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Influence of Step Height on Quadriceps Onset Timing and Activation During Stair Ascent in Individuals With Patellofemoral Pain Syndrome

STUDY DESIGN: A case control study, with single observation.

OBJECTIVES: To compare the onset timing and activation of the vastus medialis oblique (VMO) and vastus lateralis (VL) between subjects with and without patellofemoral pain syndrome (PFPS) at various step heights.

BACKGROUND: It has been theorized that delayed or reduced VMO activity relative to the VL contributes to lateral patellar tracking and PFPS. However, conflicting evidence exists in the literature regarding this proposed mechanism. The lack of agreement among studies may be attributed to inconsistent knee flexion angles used in previous studies.

METHODS AND MEASURES: Twenty subjects with PFPS (mean ± SD age, 29.5 ± 10 years) and 20 control subjects (mean ± SD age, 25.4 ± 3.1 years) ascended 5 different step heights, while knee kinematics and quadriceps EMG data were collected. Knee flexion angle at foot-step contact, VMO-VL onset timing, and VMO/VL activation ratios were analyzed between groups and step heights using 2-factor analyses of variance (ANOVAs) with repeated measures ($\alpha = .05$).

RESULTS: Individuals with PFPS demonstrated 4.7° ($P = .038$) more knee flexion at foot-step contact than control subjects. Despite greater knee flexion with increased step height ($P < .001$), no differences in onset timing or activation magnitude ratio were present between groups or across step heights. However, individuals with PFPS displayed a significantly increased activation duration ratio compared to the control group ($P = .043$).

CONCLUSION: Quadriceps onset timing and activation magnitude during stair ascent was similar between individuals with and without PFPS, regardless of step height. Thus, the results of this study are in agreement with evidence indicating no difference in VMO-VL timing and VMO/VL activation magnitude ratio between individuals with and without PFPS. *J Orthop Sports Phys Ther 2007;37(5):239-244. doi:10.2519/jospt.2007.2421*

KEY WORDS: activation ratio, anterior knee pain, EMG, onset delay, stair climbing

Patellofemoral pain syndrome (PFPS) is one of the most common conditions seen in orthopaedic and sports physical therapy. Of all individuals with knee injuries treated in a sports medicine clinic, 25% were diagnosed with PFPS.[14] In addition, the incidence rate of PFPS in the general population has been reported to be between 10% and 25%.[21,32] While the annual cost of treating PFPS has not been reported, such a high prevalence would suggest that it would be rather substantial.

Although many theories exist to explain the cause of PFPS, improper activation of the quadriceps muscle remains a commonly proposed mechanism. It has been suggested that delayed onset timing and reduced activation magnitude of the vastus medialis oblique (VMO) with respect to the vastus lateralis (VL) promote a laterally tracking patella and eventually PFPS.[19,29,31-33] However, contrasting evidence is present in the literature with respect to the existence of either activation or timing differences between the VMO and VL in contributing to PFPS.

During stair ascent, Cowan et al[9] found that the VMO onset was delayed relative to the VL onset by 15.8 milliseconds in subjects with PFPS when compared to an asymptomatic group. While this finding has been repeatedly cited by this research group,[10,12,13] similar studies involving stair climbing have not found significant differences in onset timing of the VMO and VL between persons with and without PFPS.[17,22,28] Despite these disparate findings, quadriceps training with an emphasis on restoring synchronous VMO-VL onset timing among persons with PFPS has been advocated[11] and has been reported to contribute to positive treatment outcomes.[13]

While differences in subject inclusion criteria and electromyographic (EMG) signal-processing techniques[16] across these investigations may help to explain their contrasting findings, knee flexion angle at the time of muscle onset may also be an important factor. Knee flexion angle has been shown to influence the reflex activation and peak activation onset of the vasti muscle group.[1,2,8] In addition, knee flexion angle at foot-step contact

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is influenced by the heights of the subject and step. Consequently, subjects of similar height may demonstrate different knee flexion angles when ascending steps of differing heights. Similarly, subjects of varying heights ascending a fixed step height will likely have different knee flexion angles. Measuring VMO and VL activity during stepping, while systematically manipulating step height, may reconcile some of the opposing results of prior investigations.

The influence of knee flexion angle has also been evaluated with respect to activation magnitude ratio of the VMO and VL. Smaller ratios indicate that the VMO has less activity than the VL, which, theoretically, allows the patella to track laterally on the femur. Tang et al[30] showed that the VMO/VL activation magnitude ratio increased by as much as 25% as the knee flexion angle increased from 0° to 60° during weight bearing. This interaction between knee flexion angle and VMO/VL activation magnitude ratio has also been demonstrated by Lam and Ng.[18] Therefore, the evaluation of variable knee angles owing to different step heights may explain the inconsistent findings across studies with regard to the altered VMO/VL activation ratio between persons with and without PFPS.[5,29,30,34]

The purpose of this study was to compare the onset timing and activation ratios of the VMO and VL between subjects with and without PFPS during stair stepping at various step heights. To address the influence of joint angle on muscle activity, the knee flexion angle at initial foot-step contact was measured.

