Static and Dynamic Quadriceps Stretching Exercises in Patients With Patellofemoral Pain: A Randomized Controlled Trial

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Background: Limited data are available on the effect of stretching exercise in patients with patellofemoral pain (PFP) who have inflexible quadriceps, which is one of the various causes of PFP syndrome. This study compares quadriceps flexibility, strength, muscle activation time, and patient-reported outcomes after static and dynamic quadriceps stretching exercises in patients with PFP who had inflexible quadriceps.

Hypothesis: Quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes would improve with dynamic quadriceps stretching as compared with static quadriceps stretching exercises.

Study Design: Randomized controlled trial.

Level of Evidence: Level 2.

Methods: Of the 44 patients included in the study, 20 performed static stretching and 24 performed dynamic stretching. Quadriceps flexibility was assessed by measuring the knee flexion angle during knee flexion in the prone position (the Ely test). Muscle strength and muscle activation time were measured using an isokinetic device. The patient-reported outcomes were evaluated using the visual analogue scale for pain and anterior knee pain scale.

Results: No significant differences in quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes in the involved knees were found between the 2 groups (P values > 0.05).

Conclusion: Quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes in patients with PFP who had inflexible quadriceps showed no significant differences between the static and dynamic quadriceps stretching exercise groups.

Clinical Relevance: Both static and dynamic stretching exercises may be effective for improving pain and function in patients with PFP who have inflexible quadriceps.

Keywords: dynamic stretching; static stretching; quadriceps flexibility; muscle strength; muscle activation time

Patellofemoral pain syndrome (PFPS) is known as "runner's knee"[13] and is defined as anterior knee pain involving the patella, occurring with knee flexion and extension motions.[13,63] Several studies have reported various factors that lead to PFPS, such as quadriceps,[7,53,65] abnormal hip biomechanics,[62] inflexibility[50,64] and malalignment[17] of the lower limbs, and altered neuromuscular control.[1] Among these, quadriceps tightness can lead to patellar alta and patellar tilt,[64,65,67] which result in quadriceps weakness and muscle imbalance caused by pain due to increased compression force of the patellofemoral joint and abnormal movements of the patella during knee motion[65,67]; thus, the progression of PFPS may be accelerated.[53,67] Therefore, many authors have focused on the restoration and measurement of inflexible quadriceps in patients with patellofemoral pain (PFP).[25,44,53,65]

Recent studies[40,51,56,65] have reported that stretching exercises are as effective as muscle strengthening exercises for improving

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pain and function of muscles, including the quadriceps and hip muscles, in patients with PFP; thus, stretching exercises were recommended for patients with PFP.[47,64,65] However, results in terms of pain and muscle performance were reported to vary among different types of stretching exercises such as static, dynamic, or precontraction stretching.[46,68,69] A recent study[32] reported that dynamic hamstring stretching exercises are more effective than static hamstring stretching for improving muscle performance such as muscle activation time and pain in patients with PFP who have inflexible hamstrings. Furthermore, only one previous study[44] measured the change in quadriceps flexibility in patients with PFP after static and precontraction stretching exercises. To date, therefore, no studies have compared the flexibility and strength of the quadriceps muscles, neuromuscular control, and patient-reported outcomes such as those assessed using the visual analogue scale (VAS) for pain and anterior knee pain scale (AKPS) between static and dynamic quadriceps stretching exercises in patients with PFP who have inflexible quadriceps.

Quadriceps flexibility and strength, neuromuscular control, and patient-reported outcomes between static and dynamic quadriceps stretching exercises in patients with PFP who had inflexible quadriceps were compared. The hypothesis is that the dynamic stretching group would have better improvement in all the parameters than the static stretching group.

METHODS

Enrollment of Patients

This prospective randomized study enrolled 116 patients with anterior knee pain who were recruited consecutively between January 2018 and August 2019, except patients with a history of surgery. This study was approved by the institutional review board (2017AN0830); all participants provided informed consent; and the rights of the subjects were protected. All the patients were confirmed to have normal ranges of the parameters measured in the various radiological imaging assessments,[41] including the Insall-Salvati ratio (normal range, 0.8-1.2; with ratios >1.2 indicating patella alta and <0.8 indicating patella baja),[51] congruence angle, and sulcus angle. Physical examinations were performed by 2 orthopaedic knee surgeons to find any definite patellofemoral pathologies. Any disagreements were resolved by discussion to reach a consensus. The inclusion criterion was inflexible quadriceps with a knee flexion angle <125° during the Ely test,[67] defined as the knee flexion angle at which the quadriceps resist knee flexion without hip flexion in the prone position. The exclusion criteria were as follows (Figure 1): chondromalacia patella (known as sick cartilage, which is pain caused by erosion, fissuring, and subsequent tearing of the hyaline cartilage of the articular surfaces of the bone),[21] patellar dislocation, plica syndrome, osteoarthritis, and tight hamstrings with normal quadriceps flexibility, with the latter being an exclusion criterion because it does not fall within the purposes of this study. Fifty-two patients were randomized. Allocation to the 2 groups was achieved with the use of a random-number table. Treatment using a 6-month intervention protocol was performed by 1 of the physical therapists who was blinded to the details of the assessments and data analyses. The assessments and data analyses were performed by an independent physical therapist blinded to the rehabilitation protocol. Of the 116 patients enrolled, 72 were excluded and 44 were analyzed in this study, 20 in the static stretching group and 24 in the dynamic stretching group.

