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original research

Changes in Knee Biomechanics After a Hip-Abductor Strengthening Protocol for Runners With Patellofemoral Pain Syndrome

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Context: Very few authors have investigated the relationship between hip-abductor muscle strength and frontal-plane knee mechanics during running.

Objective: To investigate this relationship using a 3-week hip-abductor muscle-strengthening program to identify changes in strength, pain, and biomechanics in runners with patellofemoral pain syndrome (PFPS).

Design: Cohort study.

Setting: University-based clinical research laboratory.

Patients or Other Participants: Fifteen individuals (5 men, 10 women) with PFPS and 10 individuals without PFPS (4 men, 6 women) participated.

Intervention(s): The patients with PFPS completed a 3-week hip-abductor strengthening protocol; control participants did not.

Main Outcome Measure(s): The dependent variables of interest were maximal isometric hip-abductor muscle strength, 2-dimensional peak knee genu valgum angle, and stride-to-stride knee-joint variability. All measures were recorded at baseline and 3 weeks later. Between-groups differences were compared using repeated-measures analyses of variance.

Results: At baseline, the PFPS group exhibited reduced strength, no difference in peak genu valgum angle, and increased stride-to-stride knee-joint variability compared with the control group. After the 3-week protocol, the PFPS group demonstrated increased strength, less pain, no change in peak genu valgum angle, and reduced stride-to-stride knee-joint variability compared with baseline.

Conclusions: A 3-week hip-abductor muscle-strengthening protocol was effective in increasing muscle strength and decreasing pain and stride-to-stride knee-joint variability in individuals with PFPS. However, concomitant changes in peak knee genu valgum angle were not observed.

Key Words: gait, hip muscles, anterior knee pain

Key Points

- After a 3-week hip-abduction strengthening program, patients with patellofemoral pain syndrome increased muscle strength and displayed decreases in both pain and stride-to-stride knee-joint variability. No changes were noted in peak knee genu valgum.
- Stride-to-stride knee-joint variability may be a better indicator of injury rehabilitation than are peak angles.
- Hip-abductor muscle strengthening should be incorporated into patellofemoral pain syndrome rehabilitation protocols.

A number of authors[1–7] have hypothesized that a primary contributing factor to patellofemoral pain syndrome (PFPS) is weakness of the hip-abductor musculature. The hip-abductor muscles have been theorized[1–9] to eccentrically control hip adduction and, thus, knee genu valgum angle during the stance phase of running. A greater genu valgum angle (or increase in the dynamic Q-angle) has been purported[2,3,5,8–12] to increase patellofemoral contact pressure and to lead to PFPS. However, very few researchers have investigated the relationship between hip-abductor muscle strength and frontal-plane knee mechanics.

Willson and Davis[11] reported that compared with controls, patients with PFPS exhibited greater hip adduction during single-leg squats, running, and repetitive single-leg jumps, and they attributed the atypical frontal-plane mechanics to weakness of the hip-abductor musculature. However, measures of hip-abductor strength were not collected. Other authors[7–10,13] have also reported similar findings, with PFPS patients demonstrating greater hip adduction, knee genu valgum, or reduced strength of the hip-abductor musculature (or all of these) than do healthy people. Yet these studies mainly investigated each variable in isolation and did not directly address the relationship between hip-abductor muscle strength and knee genu valgum angle.

Few experts have examined the relationship between hip-abductor muscle strength and knee mechanics and how gains or reductions in strength may affect frontal-plane knee mechanics. Bolgla et al[7] measured hip-abductor strength and knee and hip kinematics and reported that those with PFPS exhibited reduced hip-abductor muscle strength but no differences in knee genu valgum angle during stair descent compared with the control group. Similar to Bolgla et al,[7] Dierks et al[2] reported reduced hip-abductor muscle strength in both PFPS patients and the control group after a prolonged and exhaustive run. However, in contrast to the findings of Bolgla et al,[7] the PFPS patients in this study exhibited an increase in peak hip adduction, a component of the knee genu valgum angle, over the course of the run, compared with healthy runners. Recently, Snyder et al[14] reported that after a 6-week hip strengthening protocol, healthy female runners exhibited a 13% gain in abductor strength, but the hip-adduction angle during running increased by 1.4°, contrary to their hypotheses and the results of previous studies. Moreover, to date, no authors have specifically tested whether improvements in muscle strength would lead to a reduced peak knee genu valgum angle for runners with PFPS. Thus, based on the conflicting results of these studies, further investigation into the relationship between hip-abductor muscle strength and knee mechanics is warranted. In light of these contradictory findings in the literature, it may be worthwhile to examine the relationship between hip-abductor muscle strength and knee mechanics using a more novel approach.