METHODS

Subject Selection

Twenty subjects with PFPS (9 females and 11 males) and 20 healthy individuals (10 females and 10 males) for the control group volunteered for this study. Mean ± SD age, height, and body mass of the individuals in the PFPS group were 29.5 ± 10.0 years, 1.73 ± 0.10 m, and 75.9 ± 9.9 kg, respectively; these characteristics for individuals in the control group were 25.4 ± 3.1 years, 1.72 ± 0.12 m, and 78.7 ± 19.9 kg, respectively. Based on the effect size (Cohen d = 0.85) of VMO and VL onset difference between persons with and without PFPS during a 20-cm stair-stepping task obtained from Cowan et al,[9] a minimum of 18 subjects per group was estimated to be needed to ensure 80% power (α = .05).

In accordance with previously established criteria,[9,24] symptomatic subjects were admitted to the study if they had reproducible pain with at least 2 activities associated with exacerbating PFPS (ie, squatting, stair climbing, kneeling, prolonged sitting, isometric quadriceps contraction) and reported a minimum pain scale rating of 3 on a 0-to-10 visual analog scale (VAS), with 0 being no pain and 10 being maximum pain. Subjects were excluded if ligamentous laxity or internal derangement was suspected during a preparticipation screening by a physical therapist, or if the subjects reported having prior knee surgery.

The control subjects were examined by a physical therapist and excluded if they demonstrated discomfort with the activities used as criteria for the PFPS group, had a history of knee surgery or pathology, or reported any current knee pain. All procedures were approved by The Institutional Review Boards of Des Moines University-Osteopathic Medical Center and the University of Wisconsin-Madison. Written informed consent was obtained from all subjects prior to participation and the rights of human subjects were protected.

Procedures

Each subject performed a step-up/step-down task 6 consecutive times at each of 5 step heights (8, 14, 20, 26, and 32 cm). Each repetition was initiated with a forward step from a fixed point on the floor leading with the test leg and followed by the opposite leg. After the forward step, subjects immediately stepped back down to the starting position, again leading with the test leg. The stepping rate was maintained at 96 steps per minute through pacing by a metronome. Each subject was given 5 practice trials per step height to become familiar with the task. Step height testing order was randomized across subjects to prevent a presentation order effect, with subjects allowed 60 seconds of rest between each step height. Immediately after completing each step height, subjects indicated their perceived knee pain using a 10-cm VAS.

Three-dimensional kinematic data of the tested knee were recorded (60 Hz) using an 8-camera, passive-marker, motion capture system (Motion Analysis Corporation, Santa Rosa, CA). The involved knee of the subjects with PFPS was used for analysis (13 left, 7 right), while the tested knee of the control subjects was randomly selected (7 left, 13 right). Reflective marker triads composed of 3 noncollinear hollow polypropylene spheres fastened to a polypropylene base were securely placed on the lateral surface of the thigh and leg. Additional markers to be used in the identification of foot-step contact were located on the heel and toe. Following marker placement, marker orientations were recorded as each subject stood in a relaxed upright posture.

Muscle activity of the VMO and VL were collected synchronously using a wired surface EMG system (Motion Lab Systems, Inc, Baton Rouge, LA). The preamplified (20 times) single-differential electrodes were centered on the muscle bellies of the VMO and VL, as described by Basmajian.[4] EMG data were sampled at 960 Hz using a 12-bit A-D converter interfaced with the motion capture system. EMG amplifier (band-pass filtered between 20 and 2000 Hz; common-mode rejection ratio, 100 dB at 65 Hz; input impedance, greater than 100 MΩ) gain was adjusted to maximize signal resolution without clipping.

Data Reduction

All data were processed using custom software in MATLAB (The Mathworks, Natick, MA). The 3-dimensional marker

coordinates were low-pass filtered using a second-order Butterworth filter (6-Hz cutoff). Based on a 2-segment rigid-body model, knee flexion angles during the stepping task were calculated from the marker coordinates using a joint coordinate system.[15] Foot-step contact times were ascertained by identifying a contact-induced horizontal acceleration of the heel marker (**FIGURE**).

EMG data were full-wave rectified and low-pass filtered (6-Hz cutoff)[20] using a bidirectional sixth-order Butterworth filter. The EMG activity onset approximating initial foot-step contact and cessation was determined by a computer algorithm and confirmed by visual inspection. Visual adjustment of the computer-identified onset times was performed in a blinded manner and was required in less than 10% of the stepping trials. The threshold for muscle activity onset and cessation was identified as the point at which the EMG signal exceeded (onset) or fell below (cessation) 2 standard deviations of baseline for a minimum of 20 milliseconds (**FIGURE**). This threshold was selected as it demonstrated the greatest repeatability across stepping trials ($ICC_{3,1}>0.82$) in comparison to 2 other commonly used thresholds—5% of peak EMG activation ($ICC_{3,1}>0.22$) and 95% confidence interval of baseline EMG activation ($ICC_{3,1}>0.44$)—as determined from a preliminary analysis of EMG onset times from 10 randomly selected subjects. Relative onset timing between the VMO and VL was determined by subtracting the VL onset from the VMO onset. Thus positive values indicate that VMO onset follows VL and negative values indicate that VMO onset precedes VL.