Patient-Reported Outcomes

The patient-reported outcomes were confirmed using the VAS score for pain and the AKPS score.[12] In the VAS, with scores ranging from 0 to 10 points, 0 points means no pain and 10 points means the worst pain. The AKPS is also known as the Kujala scale and contains 13 items, for a total score ranging from 0 to 100[30]; higher scores indicate lower disability. Similar to a previous report,[12] a 1.5- to 2-point difference in VAS score and an 8- to 10-point difference in AKPS score were defined as minimal clinically important differences (MCIDs).

Quadriceps Flexibility Test (the Ely Test)

In a systematic review[64] and several previous studies,[41,47,67] quadriceps flexibility in patients with PFP was measured using the knee flexion angle in the prone position. This test is called the Ely test. According to a previous study by Peeler and Anderson,[48] 0.83 is a high intraclass correlation coefficient (ICC) in the Ely test.

Isokinetic Muscle Performance Test

Muscle strength and neuromuscular control were evaluated using an isokinetic device (Biodex Multi-Joint System 4, Biodex Medical Systems, Inc). The participants were seated in an upright position in an isokinetic chair, with hips and knees flexed at 90° and with 2 straps fixed across their chest. The lateral femoral condyle of the knee joint was aligned with the rotational axis of an isokinetic dynamometer. The participants were allowed 5 submaximal flexion repetitions and extension motions at 180 deg/s for warm-up before testing, followed by 5 maximal contractions at 180 deg/s after 1-minute rest periods. Muscle strength was evaluated by peak torque, normalized to body weight (peak torque/body weight, $N{\cdot}m{\cdot}kg^{-1} \times 100$).[34,35] Neuromuscular control is defined as the efferent motor response to afferent sensory stimulation[38,55]; thus, in the present study, it was measured as acceleration time (milliseconds),[31,33,35] defined as the muscle activation time required for attaining a preset angular velocity (180 deg/s in our study) during muscle contraction. Therefore, a slow acceleration time was associated with delayed muscle activation responses and muscular recruitment ability. Gravity and limb weight were corrected at 30° of knee extension by the Biodex Advantage software.

