully address muscle inhibition because it is a reflexive response to joint pathology.^{15,17,37–39} Persistent inhibition might limit the advancement of rehabilitation programs,⁴⁰ and comprehensive interventions that restore optimal quadriceps strength, activation, and previous pain-free level of function must be developed to prevent future dysfunction.

Joint mobilization and manipulation have been used to reduce pain^{27,41,42} and increase muscle activation^{8,9} in people with PFPS. Joint mobilization and manipulation stimulate sensory receptors within and around the joint.^{43–45} Afferent signals from these sensory receptors synapse on interneurons at the spinal level and can affect motoneuron pool availability and efferent motor output.⁴⁰ Joint mobilization and manipulation have been shown to affect muscle activation both near^{13,46–48} and distant from the site of intervention.^{8,9,49,50} Similar effects on local and distant muscle activation have been demonstrated using cryotherapy.⁵¹ Because the sacroiliac joint (L2–S3), quadriceps (L2–4), and knee joints (L2–S2) share common nerve root levels,⁵² afferent information from one structure might alter efferent signals to all structures that a similar nerve root level innervates. A lumbopelvic joint manipulation has been shown to acutely reduce patellofemoral pain when people perform squats, step-ups, and step-downs⁴¹ and to acutely increase quadriceps force output from 11% to 17%^{8,9,53} and activation from 5% to 7.5%.^{8,9} These studies are limited because investigators examined only immediate effects after intervention. Researchers have demonstrated that the effects of lumbopelvic joint manipulation on quadriceps activation and force output might be of limited duration (<20 minutes) in asymptomatic people.⁴⁹ No evidence exists about the duration of increased quadriceps strength or activation after lumbopelvic joint manipulation in a symptomatic population. We also do not know whether lower-grade joint mobilizations might have a similar effect. The associated neurophysiologic effect might depend on the forces (high-grade or low-grade joint mobilizations) applied during the manual intervention.^{54,55} Therefore, the purpose of our study was to determine whether quadriceps strength and activation are increased and maintained for 1 hour after high-grade or low-grade joint mobilization or manipulation applied at the lumbopelvic region in people with PFPS.

METHODS

A single-blind randomized controlled trial was used to examine the effects of lumbopelvic manipulation or mobilization on quadriceps strength and activation. Independent variables included group (lumbopelvic joint manipulation, lumbar pas-

sive range of motion [PROM], or prone extension) and time (before intervention and 0, 20, 40, and 60 minutes after intervention). Outcome variables included force output and percentage of quadriceps activation.

Participants

Forty-eight people with PFPS volunteered (Table). We classified PFPS as self-reported insidious onset of unilateral or bilateral pain that could be reproduced with at least 2 of the following: patellar compression, squatting, prolonged sitting, walking up or down stairs, or isometric quadriceps contraction.^{27,57} Exclusion criteria were symptoms for less than 1 month, ligamentous insufficiency at the knee, meniscus damage, patellar tendinitis, history of patellar subluxation or dislocation, signs or symptoms indicating nerve root compression, history of spine or lower extremity surgery, osteoporosis, pregnancy, or spinal or neurologic disorders. All participants provided written informed consent, and the study was approved by the Institutional Review Board for Health Sciences Research at the University of Virginia. Forty-one participants completed all postintervention testing intervals (Table), whereas 7 participants (6 women, 1 man) withdrew after the 0-minute (n=5) or the 20-minute (n=2) postintervention measurements. Data from participants who withdrew from the study were not used in the final statistical analysis.

Instrumentation

Quadriceps Force Output. Isometric quadriceps force was measured using a load cell (model 41; Sensotec, Inc, Columbus, OH) with a range of 1 to 1000 lb (0.45–453.59 kg) that was interfaced with a data acquisition system (model MP150; BIOPAC Systems, Inc, Goleta, CA) and amplifier (model DA100B; BIOPAC Systems, Inc) and sampled at 125 Hz. Participants were seated in a custom-made chair with their hips flexed to 85°, knees flexed to 90°, and arms folded across their chests. The pelvis was secured to the chair using hook-and-loop straps, and a padded ankle strap was placed 3 cm proximal to the lateral malleolus and connected to the load cell via an S hook.