Previous authors[15–21] have suggested that movement variability may be an important consideration with respect to injury prevention and rehabilitation. However, one must first define *movement variability*. When a motion is performed repeatedly, as in the stride-to-stride pattern involved in running, and even when the goal of the motion remains constant, the exhibited kinematic movement pattern varies among strides.[17] The overall movement goal of running would be an example of *global variability*, which has been defined as a combination of between-limbs or within-limb kinematic patterns for the purpose of a movement goal or, for example, in response to balance perturbations. In contrast, *local variability* has been defined as the coupling or relative angles between joints or segments.[15]

Stride-to-stride variability in joint movement patterns during locomotion can be both beneficial and harmful depending on the global or local variability measure used. For example, increased stride-to-stride variability in stride length[18] and stride time,[19] both measures of global variability, have been associated with an increased risk of falling. With respect to local variability, in 2009 Drewes et al[20] reported less coordinated rearfoot-shank segmental coupling in those with chronic ankle instability, and McKeon et al[21] observed a decrease in rearfoot-shank segmental coupling variability in individuals with chronic ankle instability after a 4-week balance-training program. Miller et al[17] suggested that during running, tibia-rearfoot and rearfoot-thigh segmental coupling variability was reduced, but knee-rearfoot coupling variability was increased in runners with a history of iliotibial band syndrome, compared with healthy individuals. Finally, Hamill et al[15] noted less variability in lower extremity movement patterns during running in patients with PFPS compared with healthy people. Thus, although there is some discrepancy in the literature, most researchers have reported that reduced variability is associated with running-related injuries, such as PFPS, and increased variability of movement appears to be necessary to allow for flexibility in gait mechanics in response to unexpected perturbations.

The purpose of our experiment was to investigate the relationship between hip-abductor muscle strength and frontal-plane knee mechanics. We sought to assess this relationship by using a 3-week hip-abductor muscle-strengthening protocol to measure potential changes in strength, pain, and biomechanics in patients with PFPS. We operationally defined local, within-limb movement variability and quantified it as the change in knee-joint frontal-plane kinematic patterns across 10 consecutive footfalls (herein called *stride-to-stride knee-joint variability*). We hypothesized that at baseline, PFPS patients would exhibit reduced hip-abductor muscle strength, greater peak knee genu valgum angle, and decreased stride-to-stride knee-joint variability compared with the control group. After the 3-week rehabilitation protocol, we hypothesized that hip-abductor muscle strength would increase, pain would decrease, peak knee genu valgum angle would decrease, and stride-to-stride knee-joint variability would increase over baseline measures.

METHODS

Participants

We conducted an a priori sample-size power analysis ($\beta = .20$, $\alpha = .05$; desired effect size = 0.66) using variability in hip-abductor strength and knee genu valgum data obtained from pilot data and relevant literature.[8,11,14,22] Based on this analysis, a minimum of 10 to 13 participants per group were needed to adequately power the study based on the variables of interest. Specifically, 10 individuals were needed to adequately detect differences in hip-abductor strength,[11,14] and at least 13 people were needed to adequately detect differences in peak knee genu valgum angle,[8,14,22] either compared with the control group or after a strengthening protocol. Each participant signed a consent form approved by the University of Calgary Conjoint Health Research Ethics Board, which also approved the study.

All participants were active recreational athletes running at least 30 minutes per day a minimum of 3 days per week. The PFPS group consisted of 5 men and 10 women (age = 35.2 ± 12.2 years, height = 1.65 ± 0.34 m, mass = 69.1 ± 11.6 kg). The control group consisted of 4 men and 6 women (age = 29.9 ± 8.3 years, height = 1.73 ± 0.41 m, mass = 73.1 ± 15.7 kg). The control volunteers were pain free at the time of testing, had no history of orthopaedic surgery, had not sustained a musculoskeletal injury in the past year, and did not meet any of the exclusion criteria.