Quadriceps Stretching Interventions

1. Static stretching: In the prone and standing positions, the involved leg maintained 90° of knee flexion, followed by

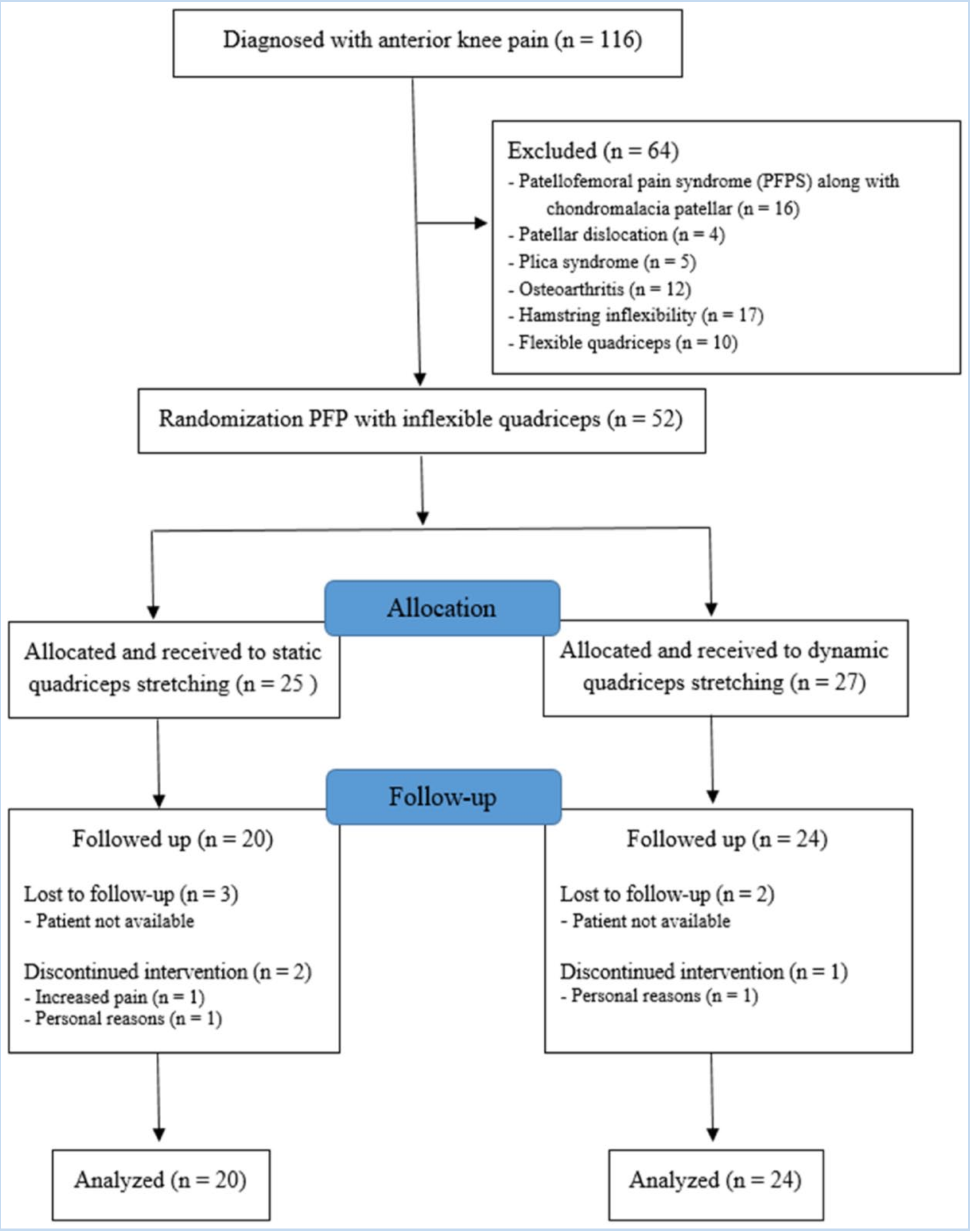

Figure 1. Study flow diagram.

grasping of the foot using the ipsilateral hand, with the heel of the involved leg slowly pressed on the buttock.[49,58] For the static stretching, 3 sets were repeated, with a holding time of 15 seconds.

2. Dynamic stretching: In the prone position, the knee joint of the involved leg was flexed maximally, followed by hip extension and hyperextension of the hip joint.[26] In the standing position, the involved leg maintained 90° of knee flexion, followed by continuing with the hip extension motion actively.[2,49] For the dynamic stretching, 3 sets were performed, with 15 repetitions with a holding time of 1 second.

The holding time and number of sets of the static and dynamic stretching exercises were similar, at 15 seconds and 3 sets, respectively. After the 6-month follow-up, the final isokinetic test was performed in our institution after a 4-minute recovery period for each type of stretching.

Conservative Rehabilitation Protocol

All the participants were treated and educated in our clinic with the same rehabilitation protocol except for stretching exercises, with a total of 6 visits once a month for 6 months.[14,19] In addition, the home exercise program recommended 3 sets twice a day for each stretching with strengthening exercise, and

Table 1. Demographic data of the patients in the static and dynamic quadriceps stretching groups

	Static Stretching Group (n = 20)	Dynamic Stretching Group (n = 24)	*P*
Sex (male/female), n	7/13	8/16	
Age,[a] y	26.5 ± 6.8	28.1 ± 4.2	0.77
Height,[a] cm	173.4 ± 4.0	171.8 ± 4.3	0.48
Weight,[a] kg	68.9 ± 8.2	71.3 ± 5.4	0.82
Body mass index,[a] kg/m^2	25.1 ± 3.2	26.7 ± 2.6	0.51
Duration of symptoms,[a] mo	3.8 ± 2.1	4.1 ± 1.6	0.32
Injured side (right/left), n	17/3	20/4	
Sports and activity (low:high), n	4:16	7:17	0.66
Insall-Salvati ratio	1.16	1.13	0.90

[a]Values are expressed as mean ± standard deviation.

compliance with the protocol was checked continuously during clinic visits. The goals of the rehabilitation program were to improve strength, proprioception, and neuromuscular control and to normalize biomechanics. In the open kinetic chain exercises, multidirectional straight leg raises, including flexion, extension, abduction, and adduction, were performed to improve quadriceps, hamstring, and hip muscle strengths. In addition, short arc knee extensions with knee adduction in the pain-free range were performed. However, if the patients had no pain during the exercise, full-range knee flexion and extension were permitted. In the closed kinetic chain exercises, wall squat exercises, along with knee adduction and single-leg squats, were performed in a range of <50°.[15] Balance exercises, with the eyes open and closed, were performed to improve proprioception and neuromuscular control. A core and hip muscle strengthening program was implemented, with all the exercises.

Statistical Analyses

A priori power analysis was performed to determine the sample size at an alpha level of 0.05 and a power of 0.8 to compare the static and dynamic quadriceps stretching exercises in patients with PFP who had inflexible quadriceps. On the basis of previous reports,[20,67] in the quadriceps muscle strengths in patients with PFP, a difference of at least >10% was regarded as clinically significant. A pilot study was performed on 5 knees from each group to estimate the sample size (Cohen *d* effect size: 0.993); thus, 34 patients were required to detect a between-group difference in quadriceps strength of >10%. In the present study, 20 patients who performed static stretching exercises and 24 who performed dynamic stretching exercises were evaluated. In the present study, the power was 0.802 for detecting a significant difference between the strengths in the 2 groups after each stretching exercise.

The ICCs were calculated for 2 trials of flexibility and strength of the quadriceps muscles to quantify the test-retest reliability. ICCs were also calculated for the 2 trials of muscle activation time. A previous study by Shrout and Fleiss[60] suggested that ICC values >0.75 and <0.4 indicate good and poor accuracies, respectively. The Student *t* test was used to compare the flexibility and strength of the quadriceps muscles, muscle activation time, and patient-reported outcomes between static and dynamic quadriceps stretching in the PFP patients with inflexible quadriceps. The paired *t* test was used to compare all variables in each group before and after quadriceps stretching. The statistical analysis was performed using SPSS (SPSS 21.0, IBM Corp). *P* values <0.05 were considered statistically significant.

