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original research

Acute Responses of Strength and Running Mechanics to Increasing and Decreasing Pain in Patients With Patellofemoral Pain

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Context: Patellofemoral pain (PFP) is typically exacerbated by repetitive activities that load the patellofemoral joint, such as running. Understanding the mediating effects of changes in pain in individuals with PFP might inform injury progression, rehabilitation, or both.

Objective: To investigate the effects of changing pain on muscular strength and running biomechanics in those with PFP.

Design: Crossover study.

Setting: University research laboratory.

Patients or Other Participants: Seventeen participants (10 men, 7 women) with PFP.

Intervention(s): Each participant completed knee pain-reducing and pain-inducing protocols in random order. The pain-reducing protocol consisted of 15 minutes of transcutaneous electric nerve stimulation (TENS) around the patella. The pain-inducing protocol was sets of 20 repeated single-legged squats (RSLS). Participants completed RSLS sets until either their pain was within at least 1 cm of their pain during an exhaustive run or they reached 10 sets.

Main Outcome Measure(s): Pain, isometric hip and trunk strength, and running mechanics were assessed before and after the protocols. Dependent variables were pain, normalized strength (abduction, extension, external rotation, lateral trunk flexion), and peak lower extremity kinematics and kinetics in all planes. Pain scores were analyzed using a Friedman test. Strength and mechanical variables were analyzed using repeated-measures analyses of variance. The α level was set at $P < .05$.

Results: Pain was decreased after the TENS (pretest: 3.10 $\pm$ 1.95, posttest: 1.89 $\pm$ 2.33) and increased after the RSLS (baseline: 3.10 $\pm$ 1.95, posttest: 4.38 $\pm$ 2.40) protocols (each $P < .05$). The RSLS protocol resulted in a decrease in hip-extension strength (baseline: 0.355 $\pm$ 0.08 kg/kg, posttest: 0.309 $\pm$ 0.09 kg/kg; $P < .001$). Peak plantar-flexion angle was decreased after RSLS (baseline: $-13.97° \pm 6.41°$, posttest: $-12.84° \pm 6.45°$; $P = .003$). Peak hip-extension (pretest: -2.31 ± 0.46) and hip-abduction (pretest: -2.02 ± 0.35) moments decreased after both the TENS (extension: -2.15 ± 0.48 Nm/kg, $P = .015$; abduction: -1.91 ± 0.33 Nm/kg, $P = .015$) and RSLS (extension: -2.18 ± 0.52 Nm/kg, $P = .003$; abduction: -1.87 ± 0.36 Nm/kg, $P = .039$) protocols.

Conclusions: This study presents a novel and effective method of increasing pain in persons with PFP. Functionally increased pain after RSLS coincides with reduced hip-extensor muscle strength and decreased plantar-flexion angle during running. The TENS treatment decreased pain during running in those with PFP but failed to influence strength. Hip moments were reduced by both protocols, which may demonstrate that acute increases or decreases in pain cause runners to change their mechanics.

Key Words: kinematics, kinetics, knee, transcutaneous electric nerve stimulation

Key Points

- Functionally increased knee pain coincided with reduced hip-extensor strength, decreased plantar-flexion angle, and decreased hip moment during running.
- Transcutaneous electric nerve stimulation reduced knee pain and hip moment during running but did not influence strength or kinematics.

Patellofemoral pain (PFP) is one of the most common injuries seen in orthopaedic outpatient clinics and general practice[1–4] and has been suggested to be multifactorial in nature.[5] Historically, faulty sagittal-plane and frontal-plane knee mechanics (ie, flexion, valgus) were proposed to result in injury.[6,7] Others[5,8–10] have cited contributing factors (ie, mechanics, muscle function) that are both distal (ie, rearfoot eversion, tibial internal rotation) and proximal (ie, hip internal rotation, adduction) to the knee. The proximal factors have been suggested as contributing to the control of the femur behind the patella.[11] Specifically, hip internal rotation (IR) and adduction (ADD) increase the contact pressure of the patella on the femur,[11,12] possibly leading to increased pain and dysfunction. Greater hip IR and ADD have been reported in women with PFP during running compared with controls.[13,14] However, some authors[15–17] have reported no difference in IR and ADD during running in those with PFP versus controls. To explain the lack of consensus, these researchers[15–17] have hypothesized that persons with PFP may use

Table 1. Inclusion and Exclusion Criteria for Patellofemoral Pain

Inclusion Critera	Exclusion Criteria
Visual analogue scale pain rating during physical activity ≥3/10	Meniscal or other intra-articular injury
Persistent pain ≥4 wk	Cruciate or collateral ligament laxity or tenderness
Insidious onset of symptoms unrelated to trauma	Patellar tendon, iliotibial band, or pes anserine tenderness
Pain in the anterior knee (retropatellar or peripatellar) with at least 3 of the following:	Positive patellar-apprehension sign
1) During or after physical activity (ie, running)	Osgood-Schlatter or Sinding-Larsen-Johansson syndrome
2) Prolonged sitting	Knee effusion
3) Stair ascent, descent, or both	Hip or lumbar referred pain
4) Squatting	History of recurrent patellar subluxation or dislocation
Pain with palpation of the patellar facets or pain during a step down from a 20-cm box or during a double-legged squat	

compensatory mechanics (ie, reduced IR or ADD or both) to decrease pain during movement. Given these conflicting findings, a better understanding of pain-compensatory mechanics in this population is needed.

Hip- and trunk-muscle weaknesses have also been cited retrospectively as contributors to PFP; however, recent prospective studies[18–20] and a systematic review[21] have failed to demonstrate that hip weakness is a cause of this injury. One group[18] proposed that hip weakness is the result of chronic pain, possibly due to the effects of muscle inhibition. Pain can be a confounding variable that is difficult to control.[22] A greater understanding of the influence of pain on strength in those with PFP is necessary to advance our knowledge of the condition.