The PFPS participants presented to the clinic and were assessed by the same certified athletic trainer for exclusion criteria. Exclusion criteria were consistent with those of Boling et al[12] and included unilateral symptoms present for more than 2 months, self-reported clinical evidence of other knee conditions, history of knee surgery, self-reported history of patellar dislocations or subluxations, or current significant injury affecting other lower extremity joints. The PFPS injury assessment was also based on that of Boling et al[12] and included anterior or retropatellar knee pain, with a severity of at least 3 on a 10-cm visual analogue scale (VAS), during at least 2 of the following activities and within the past week: (1) ascending and descending stairs, (2) hopping and running, (3) squatting or kneeling, and (4) prolonged sitting. The PFPS individuals also had to exhibit insidious onset of symptoms unrelated to trauma, pain with compression of the patella, and pain on palpation of patellar facets.

Procedures

Retroreflective markers were used to measure 2-dimensional (2-D) knee frontal-plane biomechanical motion. The markers were secured to hook-and-loop straps that were tightly wrapped around the thigh and shank to minimize movement artifact and along a line between the ischial tuberosity and the middle of the popliteal fossa and between the middle of the popliteal fossa and the Achilles tendon to represent the long axes of the femur and shank, respectively (Figure 1). After collecting a 1-second standing calibration trial, volunteers performed dynamic trials in which they ran on a treadmill (model TR 4500, Star Trac, Irvine, CA) for 20 seconds (approximately 30 footfalls) at a speed of 2.55 m/s. We chose this speed because previous authors[2,11,15–17,23] have reported using similar overground and treadmill speeds. A 2-minute warm-up period provided time for accommodation to the treadmill and speed and to achieve a steady state of comfortable running before the 20 seconds of data were collected. All participants were familiar with treadmill running. The middle 10 consecutive footfalls were selected and analyzed from the symptomatic limb for the PFPS group and from the dominant limb for the control group.

Strength of the hip-abductor muscles was measured with the side-lying volunteer exerting a maximal isometric contraction for 5 seconds in 30° of hip abduction and 5° of hip extension.[24] A force dynamometer (model 01163 manual muscle tester; Lafayette Instrument, Lafayette, IN) was used to measure force output. The dynamometer was placed immediately proximal to the lateral malleolus, and participants applied a maximal isometric force against a nonelastic strap for the "make" test method of strength testing.[3] An initial familiarization trial was performed before the average of 3 trials was recorded; all trials were within a coefficient of variation of 10%. Body weight was measured using a standard digital scale, and force values were normalized to a percentage of body weight. Pain was measured using a 10-cm VAS. All measurements were taken at baseline and at 3 weeks for both the control and PFPS volunteers.

Rehabilitation Protocol

All PFPS patients were given a 3-week hip-abductor muscle-strengthening protocol consisting of 2 exercises (Figure 2). These exercises were to be performed using a 5-ft (1.52-m) piece of Resist-A-Band (Donovan Industries, Inc, Tampa, FL) for 3 sets of 10 repetitions of each exercise, for each leg, daily over the course of the 3 weeks. The patients were instructed to move the involved limb outward for 2 seconds and inward for 2 seconds and to exercise both limbs using this common therapeutic protocol because the contralateral limb also benefits from the exercise.[25] All PFPS patients returned after 7 to 10 days for a follow-up to log exercise program adherence and to have their exercise technique checked. If the sets and repetitions were being performed too easily, a piece of band offering greater resistance was provided. The PFPS participants were asked to refrain from any therapeutic treatments other than the 2 exercises, and all volunteers were encouraged to continue with their regular running schedule at their discretion. It is important to note that all PFPS patients were running on a regular basis at the time of data collection.

Figure 1. Retroreflective marker placement used for kinematic data collection.

Data Collection and Analysis

Pain was measured using a VAS in which 0 indicated *no pain* and 10 indicated *the most pain imaginable*. The PFPS participants were asked to place a dash along the 10-cm line to indicate the average amount of pain experienced during the past week while running.