RESULTS

The patients' baseline demographic characteristics showed no significant differences between the 2 groups (Table 1). In all the participants, the test-retest reliabilities of the quadriceps flexibility and strength were good, with ICCs of 0.75 and 0.80, respectively. In addition, the test-retest reliability of muscle activation time was acceptable for the quadriceps muscle (ICCs = 0.82).

No significant differences in quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes in the involved knees were found between the 2 groups after each quadriceps stretching exercise (*P* values > 0.05; Tables 2 and 3).

In the static stretching group, the quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes in the involved knees significantly improved after the stretching

Table 2. Quadriceps flexibility and strength between the patients in the static and dynamic quadriceps stretching groups[a]

	Preintervention			Postintervention		
	Static Stretching Group (n = 20)	Dynamic Stretching Group (n = 24)	*P*	Static Stretching Group (n = 20)	Dynamic Stretching Group (n = 24)	*P*
Quadriceps flexibility[b]	109 ± 9.7	104 ± 9.2	0.13	128 ± 2.6	126 ± 7.9	0.35
MD (95% CI)	5.0 (−1.4 to 10.1)			1.0 (−1.9 to 5.5)		
Quadriceps strength[c]	94 ± 40	93 ± 37.6	0.91	165 ± 49.1	183 ± 46.5	0.21
MD (95% CI)	1.0 (−22.3 to 24.9)			−18 (−47.4 to 10.9)		

MD, mean difference.
[a]Values are expressed as mean ± standard deviation.
[b]The measurement unit for quadriceps flexibility was degrees.
[c]The measurement unit for quadriceps strength was $N{\cdot}m{\cdot}kg^{-1} \times 100$.

Table 3. Muscle activation time and functional outcomes between the patients in the static and dynamic quadriceps stretching groups[a]

	Preintervention			Postintervention		
	Static Stretching Group (n = 20)	Dynamic Stretching Group (n = 24)	*P*	Static Stretching Group (n = 20)	Dynamic Stretching Group (n = 24)	*P*
Quadriceps muscle activation time	65 ± 17	67 ± 16.7	0.70	52 ± 14.4	50 ± 16.4	0.81
MD (95% CI)	−2.0 (−12.3 to 8.3)			2.0 (−8.3 to 10.6)		
VAS	5 ± 0.9	5 ± 1.1	0.67	3 ± 1.0	2 ± 1.0	0.12
MD (95% CI)	0 (−0.5 to 0.8)			1.0 (−1.1 to 1.1)		
AKPS	48 ± 6.1	51 ± 5.8	0.12	70 ± 6.8	74 ± 8.4	0.07
MD (95% CI)	−3.0 (−6.5 to 0.8)			−4.0 (−11.7 to −3.0)		

AKPS, anterior knee pain scale; MD, mean difference; VAS, visual analogue scale.
[a]Values are expressed as mean ± standard deviation. The measurement unit for neuromuscular control was milliseconds.

exercise as compared with before the exercise (quadriceps flexibility: 109 ± 9.7 vs 128 ± 2.6, *P* = 0.00; strength: 94 ± 40 vs 165 ± 49.1, *P* = 0.00; muscle activation time: 65 ± 17 vs 52 ± 14.4, *P* = 0.007; VAS score: 5 ± 0.9 vs 3 ± 1.0, *P* = 0.00; and AKPS score: 48 ± 6.1 vs 70 ± 6.8, *P* = 0.00; Figure 2A).

In the dynamic stretching group, quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes significantly improved in the involved knees after the stretching exercise (quadriceps flexibility: 104 ± 9.2 vs 126 ± 7.9, *P* = 0.00; strength: 93 ± 37.6 vs 183 ± 46.5, *P* = 0.00; muscle activation time: 67 ± 16.7 vs 50 ± 16.4, *P* = 0.00; VAS score: 5 ± 1.1 vs 2 ± 1.0, *P* = 0.00; and AKPS score: 51 ± 5.8 vs 74 ± 8.4, *P* = 0.00; Figure 2B).

DISCUSSION

The primary finding of the present study was that in all the parameters, including quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes, no significant differences were found between the static and dynamic