Burst Superimposition Technique. Quadriceps activation was estimated by using the burst superimposition technique on a maximal voluntary isometric contraction (MVIC). The burst superimposition technique provides the muscle with a percutaneous supramaximal stimulus to recruit muscle fibers that have not been stimulated.^{16,17,38,58,59} A square-wave stimulator (model S88; Grass Technologies, West Warwick, RI) and a stimulation isolation unit (model SIU8T; Grass Technologies) were used with a corresponding isolation unit that had a 125-V stimulus and two 8- × 14-cm rubber-carbon electrodes to deliver the electric stimuli over the quadriceps. Electrode surfaces were

Table. Participant Demographics (Mean ± SD)^a

Characteristic	Total (N = 48)	Manipulation (n = 16)	Passive Range of Motion (n = 16)	Prone Extension (n = 16)
Age, y	24.6 ± 8.9	25.4 ± 7.7	25.1 ± 9.6	24.6 ± 7.4
Height, cm	174.3 ± 11.2	173.5 ± 9.1	175.5 ± 11.2	173.9 ± 13.4
Mass, kg	78.4 ± 16.8	73.0 ± 10.2	78.1 ± 21.4	84.1 ± 16.0
Lower Extremity Functional Scale ⁵⁶ score (maximum possible, 80)	65.5 ± 12.4	64.3 ± 12.6	64.6 ± 16.1	67.0 ± 10.7

^aIndicates that no differences existed among groups (*P* > .05).

covered with conductive gel and secured with an elastic bandage over the proximal lateral aspect and the distal medial aspect of the quadriceps muscle.

A superimposed burst, which consisted of 100 pulses per second, a pulse duration of 600 microseconds, and 10 pulse tetanic trains at 125 V for 100 milliseconds, was applied manually to the quadriceps approximately 2 seconds after the beginning of the MVIC when the experimenter (T.L.G.) determined a plateau in force had occurred. The burst superimposition technique has been shown to be highly reliable with repeated testing of healthy participants (intraclass correlation coefficient [ICC]=0.98).⁶⁰ The amount of muscle activation was quantified by using the central activation ratio (CAR) and was calculated by dividing the volitional MVIC force by total force ($CAR = F_{\text{volitional}} / F_{\text{volitional+electrical}}$).⁶¹ A CAR of 1.0 indicates *complete activation*; from 0.95 to 1.0, *normal activation*.^{16,17,62-65}

Procedures

Participants underwent a standard initial physical evaluation, including assessment of the lumbar spine, sacroiliac joint, and knee joints. This allowed the examiner (J.R.B. or E.M.M.) to screen for exclusionary criteria. All interventions and testing were performed on the ipsilateral side of pain or dysfunction. If the participant had bilateral patellofemoral pain, he or she was instructed to determine which lower extremity was more symptomatic. If the participant could not differentiate between limbs, then a coin toss determined the test limb.

Next, a separate examiner (T.L.G.) who was blinded to treatment group allocation measured baseline quadriceps strength and activation. Participants performed a warmup consisting of 4 submaximal isometric contractions (50%–75% MVIC) with

submaximal electric stimulation of the quadriceps, 1 MVIC with submaximal electric stimulation, and 1 MVIC without stimulation to orient them to the test procedures and ensure that an MVIC could be obtained.⁶⁶

After warmup procedures, participants performed 3 MVICs with supramaximal stimuli. Oral encouragement and visual feedback of real-time force output were given. The MVIC contraction during the warmup served as a target to ensure that participants were exerting maximal effort. Participants were instructed to build up force slowly and hold the MVICs for 3 to 5 seconds. Approximately 2 seconds after the MVIC began, a supramaximal electric stimulus, which consisted of 100 pulses per second, a pulse duration of 600 microseconds, and 10 pulse tetanic trains at 125 V for 100 milliseconds, was applied manually to the quadriceps muscle to recruit muscle fibers that had not been stimulated.^{16,17,38} If force did not plateau, a stimulus was not given, and the test was repeated. A 90-second rest period was given between MVICs. Three trials were performed, and the average MVIC and CAR were used for data analysis.

After baseline assessment of quadriceps activation, participants jogged for 5 minutes and ran for 2 to 3 minutes on a treadmill. This portion of testing was part of a larger trial in which we examined running biomechanics and which we will report in a subsequent study. After running, participants were assigned randomly to 1 of 3 treatment groups: lumbopelvic joint manipulation (grade V), side-lying lumbar midrange flexion and extension PROM (grade II) for 1 minute, or prone extension on the elbows for 3 minutes (Figure 1). Lumbopelvic joint manipulation was selected as a high-grade mobilization, whereas lumbar PROM was selected as a lower-grade (grade II) joint mobilization. The intervention in which participants were positioned prone on their elbows was selected because it is used

Figure 1. Flow diagram.⁶⁷

commonly for people with low back pain but does not require physical contact. The total duration to set up and perform each of the 3 interventions was estimated to be 3 minutes and included participant positioning and intervention. The examiner (T.L.G.) obtaining quadriceps force output and activation values was blinded to treatment group allocation.