To further understand the relationship between pain and function in those with PFP, protocols to acutely reduce or induce pain would be helpful. Transcutaneous electrical nerve stimulation (TENS) has long been used as a pain-modulating modality.[23] Pain modulation associated with sensory-level TENS is often attributed to the gate control theory of pain.[24] Whereas TENS has been demonstrated to acutely reduce knee osteoarthritis[25] and postsurgical pain,[26] reductions in pain have not led to changes in knee mechanics.[27] Few authors have investigated the effects of TENS on PFP. In 1 study[28] of participants with anterior knee pain, pressure-pain thresholds were reduced after acute exposure to TENS. Pain might be reduced in a PFP population with the acute use of TENS, which might lead to increased muscle activation through disinhibitory effects[29] and improved mechanics.

With respect to increasing pain in this population, we found no studies. Using experimental knee-pain models, researchers[29,30] have demonstrated changes in pain that are similar to those seen in participants with PFP. However, these experimental knee-pain studies involved acute changes in healthy persons, not in those with chronic pain. Pain has also been hypothesized to influence the mechanics of persons with PFP. The limitation of these studies[15–17] is that they involved increases in both pain and fatigue, so separating the influences of these factors is impossible. Investigating the effects of pain changes on lower extremity mechanics in persons with PFP could provide important information.

Therefore, the purpose of our study was to investigate the acute effects of increased and decreased pain on hip and trunk strength and lower extremity mechanics in patients with PFP. We hypothesized that (1) pain would decrease after the pain-reducing protocol and increase after the pain-inducing protocol, (2) changes in kinematics and kinetics would occur during running after the pain-inducing protocol but not after the pain-reducing protocol, and (3) hip external-rotation (ER), abduction (ABD), extension (EXT), and lateral trunk-flexion (LTF) strength would not change when pain increased or decreased.

METHODS

Participants

We recruited participants from a large, midwestern university and surrounding communities. A total of 20 participants diagnosed with PFP were recruited for this study, as described previously[15]; 3 participants were excluded (see Results section). The 20 participants' average age, height, weight, and symptom duration were 25.9 ± 5.6 years, 1.76 ± 0.07 m, 78.8 ± 12.7 kg, and 48.2 ± 46.1 (median = 39) months, respectively. Recruits were physically active men and women. *Physically active* was defined as participating in at least 3 hours of running-related activities per week (eg, running, basketball, soccer) and assessed through a self-reported general health questionnaire. Individuals with a history of lower extremity surgery, neurologic impairment, or lower extremity or trunk injury in the last 6 months and women who were pregnant were excluded from the study. The diagnosis of PFP was based on the clinical presentation of symptoms and physical examination by an athletic trainer (Table 1).[15] In participants with bilateral pain, the most painful limb was tested. Participants who used nonsteroidal anti-inflammatory drugs or corticosteroids within 24 hours of testing were rescheduled to avoid drug-related baseline reductions in knee pain.

First Testing Session and Familiarization

Testing occurred on 2 days, at least 48 hours apart (Figure 1). During the initial session, all participants were informed about the study equipment and procedures and then provided written consent in accordance with the guidelines of the institution that approved the study. Participants completed self-reported medical history and physical activity questionnaires so that we could determine eligibility, and participants' heights and weights were measured. A visual analog score (VAS) was obtained for both the right and left knees to assess the intensity of the participant's knee pain and determine eligibility. The VAS is a 100-mm line on which the participant makes a vertical mark to indicate the average weekly pain during physical