Kinematic data were collected using a 60-Hz camera (model GL2; Canon Canada Inc, Mississauga, ON, Canada). For all data collection, the camera was placed 1.2 m above the ground and 1.7 m away from the middle of the treadmill. A digital inclinometer (model 360; SmartTool Technology, Inc, Oklahoma City, OK) ensured that the camera lens was oriented parallel to the frontal plane of the laboratory and the participant and perpendicular to the treadmill platform. Raw marker trajectory data were filtered with a second-order, low-pass Butterworth filter at 10 Hz. Vicon Motus software (version 9.2; C-Motion, Inc, Rockville, MD) was used to digitize the markers and filter and to calculate 2-D angles. The kinematic data were analyzed for the stance phase and normalized to 101 data points. The stance phase was determined using kinematic marker data, with initial contact identified using a velocity-based algorithm applied to the posterior calcaneus, and

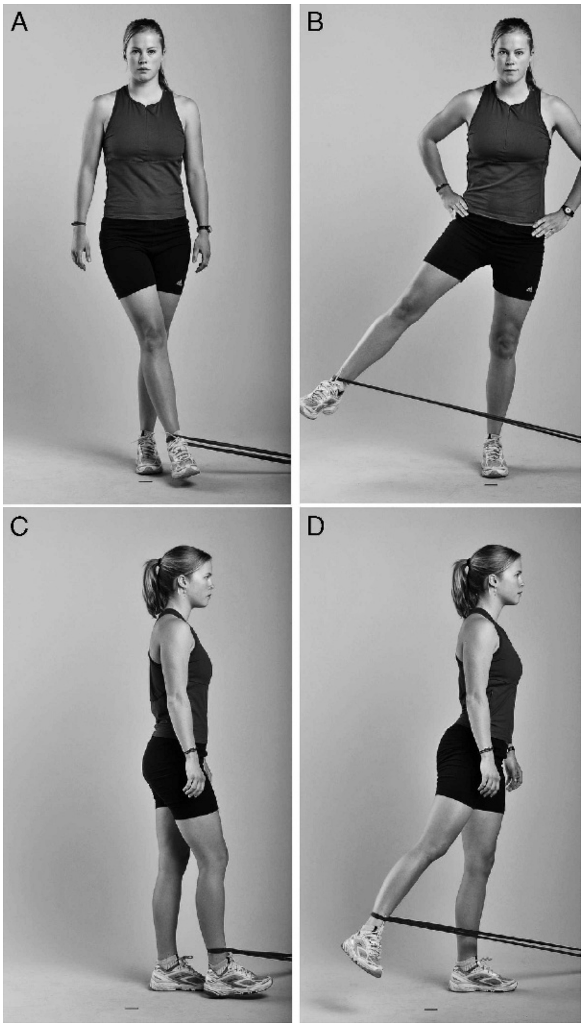

Figure 2. The 2 hip-abductor muscle-strengthening exercises performed by the patellofemoral pain syndrome group. A, B, In the first exercise, the patient moves the involved leg outward, keeping the knee straight. C, D, In the second exercise, the patient moves the involved leg back to a 45° angle, keeping the knee straight and the pelvis stable.

toe-off was defined with visual inspection.[26] Maximal isometric hip-abductor strength measures were normalized to each volunteer's body weight.

The specific kinematic variables of interest from 10 consecutive footfalls used for statistical analysis were peak knee genu valgum angle and stride-to-stride knee-joint variability. Knee genu valgum angle was calculated as the angle subtended by the line connecting the 2 thigh-segment markers and the line connecting the 2 shank markers. The *peak angle* was defined as the largest valgus angle measured after footstrike and generally occurred during the midstance portion of stance. Previous authors have shown this 2-D approach to be valid (errors $< 1.7°$) and moderately reliable for side-step ($r = 0.58$) and side jump ($r = 0.64$) maneuvers, compared with 3-dimensional (3-D) methods,[27] and data from our laboratory show this 2-D measure to be valid (errors $< 1.8°$) and highly reliable compared with 3-D treadmill running data ($r = 0.86$).

Measurement of knee frontal-plane stride-to-stride variability was based on earlier studies,[28,29] using a Pearson product moment correlation coefficient on a stride-to-stride basis over the 10 consecutive footfalls. Specifically, the temporal pattern of knee genu valgum for the first footfall was compared on a point-by-point basis with the subsequent footfall (ie, footfall 1 was compared with footfall 2) for all 101 points of data and across the 10 consecutive footfalls. Thus, using this method, a total of 9 stride-to-stride comparisons occurred for each volunteer and were then averaged for analysis. Values of $r = 1.0$ indicate perfectly matched kinematic patterns and no stride-to-stride variability; values closer to $r = 0.0$ indicate greater temporal asynchrony and increased variability.