After experimental treatment, participants again ran for 2 to 3 minutes, then we reassessed quadriceps force output and activation using similar methods. Testing was performed immediately after intervention (0 minutes) and at 20, 40, and 60 minutes after intervention. During rest periods between testing intervals, participants were instructed to remain seated and quiet. Testing concluded after the 60-minute postintervention data were collected.

Lumbopelvic Joint Manipulation. The lumbopelvic joint manipulation (Grade V) was performed on the ipsilateral side of the test limb (Figure 2). The term *lumbopelvic* was used to describe the targeted region because this manipulation technique is not exclusively specific to the lumbar, sacroiliac, or pelvic regions.⁶⁸ The manipulation procedure we used was consistent with previously used methods^{41,49,68–70} and was performed by 1 of 2 physical therapists (J.R.B. or E.M.M.) with advanced training in manual therapy. Participants were positioned supine on a treatment table while the physical therapist stood on the opposite side that would be manipulated. The participant was side bent passively toward and rotated away from the selected lumbopelvic region. Next, a posteroinferior force was delivered through the opposite anterosuperior iliac spine. If a cavitation was not heard or felt by the patient or examiner, the technique was repeated. If the second attempt did not produce cavitation, the procedure was repeated on the contralateral side using similar methods. If cavitation was not heard or felt by the participant or examiner after the second attempt on the contralateral side, the participant proceeded with the assessment of quadriceps strength and activation as usual.

Passive Range of Motion. Participants were positioned side lying on the opposite side of the test limb (Figure 3). The experimenter (J.R.B. or E.M.M.) held both knees with 1 arm while placing the opposite hand on the participant's lumbar spine. The experimenter performed 1 minute of flexion and extension PROM without reaching physiologic end range (grade II) in either direction.

Prone Extension on Elbows. Participants were positioned prone with the lumbar spine in extension, and they used their elbows for support to maintain the position for 3 minutes (Figure 4). No contact occurred between the participant and physical therapist.

Statistical Analysis

Participant demographics were compared using a 1-way analysis of variance (ANOVA). A 2-way, repeated-measures ANOVA was performed to compare quadriceps force output and CAR values among groups (lumbopelvic joint manipulation, lumbar PROM, or prone extension on elbows) across time (before intervention and at 0, 20, 40, and 60 minutes after intervention). Degrees of freedom were corrected using the Greenhouse-Geisser method if the Mauchly sphericity test revealed differences. Degrees of freedom used for the corrected *F* test were not necessarily whole numbers. The α level was set a priori at .05. If we observed differences among groups, we used post hoc *t* tests. Statistical analyses were performed with SPSS (version 16.0; SPSS Inc, Chicago, IL).

Figure 2. Lumbopelvic joint manipulation with side bending and rotation in supine position.

Figure 3. Lumbar passive range of motion.

Figure 4. Prone extension on elbows.

An a priori sample size calculation was performed using an expected change in quadriceps activation of 7.5%^{8,9} and a standard deviation of 10%.⁴⁹ Based on these values, we calculated that 15 participants per group were necessary to have an 80% chance of detecting a difference in quadriceps activation with an α level of .05.

RESULTS

We found no differences among any of the participant group demographics ($F_{2,40}$ range, 0.08–2.52, $P > .05$) (Table). Lumbopelvic joint cavitation was achieved in 53.8% of the participants (all on 1 attempt). Six of the participants in the manipulation group could not achieve joint cavitation after 4 attempts (2 per side) but were retained in the statistical analysis because cavitation might not be necessary to achieve clinically relevant changes.^{68,71}

Quadriceps force output ($F_{5,33,101,18} = 0.65$, $P = .67$, $1 - \beta = .29$) and activation ($F_{4,84,92,03} = 0.38$, $P = .86$, $1 - \beta = .18$) values were

not different among groups across time (Figures 5 and 6). When groups were pooled, we found differences across time for quadriceps force output ($F_{2,66,101,18} = 5.03$, $P = .004$, $1 - \beta = .88$) and activation ($F_{2,42,92,03} = 3.85$, $P = .02$, $1 - \beta = .74$). Quadriceps force output did not change at 0 minutes postintervention ($t_{40} = 1.68$, $P = .10$) but decreased at 20 ($t_{40} = 2.16$, $P = .04$), 40 ($t_{40} = 2.87$, $P = .01$), and 60 ($t_{40} = 3.04$, $P = .004$) minutes postintervention. All groups demonstrated decreased quadriceps activation at 0 minutes postintervention ($t_{40} = 4.17$, $P < .001$), but subsequent measures were not different from preintervention levels (t_{40} range = 1.53–1.83, $P > .09$).