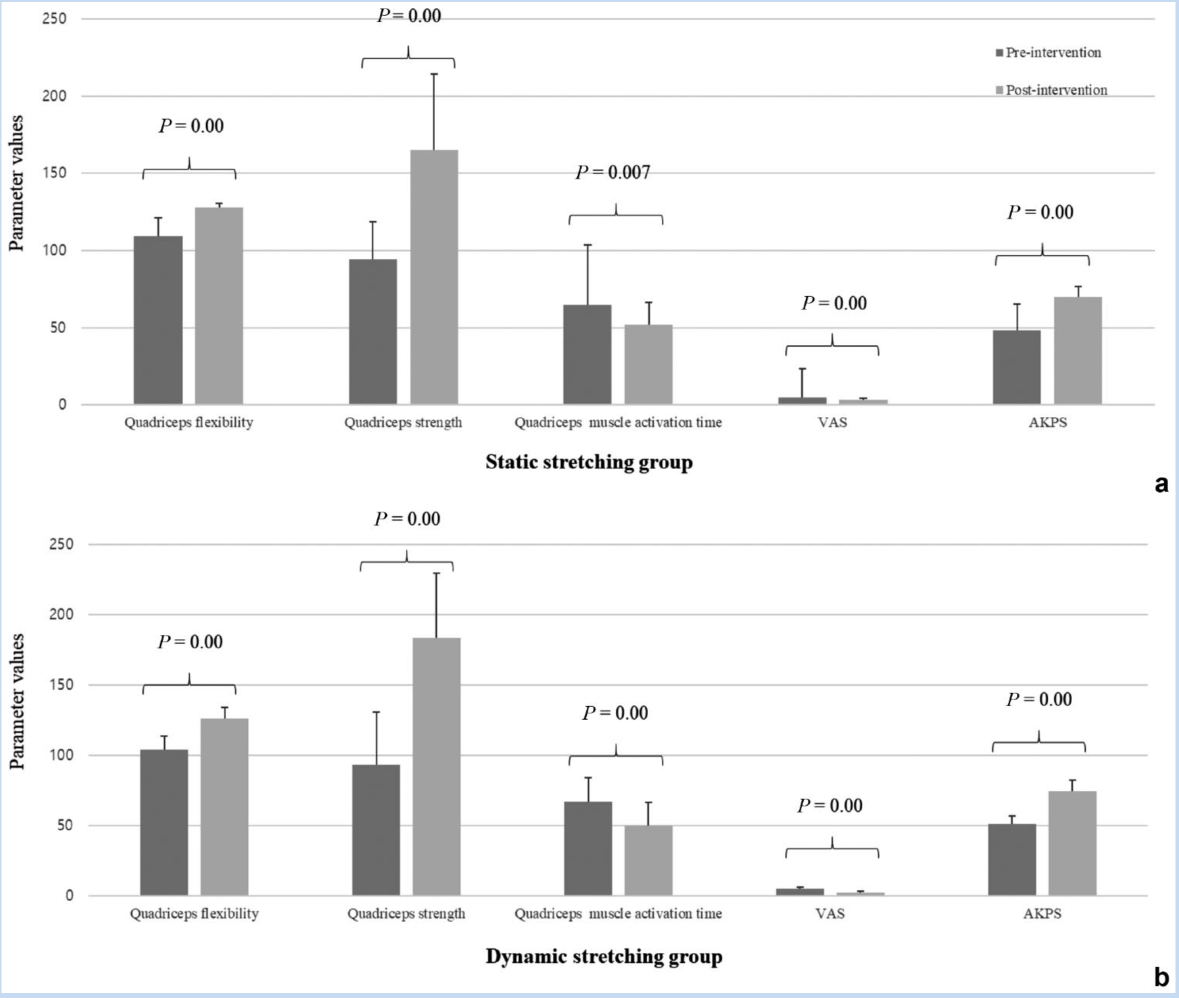

Figure 2. Quadriceps flexibility (degrees), strength (N·m·kg^{-1} × 100), muscle activation time (ms), and patient-reported outcomes (points) of the involved knees before and after quadriceps stretching in the static (A) and dynamic (B) stretching groups. AKPS, anterior knee pain scale; VAS, visual analog pain scale.

quadriceps stretching exercises in the patients with PFP who had inflexible quadriceps.

Previous studies reported that while static stretching is more effective than dynamic stretching for increasing muscle flexibility,[4,45] dynamic stretching is more effective than static stretching for improving quadriceps strength.[39,68] A possible explanation may be related to the difference in the holding time of the stretching exercises. In the present study, both the static and dynamic stretching exercises were repeated 3 times, with a holding time of 15 seconds, whereas in the aforementioned studies, they were repeated 3 times, with a holding time of 30 seconds. In a study by Bandy et al,[4] static stretching with a holding time of >30 seconds was more effective for muscle flexibility than dynamic stretching; however, no significant difference was found in the holding time of 15 seconds[3,4] because the stiffness of a musculotendinous unit may change in static stretching with a holding time of >30 seconds.[29,43] On the other hand, muscle strength may decrease in static stretching with a holding time of >30 seconds.[24] Herda et al[24] reported that muscle strength decreased in static stretching with a holding time of 30 seconds when compared with that in dynamic stretching. In addition, Siatras et al[61] investigated quadriceps strength after static stretching with different holding times, including 10, 20, 30, and 60 seconds and found that quadriceps strength significantly decreased in static stretching with a holding time of >30 seconds but did not change when the holding time was <20 seconds. This is because the compliant musculotendinous unit from the stretched muscle fibers may be insufficient to produce muscle force after static stretching with a holding time of >30 seconds.[11,61,66] Therefore, in the present study, static and dynamic stretching exercises with a holding time of 15 seconds may not be any different in terms of quadriceps flexibility and strength in patients with PFP who have inflexible quadriceps. Further study with stretching holding times of >15 seconds may be needed to identify the difference in quadriceps flexibility and strength between the 2 groups.