Statistical Design

We used a 2 × 2 repeated-measures design and analysis of variance to identify changes in the dependent variables of interest: (1) peak isometric hip-abduction force, (2) peak knee genu valgum angle, and (3) stride-to-stride knee-joint variability. The independent variables were group (PFPS, control) and time (pretest, posttest). Statistical analysis was performed with SPSS (version 17.0; SPSS Inc, Chicago, IL). Tukey post hoc tests were performed to identify significant differences, if any, when appropriate. Alpha was set at .05 for all analyses.

RESULTS

No differences were measured between groups for age ($P = .44$), height ($P = .46$), or mass ($P = 0.32$). A summary of the variables of interest at the pretest and posttest is presented in the Table. At baseline, the PFPS group's hip-abductor muscle strength was 28.71% less than that of controls ($P = .01$; Figure 3). No differences ($P = .67$) in peak genu valgum angle were noted between groups. Stride-to-stride knee-joint variability for the PFPS group was less than for the control group ($P = .01$; Figure 3).

The PFPS patients were compliant with the rehabilitation protocol and completed the exercises, on average, 6.2 days per week over the 3 weeks. At the posttest, their isometric muscle strength had increased 32.69% over baseline values ($P = .04$). However, compared with the control group, no difference in muscle strength ($P = .33$) was evident. The PFPS patients displayed a 43.10% reduction in VAS score ($P = .01$) after the rehabilitation protocol. No differences in peak genu valgum angle were measured at the posttest, compared with baseline values ($P = .55$) or the control group ($P = .65$). Stride-to-stride knee-joint variability curves for the PFPS group increased compared with baseline ($P = .01$; Figure 3), but no differences from the control group were measured ($P = .36$).

No differences in maximal isometric strength ($P = .87$), peak knee genu valgum angle ($P = .51$), or stride-to-stride knee-joint variability ($P = .84$) were found between testing sessions for the control group.

DISCUSSION

Our purpose was to investigate the relationship between hip-abductor muscle strength and frontal-plane knee mechanics. We used a 3-week hip-abductor muscle-strengthening protocol to measure potential changes in strength, biomechanics, and pain for patients experiencing PFPS. Previous authors[1–7] have hypothesized that a primary contributing factor to PFPS is weakness of the

Table. Variables of Interest for the Control and Patellofemoral Pain Syndrome Groups

	Control Group				Patellofemoral Pain Syndrome Group			
	Pretraining		Posttraining		Pretraining		Posttraining	
Variable	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval	Mean ± SD	95% Confidence Interval
Abductor muscle strength, % of body weight	18.11 ± 3.89	15.15, 21.07	18.49 ± 2.99	15.76, 21.22	12.91 ± 4.12[a]	9.89, 15.93	17.13 ± 3.08[b]	14.37, 19.89
Genu valgum, °	2.67 ± 1.19	0.40, 4.94	3.1 ± 1.02	0.88, 5.32	3.71 ± 1.38	1.39, 6.03	3.05 ± 1.34	0.74, 5.36
Consecutive footfall variability, *r*	0.81 ± 0.17	0.75, 0.87	0.83 ± 0.15	0.78, 0.88	0.39 ± 0.11[a]	0.35, 0.43	0.79 ± 0.13[b]	0.75, 0.83
Visual analogue scale pain score, cm					5.80 ± 2.10	5.10, 6.50	3.30 ± 1.90[b]	2.67, 3.93

[a] Value reduced compared with control group ($P < .05$).

[b] Value increased compared with prerehabilitation values ($P < .05$).

hip musculature, including the abductors. However, few researchers have directly investigated this possibility.

In support of the first hypothesis, the PFPS patients exhibited 28.71% reduced maximal isometric hip-abductor muscle strength at baseline, compared with the control group. These results are similar to those of several other studies[1–9,12,15–18] involving PFPS patients and indicate that weakness of the hip abductors may play a key role in the development of PFPS. We also hypothesized that over the 3-week rehabilitation protocol, hip-abductor muscle strength would increase. In support of this hypothesis, PFPS patients exhibited an average 32.69% improvement in strength. Authors of earlier strengthening studies[6,14,30–32] reported 13% to 51% increases in hip-abductor strength after rehabilitation protocols that ranged from 6 to 14 weeks in length. Thus, the increase in abductor strength reported in the current study is comparable with previous findings.