DISCUSSION

Our results indicated that changes in quadriceps force output and activation were not present over the course of 1 hour after high-grade or low-grade joint mobilization or manipulation directed at the lumbopelvic region. This finding differs from the findings reported in other studies that suggested an immediate

Figure 5. Immediate effects of quadriceps force output at 60 minutes after intervention. *Indicates decrease in force output compared with preintervention values ($P < .04$).

Figure 6. Immediate effects of quadriceps activation at 60 minutes postintervention. *Indicates decrease in quadriceps activation compared with preintervention values ($P < .001$).

increase in quadriceps force output^{8,9,53} and activation^{8,9} after lumbopelvic joint manipulation. (Our participants were not actively seeking medical care for PFPS but did have deficits in quadriceps activation and self-reported function; the latter were identified using the Lower Extremity Functional Scale⁵⁶). Investigators^{8,9,41} have demonstrated improvements in quadriceps activation and function after manual interventions directed at the spine in people who are seeking medical care for PFPS. All people with PFPS might not be candidates for lumbopelvic manipulation. Researchers demonstrating increased quadriceps force output and activation have included people with sacroiliac joint dysfunction who are symptomatic or asymptomatic.^{8,9,53} In addition, a subset of people with PFPS who have internal rotation asymmetry in the hip greater than 14° are thought to be 5 times more likely to experience pain relief after a lumbopelvic joint manipulation.⁴¹ The relationship with the hip and PFPS is consistent with findings in previous studies^{32,72–79} but might be associated with other causes, such as malalignment, muscle imbalances, patellar tracking, and cumulative microtrauma.^{4,27} We did not attempt to categorize people with PFPS into treatment based on classification systems. Although treatment-based classification systems have been used to manage low back pain,^{80,81} the use of classification systems to manage PFPS is new and has not been validated.^{41,82,83}

Quadriceps force output began to decrease 20 minutes after intervention. The amount of decreased force output was not dependent on treatment group allocation. Obtaining valid and reliable force output and activation values depends on participants producing maximal effort⁸⁴ and sufficient warmup.⁶⁶ Despite encouraging participants to give 100% effort during all trials, we found that force output declined from baseline by approximately 4% to 5%. A warmup consisting of progressive isometric knee extension exercises was performed only during the preintervention testing period. Participants also performed a 5-minute jogging bout and two 2-minute to 3-minute running bouts on a treadmill before the immediate postintervention (0 minutes) acquisition of quadriceps force output and activation data. As noted, the jogging and running bouts were part of a larger study in which we investigated changes in running mechanics. Warmup bouts were not performed during other postintervention periods (20, 40, and 60 minutes). The muscles might have cooled down during the rest periods, and this cooling might have affected quadriceps force output values. Alternatively, decreased force output also might have been attributed to fatigue associated with a combination of running (approximately 10 minutes) and performing 15 MVICs augmented with a supramaximal electric stimulus over 60 minutes.⁸⁵ Participants also were instructed to sit quietly during rest periods. Unfortunately, because of the study design, we could not differentiate between the effects of intervention and running because a true control (ie, no intervention or running) was not used. Whether this fatigue was related to peripheral or central mechanisms is not known. Electromyographic analysis of median frequency of muscle might help quantify peripheral muscle fatigue associated with repeated MVICs.^{86,87} We examined participants 60 minutes after intervention to determine whether changes in muscle force output and activation could be sustained over a period that was consistent with rehabilitation programs. In future studies, researchers might consider examining similar time intervals while having participants perform activities, such as therapeutic exercises, commonly used in clinical settings.

Quadriceps activation decreased at 0 minutes postintervention, but values obtained 20, 40, and 60 minutes postintervention

were not different from preintervention values. A brief bout of running might acutely decrease quadriceps activation. Investigators^{8,9,49} have determined that a lumbopelvic joint manipulation immediately affects quadriceps activation. The typical increase in muscle activation (range, 5%–7.5%)^{8,9,49} after lumbopelvic joint manipulation might have been attenuated by a decrease in muscle activation due to fatigue associated with running.⁶⁵ If running attenuated the typical increase in quadriceps force output and activation, the clinical utility of this intervention might be limited. Our participants were part of a larger trial in which we concurrently examined changes in running mechanics. We did not control for the effects of the running variable on quadriceps force output and activation, so we could not determine the effects of the running bout on muscle activation. In future studies, researchers should quantify the amount of change in quadriceps muscle activation due to running.

A limitation of our study was that 7 participants (6 women, 1 man) withdrew from the study because of discomfort associated with burst superimposition testing. Five of these 7 participants withdrew immediately after the first postintervention (0 minutes) measurement, and 2 withdrew after the 20-minute postintervention measurement. Miller et al⁸⁸ reported that participants described the pain associated with burst superimposition testing as mild to moderate and rated it as 3.5/10 on a visual analog scale. Perceived discomfort is thought to decrease in consecutive trials.⁸⁸ Although the discomfort was not quantified, participants who withdrew appeared to experience anxiety or apprehension during burst superimposition testing. These people tended to be female and had activation levels greater than 0.90.