Several previous studies reported reduced neuromuscular control of the quadriceps muscle in patients with PFP,[10,52] particularly during static stretching exercises.[6,9] This study found no significant difference in muscle activation time between the static and dynamic stretching groups among the PFP patients with inflexible quadriceps. Although the reasons for these results are unclear, they may be due to activation of the motor unit (MU) improved by the eccentric contraction of the quadriceps muscle from the hip-strengthening exercises performed in the 2 groups. The activation of a MU is associated with an improvement in neuromuscular control.[59] In the present study, hip-strengthening exercises were performed in the 2 groups. Hip-strengthening exercises are a combination of hip external rotation and extension, which causes an eccentric contraction of the quadriceps muscles.[28,37] Several previous studies reported that eccentric contraction is more effective in the recruitment of fast-twitch MU than concentric contraction[23,42] because eccentric contraction can affect the regulation of the central descending pathways through the Golgi tendon organ reflex, such as the inhibitory pathways[23]; that is, the inexcitability of motor neurons caused by the Golgi tendon organ reflex may be prevented.[16] Therefore, the eccentric contraction of the quadriceps muscle from hip-strengthening exercises may enhance the activation of the MU, which may lead to an improvement in neuromuscular control.[36] Some researchers have suggested that eccentric contraction is more effective than other methods for improving pain and function in patients with anterior knee pain, such as those with PFPS or chondromalacia.[22,27]

In the present study, no statistically significant differences in patient-reported outcomes were found between the static and dynamic stretching groups. The VAS and AKPS scores improved after each stretching exercise by more than the MCID results presented in a previous study by Crossley et al[12] because patient-reported outcomes may be affected by the recovery of neuromuscular control.[54] Another possible reason why no significant differences in muscle activation time and patient-reported outcomes were found between the groups may be related to the improved hip muscle strength. The hip muscle strengthening program was included in the conservative rehabilitation protocol for both groups. According to a systematic review by Barton et al,[5] the hip muscles can affect the biomechanics of the knee joint in patients with PFPS, which can be associated with knee joint pain and function.[5,57] Hip muscle strength plays an important role in improving the neuromuscular control of the hip and knee joints in patients with knee injuries.[8,18,65] The reason why no significant differences in muscle activation time and patient-reported outcomes were found between the static and dynamic stretching groups may be related to the improvement of the quadriceps MU and enhancement of the gluteal muscles strength by the hip-strengthening exercises.

The present study has several limitations. Hip muscle strength, which plays an important role in the biomechanics of the lower extremity, was not measured.[50] Another important limitation was the absence of an electromyographic device to assess neuromuscular control. Finally, there was not a healthy control group in this study, which limits the interpretation of these results.

CONCLUSION

Quadriceps flexibility and strength, muscle activation time, and patient-reported outcomes in patients with PFP who had inflexible quadriceps showed no significant differences between the static and dynamic quadriceps stretching exercise groups. Therefore, both static and dynamic stretching exercises may be effective for improving pain and function in patients with PFP who have inflexible quadriceps.

REFERENCES

1. Aminaka N, Pietrosimone BG, Armstrong CW, Meszaros A, Gribble PA. Patellofemoral pain syndrome alters neuromuscular control and kinetics during stair ambulation. *J Electromyogr Kinesiol*. 2011;21:645-651.
2. Amiri-Khorasani M, Kellis E. Static vs. Dynamic acute stretching effect on quadriceps muscle activity during soccer instep kicking. *J Hum Kinet*. 2013;39:37-47.
3. Bandy WD, Irion JM. The effect of time on static stretch on the flexibility of the hamstring muscles. *Phys Ther*. 1994;74:845-850.
4. Bandy WD, Irion JM, Briggler M. The effect of static stretch and dynamic range of motion training on the flexibility of the hamstring muscles. *J Orthop Sports Phys Ther*. 1998;27:295-300.
5. Barton CJ, Lack S, Malliaras P, Morrissey D. Gluteal muscle activity and patellofemoral pain syndrome: a systematic review. *Br J Sports Med*. 2013;47:207-214.
6. Bradley PS, Olsen PD, Portas MD. The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. *J Strength Cond Res*. 2007;21:223-226.
7. Callaghan MJ, Oldham JA. Quadriceps atrophy: to what extent does it exist in patellofemoral pain syndrome? *Br J Sports Med*. 2004;38:295-299.
8. Carroll TJ, Riek S, Carson RG. Neural adaptations to resistance training: implications for movement control. *Sports Med*. 2001;31:829-840.
9. Cornwell A. Acute effects of muscle stretching on vertical jump performance. *J Hum Mov Stud*. 2001;40:307-324.
10. Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome. *Arch Phys Med Rehabil*. 2001;82:183-189.
11. Cramer JT, Beck TW, Housh TJ, et al. Acute effects of static stretching on characteristics of the isokinetic angle–torque relationship, surface electromyography, and mechanomyography. *J Sports Sci*. 2007;25:687-698.
12. Crossley KM, Bennell KL, Cowan SM, Green S. Analysis of outcome measures for persons with patellofemoral pain: which are reliable and valid? *Arch Phys Med Rehabil*. 2004;85:815-822.
13. Crossley KM, Stefanik JJ, Selfe J, et al. Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 1: terminology, definitions, clinical examination, natural history, patellofemoral osteoarthritis and patient-reported outcome measures. *Br J Sports Med*. 2016;50:839-843.
14. Dixit S, DiFiori JP, Burton M, Mines B. Management of patellofemoral pain syndrome. *Am Fam Physician*. 2007;75:194-202.
15. Escamilla RF, Zheng N, MacLeod TD, et al. Patellofemoral compressive force and stress during the forward and side lunges with and without a stride. *Clin Biomech (Bristol, Avon)*. 2008;23:1026-1037.
16. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantarflexors. *J Appl Physiol (1985)*. 2000;89:1179-1188.
17. Fulkerson JP. Diagnosis and treatment of patients with patellofemoral pain. *Am J Sports Med*. 2002;30:447-456.
18. Garrison JC, Bothwell J, Cohen K, Conway J. Effects of hip strengthening on early outcomes following anterior cruciate ligament reconstruction. *Int J Sports Phys Ther*. 2014;9:157-167.
19. Gulati A, McElrath C, Wadhwa V, Shah JP, Chhabra A. Current clinical, radiological and treatment perspectives of patellofemoral pain syndrome. *Br J Radiol*. 2018;91:20170456.