We hypothesized that over the 3-week rehabilitation protocol, the level of pain experienced by the PFPS patients would decrease. In support of this hypothesis, the level of pain for 14 of the 15 patients decreased 40% over the course of the study. These results are in agreement with those of previous studies[1–9,12,15–18] whose authors also suggested that hip-abductor muscle weakness is a contributing factor in the development and treatment of PFPS and should be targeted in its treatment. An asset of our investigation is that the rehabilitation protocol consisted of exercises intended solely to increase the strength of the hip abductors. Thus, these results provide further evidence that hip-abductor muscle-strengthening exercises should be considered for preventing musculoskeletal injury and treating PFPS.

Tyler et al[32] examined the benefits of a hip-strengthening program on 35 patients diagnosed with PFPS. All volunteers participated in a 6-week intervention that consisted primarily of hip-strengthening exercises. Hip strength improved in 66% of the PFPS patients, which is consistent with our results. Based on a minimum decrease of 1.5 cm in the VAS scores, 21 patients (26 knees) had a successful outcome and 14 patients (17 knees) had an unsuccessful outcome. Interestingly, and in contrast to our results, these authors[32] reported that, based on their statistical analysis, improvement in hip-abduction strength was unrelated to PFPS pain and treatment outcome. Thus, other muscles in addition to the hip abductors may be important in treating PFPS.[31,32] Future studies involving a more comprehensive hip muscle-strengthening protocol are necessary to answer this question.

In such a short period of time, improvements in muscle strength are largely attributable to changes in neuromuscular activation of muscles and not to changes in muscle-fiber composition or hypertrophy.[33,34] Previous authors[33,34] have shown that after 10 or 14 days of daily strengthening, an increased number of motor units are recruited, concomitant with greater maximal voluntary contraction. These results support the notion that neural adaptation, not hip-abductor muscle-fiber hypertrophy, was primarily responsible for the increased strength exhibited by the PFPS participants after only 3 weeks of muscle strengthening.

Similar to earlier researchers,[2,3,8,9,11] we hypothesized that reduced hip-abductor muscle strength would result in a greater peak knee genu valgum angle when running and, thus, would contribute to the development of PFPS, because the hip abductors would not be able to adequately control hip adduction via eccentric contraction. However, no differences in peak knee genu valgum angle were measured between groups or across time.

To date, few investigators[2,6,7,14] have evaluated the relationship between hip-abductor muscle strength and knee kinematics. Our findings are similar to those of Bolgla et al,[7] who reported that 18 patients with PFPS had hip weakness but did not demonstrate altered hip or knee kinematics while descending stairs, compared with a control group. Yet our results contrast with those of Mascal et al.[6] In their case study, the participant who underwent a biomechanical assessment after a 14-week strengthening protocol demonstrated improved hip strength and reduced hip adduction (a component of knee genu valgum) during a step-down maneuver, compared with baseline values. Our findings also contrast with those of Dierks et al,[2] who reported an inverse relationship between decreased hip-abductor muscle strength and increased hip adduction at the beginning and end of a prolonged run for PFPS patients.