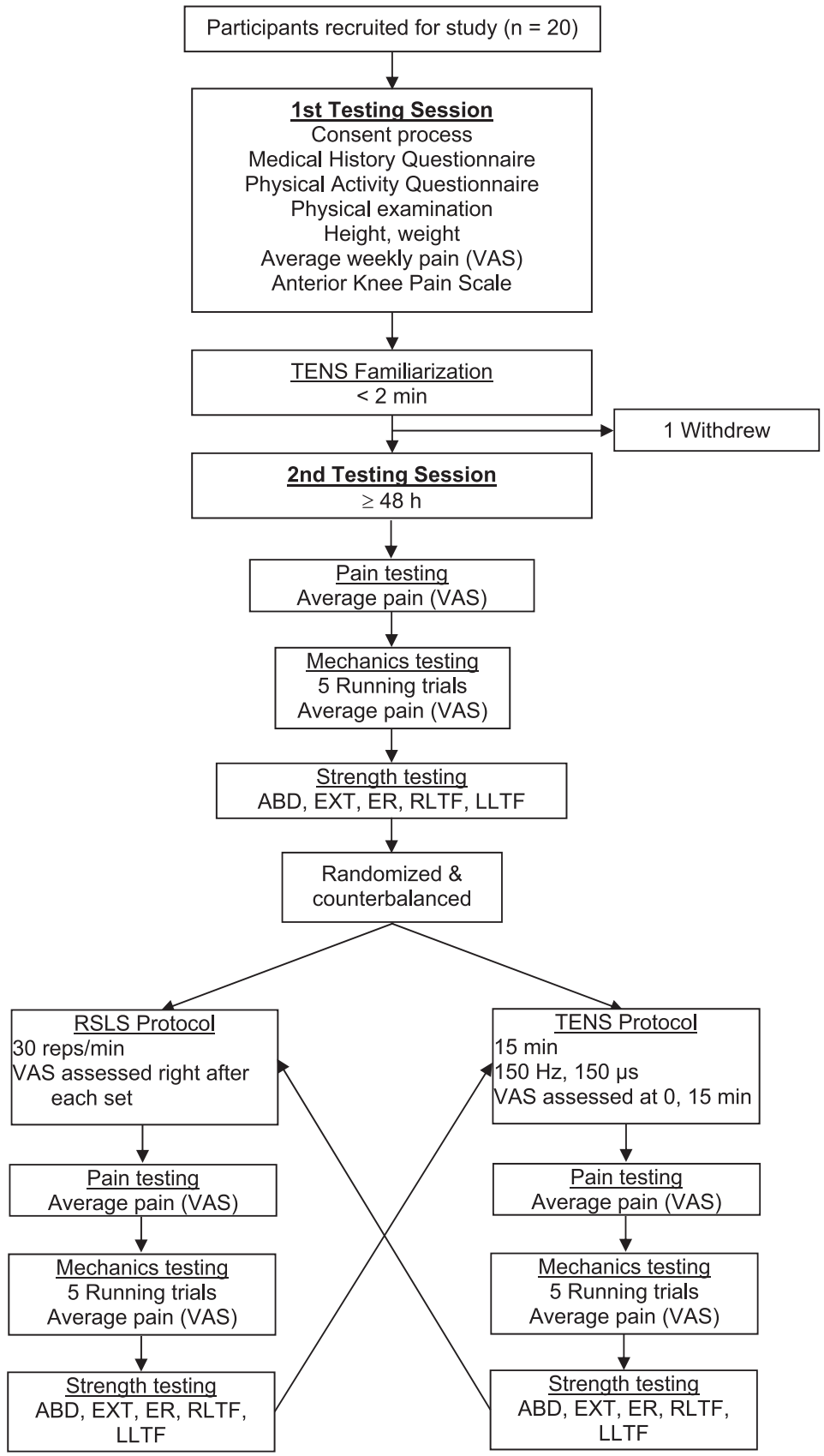

Figure 1. Study flow chart. Abbreviations: ABD, abduction; ER, external rotation; EXT, extension; LLTF, left lateral trunk flexion; RLTF, right lateral trunk flexion; RSLS, repeated single-legged squats; TENS, transcutaneous electrical nerve stimulation; VAS, visual analog scale.

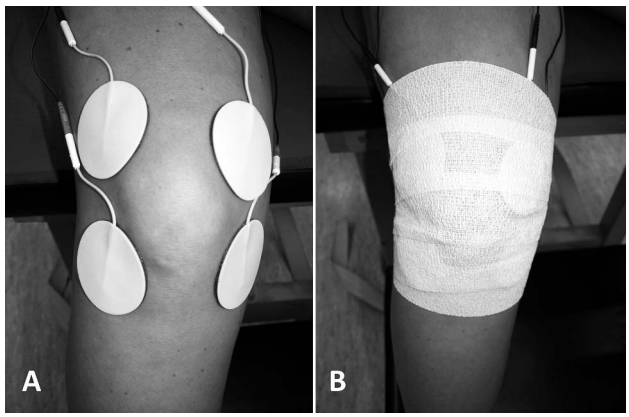

Figure 2. A, Application of the electrodes for the transcutaneous electrical nerve stimulation protocol. B, PowerFlex tape (Andover Healthcare, Inc, Salisbury, MA) was wrapped around the electrodes to reduce movement during the running tests.

activity. Participants were instructed to report their average pain during physical activity over the previous week. The Kujala Anterior Knee Pain Scale questionnaire was also used to measure and describe the participant's perceived level of function. Crossley et al[31] reported that these measures were both reliable and valid in a population with PFP.

Participants were then familiarized with the TENS protocol to reduce any anxiety that they might have had about electric stimulation. During the familiarization, the electrodes and TENS unit were applied per the protocol to be used during the following testing session (see detailed description in the next section). The duration of TENS exposure was less than 2 minutes to avoid any possible treatment effect.

Second Testing Session

The second testing session occurred no less than 2 days after the initial session and consisted of additional VAS pain assessments, strength assessments, and biomechanical analyses. The VAS was used to reassess the participant's average right and left leg pain during physical activity. In participants with bilateral knee pain, the limb with the higher VAS score was tested. Three-dimensional joint kinematics and kinetics data were collected during overground running using a 10-camera Eagle System (Motion Analysis Corp, Santa Rosa, CA) and ground reaction force was collected via a force plate (model OR6-5; Advanced Mechanical Technology Inc, Watertown, MA). Positional and force data were synchronously collected using Cortex Real Time software (version 1.0; Motion Analysis Corp) at 200 Hz and 1000 Hz, respectively. Participants were provided with shoes (model Jazz; Saucony, Lexington, MA) and tight-fitting shorts to maintain shoe and clothing consistency.

Before data collection, we shaved the skin of the participant's anterior knee if needed and cleansed with an alcohol wipe to ensure proper electrode adherence. To deliver the TENS (TENS 3000; Current Solutions, LLC, Austin, TX) to the peripatellar region, we applied 4 separate, 2 × 2-in (5.08- × 5.08-cm) self-adhesive electrodes (model Dura-Stick II; Chattanooga Group, Hixson, TN) medially and laterally to the superior and inferior borders of the patella (Figure 2A).[27] The electrodes were wrapped with PowerFlex tape (Andover Healthcare, Inc, Salisbury, MA) to ensure that they did not move during testing (Figure 2B). Skin preparation and electrode placement were performed before the warm-up and initial tests to ensure that taping did not influence the subsequent trials.