20. Guney H, Yuksel I, Kaya D, Doral MN. The relationship between quadriceps strength and joint position sense, functional outcome and painful activities in patellofemoral pain syndrome. *Knee Surg Sports Traumatol Arthrosc*. 2016;24:2966-2972.
21. Habusta SF, Griffin EE. Chondromalacia patella. *StatPearls* [Internet]. *StatPearls* Publishing; 2019.
22. Hafez AR, Zakaria A, Buragadda S. Eccentric versus concentric contraction of quadriceps muscles in treatment of chondromalacia patellae. *World J Med Sci*. 2012;7:197-203.
23. Hedayatpour N, Falla D. Physiological and neural adaptations to eccentric exercise: mechanisms and considerations for training. *Biomed Res Int*. 2015;2015:193741.
24. Herda TJ, Cramer JT, Ryan ED, McHugh MP, Stout JR. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. *J Strength Cond Res*. 2008;22:809-817.
25. Herrington L, Al-Sherhi A. A controlled trial of weight-bearing versus non-weight-bearing exercises for patellofemoral pain. *J Orthop Sports Phys Ther*. 2007;37:155-160.
26. Hough PA, Ross EZ, Howatson G. Effects of dynamic and static stretching on vertical jump performance and electromyographic activity. *J Strength Cond Res*. 2009;23:507-512.
27. Jan M-H, Wei T-C, Song C-Y. Comparisons of quadriceps strength training, taping, and stretching on clinical outcomes in patients with patellofemoral pain syndrome. *J Biomech*. 2007;40:S410.
28. Kary JM. Diagnosis and management of quadriceps strains and contusions. *Curr Rev Musculoskelet Med*. 2010;3:26-31.
29. Kubo K, Kanehisa H, Fukunaga T. Effect of stretching training on the viscoelastic properties of human tendon structures in vivo. *J Appl Physiol (1985)*. 2002;92:595-601.
30. Kujala UM, Jaakkola LH, Koskinen SK, Taimela S, Hurme M, Nelimarkka O. Scoring of patellofemoral disorders. *Arthroscopy*. 1993;9:159-163.
31. Lee JH, Han SB, Park JH, Choi JH, Suh DK, Jang KM. Impaired neuromuscular control up to postoperative 1 year in operated and nonoperated knees after anterior cruciate ligament reconstruction. *Medicine (Baltimore)*. 2019;98:e15124.
32. Lee JH, Jang KM, Kim E, Rhim HC, Kim HD. Effects of static and dynamic stretching with strengthening exercises in patients with patellofemoral pain who have inflexible hamstrings: a randomized controlled trial. *Sports Health*. 2021;13:49-56.
33. Lee JH, Lee SH, Choi GW, Jung HW, Jang WY. Individuals with recurrent ankle sprain demonstrate postural instability and neuromuscular control deficits in unaffected side. *Knee Surg Sports Traumatol Arthrosc*. 2020;28:184-192.
34. Lee JH, Lee SH, Jung HW, Jang WY. Modified Broström procedure in patients with chronic ankle instability is superior to conservative treatment in terms of muscle endurance and postural stability. *Knee Surg Sports Traumatol Arthrosc*. 2020;28:93-99.
35. Lee JH, Park JS, Hwang HJ, Jeong WK. Time to peak torque and acceleration time are altered in male patients following traumatic shoulder instability. *J Shoulder Elbow Surg*. 2018;27:1505-1511.
36. Lepley LK, Lepley AS, Onate JA, Grooms DR. Eccentric exercise to enhance neuromuscular control. *Sports Health*. 2017;9:333-340.
37. Maeo S, Saito A, Otsuka S, Shan X, Kanehisa H, Kawakami Y. Localization of muscle damage within the quadriceps femoris induced by different types of eccentric exercises. *Scand J Med Sci Sports*. 2018;28:95-106.
38. Mandelbaum BR, Silvers HJ, Watanabe DS, et al. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med*. 2005;33:1003-1010.
39. Manoel ME, Harris-Love MO, Danoff JV, Miller TA. Acute effects of static, dynamic, and proprioceptive neuromuscular facilitation stretching on muscle power in women. *J Strength Cond Res*. 2008;22:1528-1534.
40. Mason M, Keays SL, Newcombe PA. The effect of taping, quadriceps strengthening and stretching prescribed separately or combined on patellofemoral pain. *Physiother Res Int*. 2011;16:109-119.
41. McCarthy MM, Strickland SM. Patellofemoral pain: an update on diagnostic and treatment options. *Curr Rev Musculoskelet Med*. 2013;6:188-194.
42. McHugh MP, Tyler TF, Greenberg SC, Gleim GW. Differences in activation patterns between eccentric and concentric quadriceps contractions. *J Sports Sci*. 2002;20:83-91.
43. Morse CI, Degens H, Seynnes OR, Maganaris CN, Jones DA. The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. *J Physiol*. 2008;586:97-106.