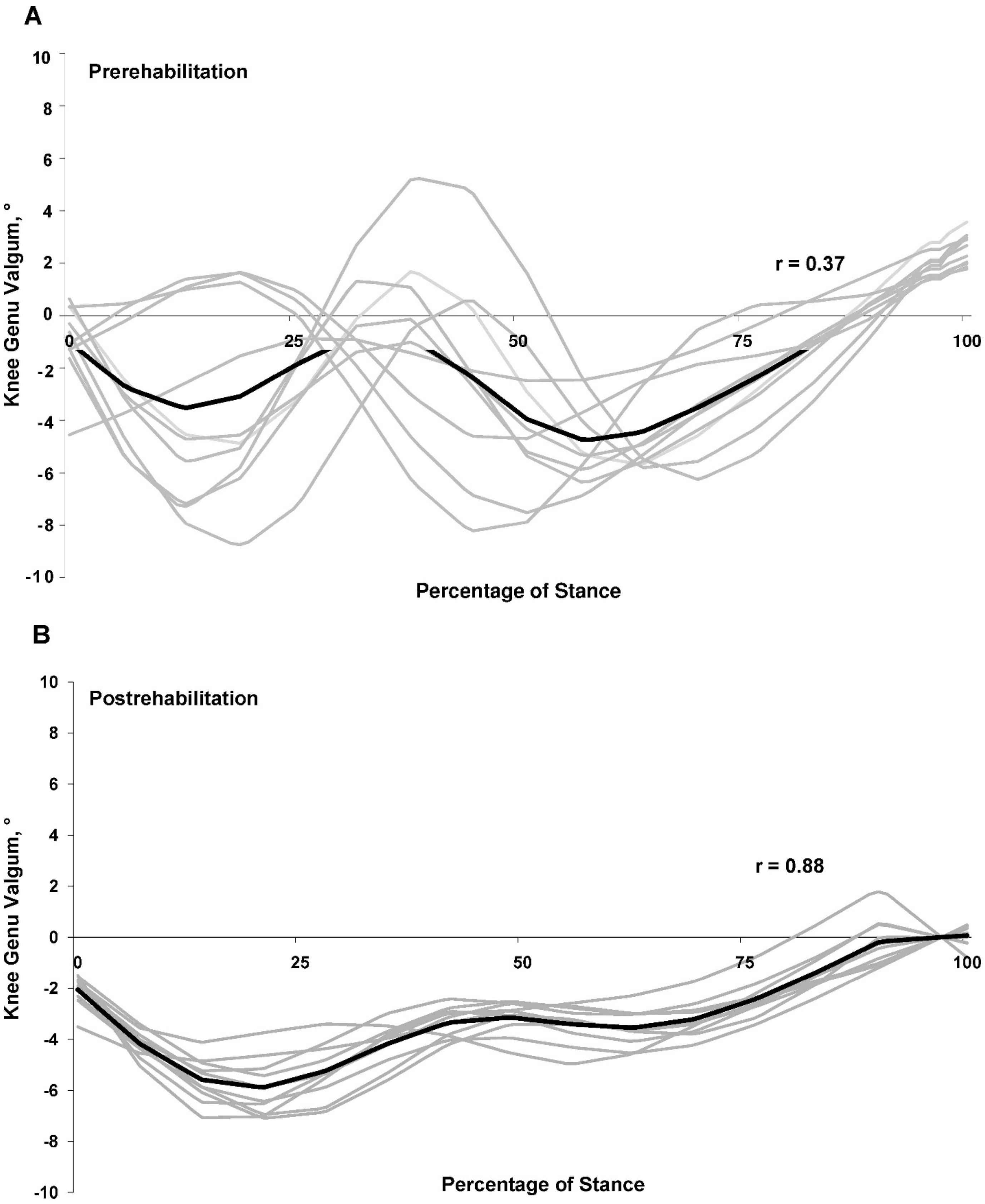

Figure 3. Representative example of reduced stride-to-stride knee-joint variability of movement patterns for a patient with patellofemoral pain syndrome before (A) and after (B) the 3-week rehabilitation protocol. The thin lines represent the 10 individual footfalls over the stance phase of running gait, and the thick, dark line is the ensemble average. Note how the overall patterns for the ensemble averages are similar, thus contributing to no measured differences in peak knee genu valgum angle.

The single-subject design and stair-descent method used by Mascal et al[6] make comparison of their results with ours difficult. We measured 2-D knee genu valgum angle, which is a combination of thigh adduction and shank abduction. Thus, comparison with studies of 3-D angles is challenging. In addition, Dierks et al[2] used a fatigue protocol to determine the association between hip-abductor muscle strength and mechanics, whereas we used a muscle-strengthening protocol. Future studies are therefore necessary to help resolve these conflicting data.

Based on the PFPS data reported by Hamill et al[15] and others, we hypothesized that over the 3-week rehabilitation protocol, stride-to-stride knee-joint variability would increase as pain-free status and more typical movement patterns were restored. However, at baseline we measured a marked increase in variability for the PFPS group compared with the control group. Moreover, we measured reductions in stride-to-stride knee-joint variability after the strengthening protocol.

Inspection of Figure 3 reveals that the PFPS group adopted a more consistent stride-to-stride kinematic pattern after the rehabilitation protocol. From a clinical perspective, it is reasonable to assume that restoring a more consistent and predictable movement pattern, concomitant with increased muscle strength and reduced pain, would be expected after such an exercise regime. By providing the knee joint with more consistent (ie, less variable) movement patterns on a stride-to-stride basis, it is possible that a more optimal environment is established, allowing for tissue healing and pain resolution. Additional clinical studies are necessary to answer these questions.