The purpose of our study was to examine changes in quadriceps force output and activation after a manual therapeutic intervention directed at the lumbopelvic region. This mechanistic study was designed to evaluate only 1 intervention. Lumbopelvic joint manipulation might address specific impairments associated with PFPS (decreased quadriceps activation, asymmetries in hip rotation) but might need to be used as an adjunctive intervention that is part of a comprehensive rehabilitation program.

CONCLUSIONS

Based on our findings, we demonstrated that interventions applied at the lumbopelvic region did not have an immediate effect on quadriceps force output or activation. Local muscle fatigue might have been responsible for decreased force output and activation over the 1-hour testing session.

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REFERENCES

1. McConnell J. Management of patellofemoral problems. *Man Ther.* 1996;1(2):60–66.

2. Fairbank JC, Pynsent PB, van Poortvliet JA, Phillips H. Mechanical factors in the incidence of knee pain in adolescents and young adults. *J Bone Joint Surg Br.* 1984;66(5):685–693.
3. Witvrouw E, Lysens R, Bellemans J, Cambier D, Vanderstraeten G. Intrinsic risk factors for the development of anterior knee pain in an athletic population: a two-year prospective study. *Am J Sports Med.* 2000;28(4):480–489.
4. Thomee R, Augustsson J, Karlsson J. Patellofemoral pain syndrome: a review of current issues. *Sports Med.* 1999;28(4):245–262.
5. Powers CM, Perry J, Hsu A, Hislop HJ. Are patellofemoral pain and quadriceps femoris muscle torque associated with locomotor function? *Phys Ther.* 1997;77(10):1063–1075.
6. Duffey MJ, Martin DF, Cannon DW, Craven T, Messier SP. Etiologic factors associated with anterior knee pain in distance runners. *Med Sci Sports Exerc.* 2000;32(11):1825–1832.
7. Suter E, Herzog W, Bray RC. Quadriceps inhibition following arthroscopy in patients with anterior knee pain. *Clin Biomech (Bristol, Avon).* 1998;13(4–5):314–319.
8. Suter E, McMorland G, Herzog W, Bray R. Conservative lower back treatment reduces inhibition in knee-extensor muscles: a randomized controlled trial. *J Manipulative Physiol Ther.* 2000;23(2):76–80.
9. Suter E, McMorland G, Herzog W, Bray R. Decrease in quadriceps inhibition after sacroiliac joint manipulation in patients with anterior knee pain. *J Manipulative Physiol Ther.* 1999;22(3):149–153.
10. Suter E, Herzog W, De Souza K, Bray R. Inhibition of the quadriceps muscles in patients with anterior knee pain. *J Appl Biomech.* 1998;14(4):360–373.
11. Morrissey MC. Reflex inhibition of thigh muscles in knee injury: causes and treatment. *Sports Med.* 1989;7(4):263–276.
12. Wang K, Arendt-Nielsen L, Svensson P. Capsaicin-induced muscle pain alters the excitability of the human jaw-stretch reflex. *J Dent Res.* 2002;81(9):650–654.
13. Brenner AK, Gill NW, Buscema CJ, Kiesel K. Improved activation of lumbar multifidus following spinal manipulation: a case report applying rehabilitative ultrasound imaging. *J Orthop Sports Phys Ther.* 2007;37(10):613–619.
14. Thomee R, Renstrom P, Karlsson J, Grimby G. Patellofemoral pain syndrome in young women, II: muscle function in patients and healthy controls. *Scand J Med Sci Sports.* 1995;5(4):245–251.
15. Hurley MV, Jones DW, Wilson DR, Newham DJ. Rehabilitation of quadriceps inhibition due to isolated rupture of the anterior cruciate ligament. *J Orthop Rheumatol.* 1992;5(3):145–154.
16. Stevens JE, Mizner RL, Snyder-Mackler L. Quadriceps strength and voluntary activation before and after total knee arthroplasty for osteoarthritis. *J Orthop Res.* 2003;21(5):775–779.
17. Mizner RL, Stevens JE, Snyder-Mackler L. Voluntary activation and decreased force production of the quadriceps femoris muscle after total knee arthroplasty. *Phys Ther.* 2003;83(4):359–365.
18. Mizner RL, Petterson SC, Stevens JE, Vandenborne K, Snyder-Mackler L. Early quadriceps strength loss after total knee arthroplasty: the contributions of muscle atrophy and failure of voluntary muscle activation. *J Bone Joint Surg Am.* 2005;87(5):1047–1053.
19. Shakespeare DT, Stokes M, Sherman KP, Young A. Reflex inhibition of the quadriceps after meniscectomy: lack of association with pain. *Clin Physiol.* 1985;5(2):137–144.
20. Hides JA, Richardson CA, Jull GA. Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine (Phila Pa 1976).* 1996;21(23):2763–2769.
21. Krebs DE, Staples WH, Cuttita D, Zickel RE. Knee joint angle: its relationship to quadriceps femoris activity in normal and postarthrotomy limbs. *Arch Phys Med Rehabil.* 1983;64(10):441–447.
22. Santavirta S. Integrated electromyography of the vastus medialis muscle after meniscectomy. *Am J Sports Med.* 1979;7(1):40–42.