44. Moyano FR, Valenza MC, Martin LM, Caballero YC, Gonzalez-Jimenez E, Demet GV. Effectiveness of different exercises and stretching physiotherapy on pain and movement in patellofemoral pain syndrome: a randomized controlled trial. *Clin Rehabil*. 2013;27:409-417.
45. O'Sullivan K, Murray E, Sainsbury D. The effect of warm-up, static stretching and dynamic stretching on hamstring flexibility in previously injured subjects. *BMC Musculoskelet Disord*. 2009;10:37.
46. Page P. Current concepts in muscle stretching for exercise and rehabilitation. *Int J Sports Phys Ther*. 2012;7:109-119.
47. Peeler J, Anderson JE. Effectiveness of static quadriceps stretching in individuals with patellofemoral joint pain. *Clin J Sport Med*. 2007;17:234-241.
48. Peeler J, Anderson JE. Reliability of the Ely's test for assessing rectus femoris muscle flexibility and joint range of motion. *J Orthop Res*. 2008;26:793-799.
49. Perrier ET, Pavol MJ, Hoffman MA. The acute effects of a warm-up including static or dynamic stretching on countermovement jump height, reaction time, and flexibility. *J Strength Cond Res*. 2011;25:1925-1931.
50. Piva SR, Goodnite EA, Childs JD. Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*. 2005;35:793-801.
51. Pourahmadi MR, Ebrahimi Takamjani I, Hesampour K, Shah-Hosseini GR, Jamshidi AA, Shamsi MB. Effects of static stretching of knee musculature on patellar alignment and knee functional disability in male patients diagnosed with knee extension syndrome: A single-group, pretest-posttest trial. *Man Ther*. 2016;22:179-189.
52. Powers CM, Landel R, Perry J. Timing and intensity of vastus muscle activity during functional activities in subjects with and without patellofemoral pain. *Phys Ther*. 1996;76:946-955.
53. Powers CM, Witvrouw E, Davis IS, Crossley KM. Evidence-based framework for a pathomechanical model of patellofemoral pain: 2017 patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester, UK: part 3. *Br J Sports Med*. 2017;51:1713-1723.
54. Rabelo ND, Lima B, Reis AC, et al. Neuromuscular training and muscle strengthening in patients with patellofemoral pain syndrome: a protocol of randomized controlled trial. *BMC Musculoskelet Disord*. 2014;15:157.
55. Reinold MM, Gill TJ, Wilk KE, Andrews JR. Current concepts in the evaluation and treatment of the shoulder in overhead throwing athletes, part 2: injury prevention and treatment. *Sports Health*. 2010;2:101-115.
56. Saad MC, Vasconcelos RA, Mancinelli LVO, Munno MSB, Liporaci RF, Grossi DB. Is hip strengthening the best treatment option for females with patellofemoral pain? A randomized controlled trial of three different types of exercises. *Braz J Phys Ther*. 2018;22:408-416.
57. Santos TR, Oliveira BA, Ocarino JM, Holt KG, Fonseca ST. Effectiveness of hip muscle strengthening in patellofemoral pain syndrome patients: a systematic review. *Braz J Phys Ther*. 2015;19:167-176.
58. Sekir U, Arabaci R, Akova B, Kadagan SM. Acute effects of static and dynamic stretching on leg flexor and extensor isokinetic strength in elite women athletes. *Scand J Med Sci Sports*. 2010;20:268-281.
59. Semmler JG. Motor unit synchronization and neuromuscular performance. *Exerc Sport Sci Rev*. 2002;30:8-14.
60. Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. *Psychol Bull*. 1979;86:420-428.
61. Siatras TA, Mittas VP, Mameletzi DN, Vamvakoudis EA. The duration of the inhibitory effects with static stretching on quadriceps peak torque production. *J Strength Cond Res*. 2008;22:40-46.
62. 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;39:12-19.
63. Thomee R, Augustsson J, Karlsson J. Patellofemoral pain syndrome: a review of current issues. *Sports Med*. 1999;28:245-262.
64. Waryasz GR, McDermott AY. Patellofemoral pain syndrome (PFPS): a systematic review of anatomy and potential risk factors. *Dyn Med*. 2008;7:9.
65. Willy RW, Hoglund LT, Barton CJ, et al. Patellofemoral pain. *J Orthop Sports Phys Ther*. 2019;49:CPG1-CPG95.
66. Wilson GJ, Murphy AJ, Pryor JF. Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. *J Appl Physiol (1985)*. 1994;76:2714-2719.
67. 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;28:480-489.
68. Yamaguchi T, Ishii K. Effects of static stretching for 30 seconds and dynamic stretching on leg extension power. *J Strength Cond Res*. 2005;19:677-683.
69. Young W, Elliott S. Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on explosive force production and jumping performance. *Res Q Exerc Sport*. 2001;72:273-279.