Biomechanical and Pain Data Collection

For the biomechanical data collection, single reflective markers were placed on the participant's iliac crests, greater trochanters, anterior- and posterior-superior iliac spines, medial and lateral condyles of the knee, medial and lateral malleoli, and first and fifth metatarsal-phalangeal joints to establish joint centers and anatomical axes during a standing calibration trial. Four-marker clusters attached to a rigid plate were also placed over the lateral aspects of the thigh and leg by attaching them to a fabric hook-and-loop strap and over the heel counter of the shoe to track foot motion. All single markers except the anterior- and posterior-superior iliac spine markers were removed after the calibration trial.

Participants then walked on a standard treadmill (model C964i; Precor Inc, Woodinville, WA) at a self-selected quick pace for 3 to 5 minutes to warm-up. After the warm-up, participants ran on the treadmill at their normal training speed (average ± standard deviation = 2.4 ± 0.49 m/s) for 30 seconds. After the 30-second treadmill run, participants stopped running and immediately completed a VAS for their average pain during the 30-second run (Table 2). Baseline and postprotocol pain assessment were performed during running, rather than during quiet sitting, to increase the functional validity of the pain assessment.

Table 2. Visual Analogue Scale Changes in Pain Between Pain-Changing Protocols

	Treadmill Running[b]				Overground Running[b]			
Variable	Mean ± SD	Median (Range)	Change, %	Effect Size	Mean ± SD	Median (Range)	Change, %	Effect Size
Pretest[a]	3.10 ± 1.95	3.6 (0.0–7.0)	NA	NA	3.10 ± 1.99	2.9 (0.1–8.0)	NA	NA
Transcutaneous electrical nerve stimulation	1.89 ± 2.33[c]	1.1 (0.0–7.4)	−39	0.704	1.61 ± 2.24[c]	0.5 (0.0–8.0)	−48	1.012
Repeated single-legged squats	4.38 ± 2.40[d]	4.3 (0.0–8.2)	41	0.836	4.09 ± 2.44	4.8 (0.1–8.0)	32	0.530

Abbreviation: NA, not applicable.

[a] Pain measured during initial 30-s treadmill run or initial overground biomechanical trial.

[b] Friedman test significant at $P < .05$.

[c] Wilcoxon post hoc test significant ($P < .05$) between pretest and transcutaneous nerve stimulation conditions.

[d] Wilcoxon post hoc test significant ($P < .05$) between pretest and repeated single-legged squat conditions.

Participants then moved to the 10-m overground runway, and 3-dimensional data during running were recorded while they ran at a speed of 4.0 ± 0.5 m/s; speed was monitored with photocells (model 2T35; RadioShack Corp, Fort Worth, TX) placed 3.7 and 2.1 m before the force plate. Running speed was calculated using a custom program (LabView; National Instruments Corp, Austin, TX). Testing in our laboratory has indicated that this is an appropriate speed for physically active individuals. This standardized speed was used to reduce the potential influence of running speed on mechanics. Participants were allowed to practice until they were able to perform with the foot striking the force plate. Five trials were recorded to capture 3-dimensional motion of the pelvis, hip, knee, and ankle and ground reaction forces. Participants then completed a VAS pain assessment for their average pain during all overground running trials (Table 2).

Strength Data Collection

After the running trials, strength was measured via maximal voluntary isometric contractions (MVICs) using a handheld dynamometer (model 01136; Lafayette Instrument Co, Lafayette, IN) secured with nonelastic straps. Testing positions were similar to those described previously.[15,32,33] For all tests, participants were instructed to maximally push against the handheld dynamometer. Participants performed 1 practice trial and then 3 MVIC tests per muscle group, with 15 seconds' rest between tests and 1 to 2 minutes of rest between muscle groups. The MVIC test was 5 seconds in length and participants were instructed to ramp up their force so they were pushing with maximal effort for the final 3 seconds of the test. Tests were performed in a randomized order. The handheld dynamometer provided a readout of kilogram of force and all 3 trials were recorded, with the average value being used for analysis. These measures have been shown to be reliable between days for the primary investigator (ABD: $r = 0.867$, ER: $r = 0.919$, EXT: $r = 0.855$, LTF: $r = 0.970$).[33]

After the first round of running and strength tests, participants completed 1 protocol to decrease and 1 to increase knee pain, in a randomized order, counterbalanced by sex. Participants were told that they would complete 2 protocols: 1 to decrease and 1 to increase their pain. They were not specifically told which protocol would decrease or increase pain, in an attempt to reduce bias toward perceived effects. Most participants immediately identified these changes, finding the TENS to be pain reducing and the RSLS to be painful. A small number of participants (n = 2) found the TENS increased their pain. No participants had previously experienced TENS.

Repeated Single-Legged Squats Protocol

For the repeated single-legged squats (RSLS) protocol, intended to increase participants' pain, participants performed sets of 20 single-legged squats, similar to a lateral step-down, in a repeated pattern. The pace of the squat repetitions was controlled with a metronome set to 60 beats per minute. Participants started by standing on a box with their nontest limb hanging laterally off the box. Participants were instructed to lower themselves until their heel lightly touched the floor lateral to the box on 1 beat of the metronome and return to the starting position on the next beat, resulting in a speed of 30 repetitions per minute. Participants were allowed to practice 5 to 10 repetitions with the metronome before pain during those 5 to 10 repetitions was assessed as their baseline RSLS pain. They then completed 20 squat repetitions and rescored their pain on the VAS during the trial. Approximately 2 to 5 minutes of rest were provided between RSLS sets in an attempt to prevent fatigue. Participants were asked if they felt any fatigue in their legs after the 2-minute rest period and were allowed to rest until all feelings of fatigue had dissipated. Participants completed RSLS sets until either their pain was within 1 cm of their pain during an exhaustive run[15] or they reached 10 sets. The mean ± standard deviation and median (range) number of sets completed were 4.4 ± 3.7 and 3.0 (1–10), respectively. After the final set of RSLS and subsequent rest period, participants completed the following, in order: pain assessment during 30 seconds of treadmill running, overground running biomechanics and pain assessment, and strength assessment. The strength assessment typically occurred 10 to 20 minutes after the final set of RSLS. At least 10 minutes were provided between protocols for the participants to rest and recover; however, the exact duration was not recorded.