23. Stokes M, Young A. The contribution of reflex inhibition to arthrogenous muscle weakness. *Clin Sci (Lond).* 1984;67(1):7–14.
24. Urbach D, Nebelung W, Becker R, Awiszus F. Effects of reconstruction of the anterior cruciate ligament on voluntary activation of quadriceps femoris: a prospective twitch interpolation study. *J Bone Joint Surg Br.* 2001;83(8):1104–1110.
25. Suter E, Herzog W. Does muscle inhibition after knee injury increase the risk of osteoarthritis? *Exerc Sport Sci Rev.* 2000;28(1):15–18.
26. Utting MR, Davies G, Newman JH. Is anterior knee pain a predisposing factor to patellofemoral osteoarthritis? *Knee.* 2005;12(5):362–365.
27. Crossley K, Bennell K, Green S, Cowan S, McConnell J. Physical therapy for patellofemoral pain: a randomized, double-blinded, placebo-controlled trial. *Am J Sports Med.* 2002;30(6):857–865.
28. Crossley K, Bennell K, Green S, McConnell J. A systematic review of physical interventions for patellofemoral pain syndrome. *Clin J Sport Med.* 2001;11(2):103–110.
29. Crossley KM, Cowan SM, McConnell J, Bennell KL. Physical therapy improves knee flexion during stair ambulation in patellofemoral pain. *Med Sci Sports Exerc.* 2005;37(2):176–183.
30. Witvrouw E, Lysens R, Bellemans J, Peers K, Vanderstraeten G. Open versus closed kinetic chain exercises for patellofemoral pain: a prospective, randomized study. *Am J Sports Med.* 2000;28(5):687–694.
31. Cowan SM, Bennell KL, Crossley K, Hodges PW, McConnell J. Physical therapy alters recruitment of the vasti in patellofemoral pain syndrome. *Med Sci Sports Exerc.* 2002;34(12):1879–1885.
32. Ireland ML, Willson JD, Ballantyne BT, Davis IM. Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2003;33(11):671–676.
33. Mascal CL, Landel R, Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther.* 2003;33(11):647–660.
34. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther.* 2003;33(11):639–646.
35. Bolgia L, Malone TR. Exercise prescription and patellofemoral pain: evidence for rehabilitation. *J Sport Rehabil.* 2005;14(1):72–88.
36. Fulkerson JP. Diagnosis and treatment of patients with patellofemoral pain. *Am J Sports Med.* 2002;30(3):447–456.
37. Chmielewski TL, Stackhouse S, Axe MJ, Snyder-Mackler L. A prospective analysis of incidence and severity of quadriceps inhibition in a consecutive sample of 100 patients with complete acute anterior cruciate ligament rupture. *J Orthop Res.* 2004;22(5):925–930.
38. Snyder-Mackler L, De Luca PF, Williams PR, Eastlack ME, Bartolozzi ARI-III. Reflex inhibition of the quadriceps femoris muscle after injury or reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am.* 1994;76(4):555–560.
39. Pietrosimone BG, Saliba S, Hart JM, Hertel J, Kerrigan DC, Ingersoll CD. Effects of transcutaneous electrical nerve stimulation and therapeutic exercise on quadriceps activation in people with tibiofemoral osteoarthritis. *J Orthop Sports Phys Ther.* 2011;41(1):4–12.
40. Hopkins JT, Ingersoll CD. Arthrogenous muscle inhibition: a limiting factor in joint rehabilitation. *J Sport Rehabil.* 2000;9(2):135–159.
41. Iverson CA, Sutlive TG, Crowell MS, et al. Lumbopelvic manipulation for the treatment of patients with patellofemoral pain syndrome: development of a clinical prediction rule. *J Orthop Sports Phys Ther.* 2008;38(6):297–312.
42. Rowlands BW, Brantingham JW. The efficacy of patella mobilization in patients suffering from patellofemoral pain syndrome. *J Neuromusc Syst.* 1999;7(4):142–149.
43. Pickar JG. Neurophysiological effects of spinal manipulation. *Spine J.* 2002;2(5):357–371.
44. Colloca CJ, Keller TS, Gunzburg R. Biomechanical and neurophysiological responses to spinal manipulation in patients with lumbar radiculopathy. *J Manipulative Physiol Ther.* 2004;27(1):1–15.
45. Colloca CJ, Keller TS, Gunzburg R. Neuromechanical characterization of in vivo lumbar spinal manipulation, part II: neurophysiological response. *J Manipulative Physiol Ther.* 2003;26(9):579–591.
46. Sung PS, Kang YM, Pickar JG. Effect of spinal manipulation duration on low threshold mechanoreceptors in lumbar paraspinal muscles: a preliminary report. *Spine (Phila Pa 1976).* 2004;30(1):115–122.
47. Gill NW, Teyhen DS, Lee IE. Improved contraction of the transversus abdominis immediately following spinal manipulation: a case study using real-time ultrasound imaging. *Man Ther.* 2007;12(3):280–285.
48. Raney NH, Teyhen DS, Childs JD. Observed changes in lateral abdominal muscle thickness after spinal manipulation: a case series using rehabilitative ultrasound imaging. *J Orthop Sports Phys Ther.* 2007;37(8):472–479.
49. Grindstaff TL, Hertel J, Beazell JR, Magrum EM, Ingersoll CD. Effects