It is important to compare the methods used by Hamill et al[15] with ours. They investigated intersegment coupling variability, whereas we assessed variability within a single joint. They theorized that increased movement variability from 2 lower extremity segments represents a healthy population and is necessary to help prevent injury. This theory can still be applied to our results because increased intersegmental coupling between the shank and thigh may have produced our observed reduction in single-joint motion. More research will address this question.

At the posttest, compared with their baseline values, all 15 PFPS patients increased muscle strength and demonstrated at least a 4-cm (33%) VAS drop in pain; in fact, 4 patients were pain free at 3 weeks. Reduced stride-to-stride knee-joint variability was seen in 13 of 15 patients. At the end of the study, we provided all patients with a more comprehensive rehabilitation program, including recommendations for stretching and strengthening exercises that focused on the low back, hip, knee, and ankle musculature. Anecdotally, we followed up after an additional 3 weeks of rehabilitation and learned that all patients were pain free and had returned to their preinjury running regimes.

Several limitations of this study are apparent. First, the biomechanical measures used a 2-D camera system, and knee motion occurs in 3 dimensions. Thus, using a 3-D motion system would provide more comprehensive data regarding the changes in pelvic and lower limb mechanics that occur as a result of muscle strengthening. However, previous authors[27] have shown this 2-D approach to be valid and moderately reliable for side-step and side-jump maneuvers, and data from our laboratory show this 2-D measure to be valid and highly reliable compared with 3-D measures during treadmill running. The control group exhibited no change in peak knee genu valgum angle over the 3 weeks, results similar to those of earlier investigations.[7,14,22] For example, Snyder et al[14] reported 0.4° and 1.4° changes in knee-abduction and hip-adduction excursion values, respectively, after a 6-week strengthening protocol. Moreover, the 0.66° and 0.43° differences we measured for the PFPS and control groups, respectively, are similar to those reported by Ferber et al,[22] who investigated 3-D kinematics for test-retest reliability in healthy runners. These authors reported mean differences of 0.64° in peak knee adduction and 1.64° in peak hip adduction over 2 days. Thus, even though we used a 2-D analysis, our results are comparable with those of previous 3-D studies.

Second, because we had a standard camera placement and did not position it at a specific height from the ground relative to the participant's height or knee location (or both), perspective error was a possibility. However, our volunteers were all of the same approximate height, and given that our day-to-day values were similar to those of an earlier investigation,[22] we are confident that this concern was minimized. Next, the investigator was aware of the participant's group allocation (PFPS or control), and only the PFPS group performed the exercises, perhaps leading to bias during testing and analysis. However, using a standardized protocol for data collection and analysis for each measure reduced this bias. Also, future research involving a PFPS group that did not perform the exercises would be helpful to better understand how the exercises and subsequent increases in hip-abductor muscle strength influenced movement mechanics. In addition, the groups were not matched for number of participants or sex. However, no differences in age, height, or mass were measured between the groups, and all study participants were recreational runners, indicating that the groups were similar. The volunteers performed a simple running task that lasted a relatively brief period of time, and all ran at the same speed. This procedure may not have been strenuous enough to reveal changes in lower extremity mechanics, so future studies involving running to fatigue, similar to the protocol of Dierks et al,[2] may be beneficial. Furthermore, the running speed chosen was a comfortable pace for all participants and was similar to their own regular running paces on a treadmill and compared with previous studies. Next, the number of patients and length of the rehabilitation protocol were limited. A study with a larger control population matched for age, sex, mass, and mileage or a longer and more comprehensive rehabilitation protocol (or both) may reveal different results, especially with respect to changes in knee genu valgum mechanics. Lastly, we measured isometric muscle-force output, which is not a direct measure of hip-abductor muscle strength and does not necessarily reflect the dynamic concentric and eccentric muscle contractions involved in running.

CONCLUSIONS

A 3-week hip-abductor muscle-strengthening protocol was effective in increasing muscle strength and decreasing the level of pain and stride-to-stride knee-joint variability in individuals with PFPS. These results also indicate that stride-to-stride knee-joint variability may be a better indicator of injury rehabilitation progression than are peak angles. Finally, incorporating hip-abductor muscle-strengthening into PFPS rehabilitation protocols is important.

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