Transcutaneous Neuromuscular Electrical Stimulation Protocol

The TENS protocol was designed to decrease pain in those with PFP. Before turning on the TENS device, we asked the participant to assess pain using the VAS while he or she performed 3 to 5 single-legged half-squats to elicit pain. Participants then received a 15-minute TENS treatment (using continuous, biphasic pulsatile current at 150 Hz and 150 μs). The 2 TENS currents were crossed to stimulate the most surface area.[34] Participants were seated with their knees slightly bent for the duration of the treatment. The TENS intensity was increased until the participant indicated that it was the maximum he or she could tolerate and the investigator ensured that a muscle contraction was not present. This protocol is similar to the one used by Pietrosimone et al[27,34] and has demonstrated disinhibitory pain effects in the knee.[29] Pain was measured using the VAS during the half-squat (n = 3–5) after 15 minutes of the TENS protocol to verify a reduction in pain. Participants were instructed to complete a few half-squats to determine their pain level. If a participant's pain had not decreased at least 1 cm after 15 minutes of TENS, these data were not included in the final analysis. Participants then completed the 30-second treadmill run and pain assessment, followed by the overground biomechanical running analysis and pain assessment as well as strength testing. The TENS stimulation was continued throughout all posttesting and was discontinued after the final strength test. At least 10 minutes of rest were provided between protocols for the participants to recover.

Data Reduction

Strength data, measured in kilograms, were averaged across the 3 recorded trials and then normalized to the participant's body mass (kg/kg).[33] The dependent strength variables were the normalized ABD, ER, EXT, and LTF values. Joint-angle and ground reaction force data were processed and used to calculate internal joint moments

Table 3. Body-Mass Normalized (kg/kg) Hip Strength Between Pain-Changing Protocols

Variable	Mean ± SD				
	Pretest	Transcutaneous Electrical Nerve Stimulation	Repeated Single-Legged Squats	*P* Value	η_p^2 Value
Abduction	0.348 ± 0.09	0.353 ± 0.09	0.339 ± 0.09	.581	0.033
External rotation	0.102 ± 0.02	0.102 ± 0.02	0.099 ± 0.02	.686	0.023
Extension[a]	0.355 ± 0.08	0.354 ± 0.09	0.309 ± 0.09	<.001	0.397
Lateral trunk flexion	0.364 ± 0.13	0.359 ± 0.14	0.350 ± 0.12	.538	0.038

[a] Difference between pretest and repeated single-legged squats ($P = .006$).

using Visual 3D software (C-Motion Inc, Germantown, MD). The kinematic and ground reaction force data were filtered using a fourth-order, zero lag, recursive Butterworth filter with a cutoff frequency of 20 Hz.[35] Segment coordinate systems followed the right-hand convention and were anatomically based. The x-axis, y-axis, and z-axis pointed in the medial-lateral, anterior-posterior, and vertical direction, respectively. Hip-, knee-, and ankle-joint angles were calculated using a joint-coordinate system approach.[36] *Joint centers for the knee and ankle* were defined as the midpoint between the medial and lateral knee and ankle joint markers, respectively. The hip-joint centers were estimated at 25% of the horizontal distance between the greater trochanters.[37] An inverse-dynamics approach[38] was used to derive the joint kinetic data of the hip, knee, and ankle from the ground reaction force and kinematic data. Kinetic data were normalized to body mass to allow comparison with previously published research. Body-segment measurements were based on Dempster.[39] For clarity of presentation during processing, left-leg data were inverted in the frontal and transverse planes so that all numeric results are presented from the perspective of the right lower extremity. Dependent variables extracted for analysis were peak angles during stance for the ankle (plantar flexion, eversion, tibial internal rotation), knee (flexion, ABD, IR), hip (EXT, ADD, IR), and pelvis (anterior tilt, contralateral drop), as well as ankle (plantar flexion, inversion, tibial external rotation), knee (EXT, ABD, ER), and hip (EXT, ABD, IR) peak internal joint moments during stance.

Statistical Analyses

All statistical analyses were performed in SPSS for Windows (version 19.0; IBM Corp, Armonk, NY). A Friedman statistical test for repeated measures was used to compare pain (VAS) during treadmill and overground running before and after the TENS and RSLS protocols. Significant results were further assessed with a Wilcoxon test between baseline and TENS or RSLS protocols. Separate analyses of variance (ANOVAs) with repeated measures were used to compare strength, kinematics, and joint moments during running. Each ANOVA was performed for 1 group at 3 times (baseline, post-RSLS, post-TENS). The Mauchly test was performed to check the sphericity of the data; if significant, the Greenhouse-Geisser statistic was used. Pairwise testing for all ANOVAs was performed using the Sidak test when necessary. The α level for determining significance was set at $P \leq .05$ for all tests. Effect sizes for the ANOVAs are reported as partial η^2 values, using the guidelines of *small* (0.01), *medium* (0.06), and *large* (0.14).[40] Effect sizes for the pain scores are reported as Cohen d using the guidelines of *small* (0.2), *medium* (0.5), and *large* (0.8).[40]

RESULTS

One participant attended the initial session and was enrolled in the study but did not return for the second session. Therefore, testing and protocols were performed on 19 individuals. Two women were removed from the final data analysis due to a lack of pain reduction from the TENS protocol. Final analyses were performed on a total of 17 persons with PFP (10 men, 7 women). Bilateral PFP was reported in 88.2% (15/17) of participants. Participants had an average baseline VAS score of 4.8 ± 1.1 cm and an average Kujala Anterior Knee Pain Scale score of 74.2 ± 7.6.