- of lumbopelvic joint manipulation on quadriceps activation and strength in healthy individuals. *Man Ther.* 2009;14(4):415–420.
50. Murphy BA, Dawson NJ, Slack JR. Sacroiliac joint manipulation decreases the H-reflex. *Electromyogr Clin Neurophysiol.* 1995;35(2):87–94.
 51. Krause BA, Hopkins JT, Ingersoll CD, Cordova ML, Edwards JE. The relationship of ankle temperature during cooling and rewarming to the human soleus H reflex. *J Sport Rehabil.* 2000;9(3):253–262.
 52. Moore KL, Dalley AF. *Clinically Oriented Anatomy*. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 1999.
 53. Hillermann B, Gomes AN, Korporaal C, Jackson D. A pilot study comparing the effects of spinal manipulative therapy with those of extra-spinal manipulative therapy on quadriceps muscle strength. *J Manipulative Physiol Ther.* 2006;29(2):145–149.
 54. Dishman JD, Dougherty PE, Burke JR. Evaluation of the effect of postural perturbation on motoneuronal activity following various methods of lumbar spinal manipulation. *Spine J.* 2005;5(6):650–659.
 55. Dishman JD, Ball KA, Burke J. Central motor excitability changes after spinal manipulation: a transcranial magnetic stimulation study. *J Manipulative Physiol Ther.* 2002;25(1):1–9.
 56. Binkley JM, Stratford PW, Lott SA, Riddle DL. The Lower Extremity Functional Scale (LEFS): scale development, measurement properties, and clinical application. North American Orthopaedic Rehabilitation Research Network. *Phys Ther.* 1999;79(4):371–383.
 57. Whittingham M, Palmer S, Macmillan F. Effects of taping on pain and function in patellofemoral pain syndrome: a randomized controlled trial. *J Orthop Sports Phys Ther.* 2004;34(9):504–510.
 58. Rutherford OM, Jones DA, Newham DJ. Clinical and experimental application of the percutaneous twitch superimposition technique for the study of human muscle activation. *J Neurol Neurosurg Psychiatry.* 1986;49(11):1288–1291.
 59. Stevens JE, Binder-Macleod S, Snyder-Mackler L. Characterization of the human quadriceps muscle in active elders. *Arch Phys Med Rehabil.* 2001;82(7):973–978.
 60. Snyder-Mackler L, Binder-Macleod SA, Williams PR. Fatigability of human quadriceps femoris muscle following anterior cruciate ligament reconstruction. *Med Sci Sports Exerc.* 1993;25(7):783–789.
 61. Kent-Braun JA, Le Blanc R. Quantitation of central activation failure during maximal voluntary contractions in humans. *Muscle Nerve.* 1996;19(7):861–869.
 62. Fitzgerald GK, Piva SR, Irrgang JJ, Bouzubar F, Starz TW. Quadriceps activation failure as a moderator of the relationship between quadriceps strength and physical function in individuals with knee osteoarthritis. *Arthritis Rheum.* 2004;51(1):40–48.
 63. Lewek MD, Rudolph KS, Snyder-Mackler L. Quadriceps femoris muscle weakness and activation failure in patients with symptomatic knee osteoarthritis. *J Orthop Res.* 2004;22(1):110–115.
 64. Stackhouse SK, Dean JC, Lee SCK, Binder-MacLeod SA. Measurement of central activation failure of the quadriceps femoris in healthy adults. *Muscle Nerve.* 2000;23(11):1706–1712.
 65. Stackhouse SK, Stevens JE, Lee SC, Pearce KM, Snyder-Mackler L, Binder-Macleod SA. Maximum voluntary activation in nonfatigued and fatigued muscle of young and elderly individuals. *Phys Ther.* 2001;81(5):1102–1109.
 66. Shield A, Zhou S. Assessing voluntary muscle activation with the twitch interpolation technique. *Sports Med.* 2004;34(4):253–267.
 67. Schulz KF, Altman DG, Moher D; the CONSORT Group. CONSORT 2010 Statement: updated guidelines for reporting parallel group randomized trials. *BMJ.* 2010;340:c332.