Differences in pain after the RSLS and TENS protocols (Table 2) were significant for both treadmill ($\chi^2_2 = 14.7$, $P = .001$) and overground ($\chi^2_2 = 19.1$, $P < .001$) running. Pairwise comparisons demonstrated that the TENS protocol decreased pain during both treadmill ($z = -2.614$, $P = .009$, Cohen d = 0.704) and overground ($z = -3.158$, $P = .002$, Cohen d =1 .012) running. The RSLS protocol increased pain during treadmill running ($z = -2.675$, $P = .007$, Cohen d = 0.836), and a trend toward an increase was found in overground running ($z = -1.914$, $P = .056$, Cohen d = 0.530).

A significant change was noted only in EXT strength ($F_{2,32} = 10.51$, $P < .001$), with no other changes after the TENS and RSLS protocols (ABD: $F_{2,32} = 0.553$, $P = .581$; ER: $F_{2,32} = 0.382$, $P = .686$; LTF: $F_{2,32} = 0.632$, $P = .538$). Sidak pairwise comparisons indicated that hip EXT strength decreased after the RSLS protocol ($P = .006$) but not after the TENS protocol ($P = 1.00$; Table 3).

A difference for peak ankle plantar-flexion angle ($F_{2,32} = 4.058$, $P = .041$, $\eta_p^2 = 0.202$) was found. Pairwise comparisons identified a decreased ankle plantar-flexion angle after the RSLS ($P = .012$) but not after the TENS ($P = .996$) protocol. No other significant changes ($P > .05$) in kinematics occurred after the TENS or RSLS protocols (Table 4).

Main effects were observed for 2 kinetic variables (Table 5). Hip EXT moment displayed a main effect ($F_{2,32} = 8.450$, $P = .001$), with pairwise analyses demonstrating reductions in the hip EXT moment after the TENS ($P = .015$) and RSLS ($P = .003$) protocols. The main effect for hip ABD moment was also significant ($F_{2,32} = 6.112$, $P = .006$), and pairwise comparisons identified reductions after both the TENS ($P = .015$) and RSLS ($P = .039$) protocols. No main-effect differences were identified for any other variables ($P > .05$).

Table 4. Peak Running Kinematic Variables (°) Between Pain-Changing Protocols

Variable	Mean ± SD				
		Protocol			
	Pretest	Transcutaneous Electrical Nerve Stimulation	Repeated Single-Legged Squats	*P* Value	η_p^2 Value
Ankle plantar flexion[a,b]	−13.97 ± 6.41	−14.08 ± 6.83	−12.84 ± 6.45	.041	0.202
Ankle eversion	−6.99 ± 4.34	−6.65 ± 4.25	−6.94 ± 4.37	.577	0.025
Tibial internal rotation	−17.31 ± 5.63	−17.64 ± 5.46	−17.28 ± 5.21	.759	0.017
Knee flexion	−38.85 ± 8.50	−38.98 ± 8.72	−38.79 ± 9.12	.815	0.013
Knee abduction	−2.90 ± 2.39	−3.06 ± 2.74	−3.07 ± 3.00	.691	0.013
Knee internal rotation	4.28 ± 2.93	5.10 ± 3.94	4.35 ± 3.43	.260	0.081
Hip extension	−7.47 ± 6.01	−6.69 ± 6.22	−7.42 ± 6.31	.178	0.107
Hip adduction	13.37 ± 3.95	13.98 ± 4.37	13.67 ± 4.58	.505	0.042
Hip internal rotation	6.03 ± 5.15	5.21 ± 5.74	6.13 ± 6.02	.360	0.059
Anterior pelvic tilt	−14.04 ± 5.64	−13.66 ± 4.86	−13.64 ± 4.91	.310	0.071
Contralateral pelvic drop	−5.78 ± 2.49	−6.17 ± 2.61	−5.94 ± 2.19	.379	0.059

[a] Main effect for intervention ($P < .05$).
[b] Repeated single-legged squats different from pretest ($P < .05$).

Overall, these results showed that pain was decreased by the TENS and increased by the RSLS. Concurrent with the increased pain, the RSLS protocol resulted in decreased hip EXT strength, decreased peak ankle plantar-flexion angle, and decreased peak hip EXT and ABD moments. The TENS protocol resulted in decreased peak hip EXT and ABD moments, concurrent with decreased pain.

DISCUSSION

The purpose of our study was to investigate the acute effects of changes in anterior knee pain on hip and trunk strength and lower extremity mechanics in persons with PFP. Our results indicate that functionally increased knee pain immediately reduced hip EXT strength and hip ABD and EXT internal joint moments during running. Whereas the TENS protocol did decrease knee pain, it did not have any immediate effects on strength, and the only resulting mechanical change was a reduced hip ABD internal joint moment. Although previous researchers have suggested pain as an explanatory factor for such results, no authors have investigated how changing pain influences strength and running mechanics in persons with current, chronic knee pain.