 68. Flynn TW, Childs JD, Fritz JM. The audible pop from high-velocity thrust manipulation and outcome in individuals with low back pain. *J Manipulative Physiol Ther.* 2006;29(1):40–45.
 69. Flynn T, Fritz J, Whitman J, et al. A clinical prediction rule for classifying patients with low back pain who demonstrate short-term improvement with spinal manipulation. *Spine (Phila Pa 1976).* 2002;27(24):2835–2843.
 70. Fritz JM, Whitman JM, Flynn TW, Wainner RS, Childs JD. Factors related to the inability of individuals with low back pain to improve with a spinal manipulation. *Phys Ther.* 2004;84(2):173–190.
 71. Flynn TW, Fritz JM, Wainner RS, Whitman JM. The audible pop is not necessary for successful spinal high-velocity thrust manipulation in individuals with low back pain. *Arch Phys Med Rehabil.* 2003;84(7):1057–1060.
 72. Nicholas JA, Strizak AM, Veras G. A study of thigh muscle weakness in different pathological states of the lower extremity. *Am J Sports Med.* 1976;4(6):241–248.
 73. Willson JD, Binder-Macleod S, Davis IS. Lower extremity jumping mechanics of female athletes with and without patellofemoral pain before and after exertion. *Am J Sports Med.* 2008;36(8):1587–1596.
 74. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther.* 2008;38(8):448–456.
 75. Souza RB, Powers CM. Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med.* 2009;37(3):579–587.
 76. Souza RB, Powers CM. Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther.* 2009;39(1):12–19.
 77. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech (Bristol, Avon).* 2008;23(2):203–211.
 78. Bolgia LA, Malone TR, Umberger BR, Uhl TL. Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 2008;38(1):12–18.
 79. Cichanowski HR, Schmitt JS, Johnson RJ, Niemuth PE. Hip strength in collegiate female athletes with patellofemoral pain. *Med Sci Sports Exerc.* 2007;39(8):1227–1232.
 80. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament: a prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg Am.* 1995;77(8):1166–1173.
 81. Fritz JM, Cleland JA, Childs JD. Subgrouping patients with low back pain: evolution of a classification approach to physical therapy. *J Orthop Sports Phys Ther.* 2007;37(6):290–302.
 82. Sutlive TG, Mitchell SD, Maxfield SN, et al. Identification of individuals with patellofemoral pain whose symptoms improved after a combined program of foot orthosis use and modified activity: a preliminary investigation. *Phys Ther.* 2004;84(1):49–61.
 83. Leshner JD, Sutlive TG, Miller GA, Chine NJ, Garber MB, Wainner RS. Development of a clinical prediction rule for classifying patients with patellofemoral pain syndrome who respond to patellar taping. *J Orthop Sports Phys Ther.* 2006;36(11):854–866.
 84. Behm DG, St-Pierre DM, Perez D. Muscle inactivation: assessment of interpolated twitch technique. *J Appl Physiol.* 1996;81(5):2267–2273.
 85. Behm DG, Button DC, Barbour G, Butt JC, Young WB. Conflicting effects of fatigue and potentiation on voluntary force. *J Strength Cond Res.* 2004;18(2):365–372.
 86. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Reduced quadriceps activation after lumbar paraspinal fatiguing exercise. *J Athl Train.* 2006;41(1):79–86.
 87. Hart JM, Fritz JM, Kerrigan DC, Saliba EN, Gansneder BM, Ingersoll CD. Quadriceps inhibition after repetitive lumbar extension exercise in persons with a history of low back pain. *J Athl Train.* 2006;41(3):264–269.
 88. Miller M, Holmbäck AM, Downham D, Lexell J. Voluntary activation and central activation failure in the knee extensors in young women and men. *Scand J Med Sci Sports.* 2006;16(4):274–281.

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