Pain

One main finding of our study was that both protocols were effective at changing pain in those with PFP. The finding that the RSLS protocol increased pain is not surprising because patients with PFP often describe pain during squatting and other activities that require repetitive knee flexion. We were unable to find any other investigations in which knee pain was purposefully increased in a population that already had knee pain. It is important to study the role of increasing pain in persons with current, chronic pain because this population typically continues their physical activity through pain (eg, runners). Continu-

Table 5. Peak Running Kinetic Variables Between Pain-Changing Protocol

Variable		Mean ± SD				
			Protocol			
		Pretest	Transcutaneous Electrical Nerve Stimulation	Repeated Single-Legged Squats	*P* Value	η_p^2 Value
Moment, Nm/kg	Ankle plantar flexion	−2.66 ± 0.35	−2.62 ± 0.33	−2.65 ± 0.37	.484	0.044
	Ankle inversion	0.14 ± 0.08	0.13 ± 0.08	0.13 ± 0.07	.475	0.045
	Tibial external rotation	0.09 ± 0.05	0.09 ± 0.05	0.08 ± 0.05	.614	0.021
	Knee extension	2.52 ± 0.44	2.47 ± 0.42	2.47 ± 0.49	.399	0.056
	Knee abduction	−1.02 ± 0.34	−1.01 ± 0.32	−0.98 ± 0.33	.213	0.092
	Knee external rotation	−0.12 ± 0.09	−0.12 ± 0.08	−0.12 ± 0.08	.690	0.023
	Hip extension[a,b,c]	−2.31 ± 0.46	−2.15 ± 0.48	−2.18 ± 0.52	.001	0.346
	Hip abduction[a,b,c]	−2.02 ± 0.35	−1.91 ± 0.33	−1.87 ± 0.36	.006	0.277
	Hip internal rotation	0.38 ± 0.16	0.38 ± 0.17	0.37 ± 0.15	.554	0.036
Ground reaction force, body weight	Vertical	2.41 ± 0.22	2.38 ± 0.19	2.41 ± 0.20	.190	0.099
	Breaking	0.39 ± 0.04	0.39 ± 0.03	0.38 ± 0.04	.262	0.080
	Propulsive	−0.29 ± 0.06	−0.28 ± 0.05	−0.29 ± 0.06	.100	0.134
	Medial	0.09 ± 0.05	0.09 ± 0.04	0.09 ± 0.05	.904	0.006
	Lateral	−0.05 ± 0.05	−0.05 ± 0.05	−0.05 ± 0.05	.869	0.009

[a] Main effect for intervention ($P < .05$).
[b] Transcutaneous electrical nerve stimulation different from pretest ($P < .05$).
[c] Repeated single-legged squats different from pretest ($P < .05$).

ing activity through pain might contribute to further progression of the injury, pain, or both.[11] Other researchers[41] have investigated the effects of experimentally induced pain via fat-pad injections in healthy persons, demonstrating increased knee pain similar to PFP. These studies are limited because the participants were pain free and the pain was transient; therefore, it is difficult to infer information about chronic pain from these studies.[42] Better models of chronic pain seem necessary for understanding PFP and the influence of pain.

We were also unable to identify previous investigations of the effectiveness of TENS in the treatment of PFP, though it has been advocated for pain reduction.[43] This is the first study to demonstrate that 15 minutes of sensory-level TENS were effective in acutely reducing knee pain in a sample experiencing PFP, a result that is similar to findings in patients with knee osteoarthritis.[25] Given that sensory-level TENS provides pain relief only during application, it might be useful during rehabilitation (eg, quadriceps strengthening) or gait retraining to hasten or improve the process. This has been demonstrated in knee osteoarthritis[44] but requires research in patients with PFP. A similar protocol using patellar taping to reduce pain and facilitate rehabilitation exercises has been shown to be beneficial.[45] This should be the focus of future examination via randomized controlled trials.

Strength

Another main finding of our study was that EXT strength decreased concurrently with increased pain after the RSLS protocol. Our results are in agreement with those of previous authors who reported increased quadriceps muscle inhibition[29] and reduced quadriceps and hamstrings strength[46] after increased pain using an experimental knee-pain model. We could not find any published experimental knee-pain studies that addressed changes to the hip musculature; however, we hypothesize that the changes would be consistent with our findings. Further supporting this are reports of changes to hip-extensor muscle activity after acute ankle sprains[47,48] and decreased ABD strength in those with chronic ankle sprains.[49] These results demonstrate that pain or injury to the distal joints contributes to the inhibition of proximal musculature, even in those currently experiencing chronic knee pain. These findings provide further support for the hypothesis that reduced hip strength is the result of pain rather than the cause of PFP.[21]

The TENS protocol reduced pain but did not change hip or trunk strength. Thus, 15 minutes of sensory-level TENS were not sufficient to reduce muscle inhibition and improve muscle function in this population. It is possible that changes would have been seen with longer treatment durations. Previous researchers have demonstrated improved quadriceps function (ie, H-reflex, central activation ratio) with 30 to 45 minutes of TENS in an experimental knee-effusion model[29] and in persons with tibiofemoral osteoarthritis.[34] However, the authors[34] did not report improvements in quadriceps strength using TENS, suggesting that MVIC tests might not be sensitive enough to detect small changes in muscle function. It is also possible that the inhibitory effects of pain remain even after pain has been relieved, which has been previously demonstrated in some[46,50,51] but not other experimental knee-pain studies.[30,52] It should be noted that TENS might be beneficial for long-term use. Strength increased when TENS was combined with rehabilitation compared with placebo TENS and rehabilitation or with rehabilitation alone.[44] Whereas we did not demonstrate strength changes with TENS-related pain reductions, long-term interventions combined with rehabilitation should be further explored.

Kinematics

The lack of changes in the hip kinematic variables we measured is consistent with previous findings. Some researchers have proposed kinematic invariance[53] after acute increases in pain.[30] *Kinematic invariance* could be described as maintaining kinematics after a perturbation (ie, increased pain) while the kinetics are adjusted.[53] Authors of experimental knee-pain studies have reported few kinematic changes, including decreased knee-flexion[54] and ankle plantar-flexion[30] angles during walking and decreased plantar-flexion and hip-adduction angles during running.[30] We also reported reduced peak ankle plantar-flexion angles during running. The primary difference between our study and previously mentioned studies[30,54] is the chronicity of pain in our participants. This might have influenced their response to pain by dampening the effect of the RSLS protocol, as can be seen in the relatively smaller magnitude of changes in pain we found (0.99–1.50 cm) compared with previous investigators (2.58 cm by Henriksen et al[54] and 4.29 cm by Seeley et al[30]). The PFP population has demonstrated variable responses to increased pain (concurrent with fatigue) at the knee during running[15,16] and jumping.[17] Considering these factors, our results are similar to those reported previously[15–17] and demonstrate limited kinematic changes in this population. The chronic nature of pain in this PFP population and the established movement patterns in response to this pain appear to be resistant to acute perturbations in pain level.

A similar discussion regarding resistance to kinematic changes is warranted in regard to the TENS protocol. We did not find any changes in kinematics despite a reduction in pain. Although the duration of the TENS protocol could be proposed as a reason for the lack of changes, a 4-week TENS and quadriceps-strengthening intervention in patients with knee osteoarthritis resulted in no differences in kinematics.[27] Our findings demonstrate that running kinematics in those with PFP are slow to change with small, acute reductions in pain.

Kinetics

Changes to joint moments were demonstrated in our study. Increased pain after the RSLS protocol resulted in decreased hip EXT (–9.9%) and ABD (–6.0%) moments. Our findings are in agreement with those of Seeley et al,[30] who reported reductions in hip ABD moment (–15%) during walking after experimental knee pain. However, in contrast with their study,[30] we did not find differences in plantar-flexion or knee-extension moments. Although the reduced hip EXT moment occurred concurrently with the reduction in hip EXT strength, additional factors (eg, trunk position) may have also influenced the change in hip EXT moment. The decrease in hip ABD moment seems counterintuitive because changes in hip ABD strength were

not significant. Changes in strength cannot be excluded as a possible factor due to the order in which mechanics and strength were tested. It might be that changes in mechanics, which were measured first, occurred during this testing, and recovery occurred before strength testing. Trunk positon could also have influenced the hip ABD moments. The hip EXT and ABD moments were also reduced after the TENS protocol, making interpretation difficult. People with PFP might respond to any abrupt change in pain, either an increase or a decrease, with adaptations to the hip moments as an unloading strategy to reduce reliance on the gluteal muscles. Reduced knee loading has been reported concurrently with decreased gluteus medius electromyographic activity,[55] supporting this hypothesis. Also, lateral trunk lean to the ipsilateral side has been noted to reduce the demand on the hip ABD muscles and could be an adaptation to compensate for hip weakness in this population.[11] However, this interpretation is limited because we did not collect trunk data.

Limitations

Several limitations of our study should be recognized. The primary limitation was that both pain-reducing and pain-inducing protocols were performed on the same day. Although future work may benefit from performing the protocols on separate days, we believe that our results provide evidence to support a decrease in hip EXT strength when knee pain is increased, regardless of fatigue. We do not believe that fatigue from the RSLS protocol influenced the results for several reasons. First, participants were provided with up to 5 minutes of rest before performing the strength testing, which allowed ample time for the quick energy systems to recover fully. Second, no significant correlation was observed between the change in hip EXT strength and the number of RSLS performed ($r = 0.114$). In addition, participants who performed 6 to 10 sets (n = 6; change = –0.053) of RSLS did not experience a greater decrease in hip EXT strength than those who performed only 1 to 2 sets (n = 8; change = –0.045; $P = .495$). Finally, a post hoc analysis revealed that participants had no change in hip EXT strength after the TENS protocol, even if they had performed the RSLS protocol first (change = –0.001). In regard to the TENS protocol, most participants had not previously received any type of electrical stimulation treatment, and some were anxious about how the TENS protocol would feel during running. Though a familiarization period was allowed and most had positive experiences with the TENS, this anxiety could have affected their running mechanics by encouraging them to use a compensatory pattern. A related limitation is that only the sensory/intensity component of pain was assessed (using the VAS) during this study. The motivational/affective dimension could have influenced participants' response to the TENS or willingness to perform the RSLS protocol. Another limitation is that we used peak values from the kinematic and kinetic data. Given that these values are single, discrete time points, differences between the conditions could have been missed. However, most investigators of PFP use discrete variables in their various analyses. Further research that addresses this limitation in the PFP literature should be pursued. Last, this study may be limited by its sample size due to the loss of 3 participants from the original recruited sample or by participation of a greater number of men than women. Comparison with other studies might be difficult because most research has been performed exclusively with women. Future authors should attempt to include a greater number of men to allow for sex comparisons in a PFP population. Despite these limitations, our findings provide valuable information in the study of pain and PFP. Further research regarding the role of pain in populations with PFP is warranted.

CONCLUSIONS

To our knowledge, we are the first to attempt to acutely change pain in persons with PFP. Although pain was easily changed, this did not simply equate to changes in strength or running mechanics. Pain was decreased with 15 minutes of sensory-level TENS, demonstrating that TENS was an effective modality for decreasing pain. Strength, however, was not affected by the acute decrease in pain. The acute reduction in pain from TENS resulted in reduced peak hip EXT and ABD joint moments. We were able to increase anterior knee pain using the novel protocol of sets of 20 RSLS. This protocol also resulted in decreased hip EXT strength, decreased peak ankle plantar-flexion angles, and peak hip EXT and ABD joint moments. These results support the hypothesis that acute changes to pain, even in a population experiencing chronic knee pain, affect the kinetics of running, specifically at the hip. Pain is often considered only a symptom of PFP. This study provides preliminary evidence that pain plays a much more complex role in the cause and progression of PFP.

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