The mean activation level for the VMO and VL was calculated from activity onset at step contact to activity cessation, as identified by the above-stated threshold criterion. Each EMG signal was then normalized to its instantaneous peak activity during the stepping tasks. The relative normalized activity magnitude between the VMO and VL was expressed as the activation magnitude ratio (VMO/VL). Values greater than 1.0 indicate greater VMO activity relative to VL activity. Similarly, the relative activation duration (time from activity onset to offset) between the VMO and VL was calculated as the activation duration ratio (VMO/VL), with values greater than 1.0 indicating that the VMO was active longer than the VL.

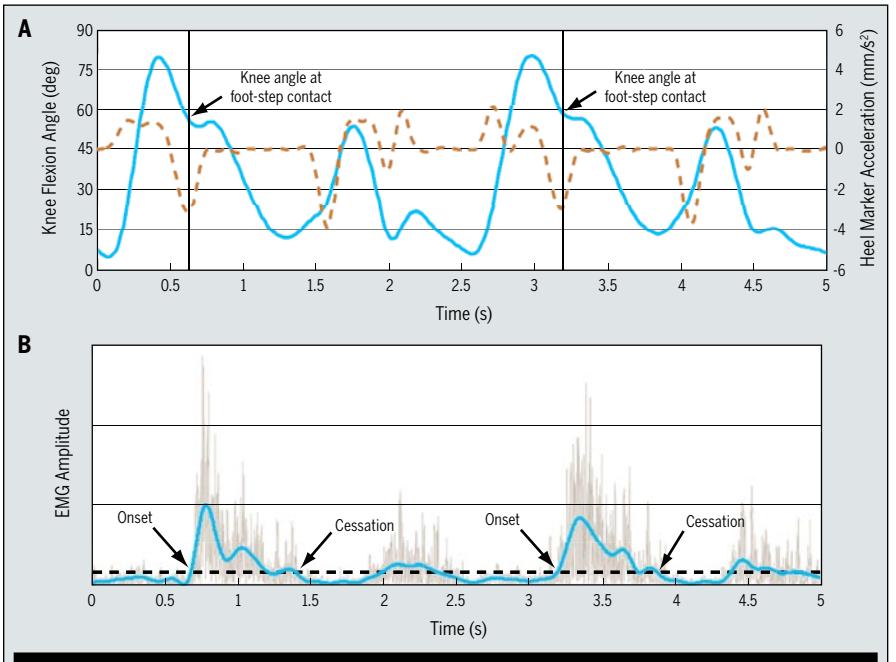

FIGURE. (A) Knee flexion angle (solid line) at foot-step contact was determined by identifying a peak acceleration of the heel marker (dashed line) in the anteroposterior direction. (B) The rectified raw EMG (gray) was low-pass filtered at 6 Hz (solid line) to determine the corresponding onset of muscle activity from the VMO and VL (only the VMO is shown). Activity onset and cessation were identified as the instant the filtered EMG signal exceeded (onset) or fell below (cessation) 2 SD of mean baseline activity (dashed line) for a minimum of 20 milliseconds. Two complete stepping trials (step height, 20 cm) are displayed from a representative subject of the control group.

Statistical Analysis

Averages of the 6 stepping repetitions at each step height were calculated for the knee flexion angles and EMG parameters. Subject demographics were compared between groups using independent *t* tests. Perceived pain scores of the PFPS group were compared across step heights using a 1-way analysis of variance (ANOVA) with repeated measures. A 2-way ANOVA (group and step height) with repeated measures (step height) was used to compare relative onset timing and activation ratios (magnitude and duration) of the VMO and VL, in addition to knee flexion angle. Significant main effects and interactions were further analyzed using the Scheffe test. The Pearson correlation coefficient was used to determine the association across all step heights between knee flexion angle and each of the following variables: (1) relative onset timing, (2) activation magnitude ratio, (3) activation duration ratio, and (4) subject height. Statistical significance for all tests was established at $P\leq.05$, with all analyses performed using STATISTICA, Version 6.0 (StatSoft, Inc, Tulsa, OK).

RESULTS

Demographics and Pain Ratings

Subject age ($P = .09$), height ($P = .85$), and mass ($P = .66$) were not statistically significant between groups. The 1-way ANOVA revealed that pain was significantly different across step heights ($P<.001$). Pain levels reported by subjects with PFPS were greater at 26- and 32-cm step heights than for the 2 lowest

step heights (8 and 14 cm) ($P<.05$), yet did not differ from the 20-cm step height. Also, no significant difference in knee pain was reported between the lower 3 step heights (8, 14, and 20 cm) (**TABLE**). Control group subjects reported no pain (0/10) at each step height.

Knee Flexion Angle

Based on the 2-way ANOVA, knee flexion angle at foot-step contact did not reveal a significant interaction between group and step height ($P = .25$). However, knee flexion angle was observed to increase for both groups as step height increased ($P<.001$) (**TABLE**). In addition, a group main effect revealed that subjects with PFPS demonstrated an average (±SD) of 4.7° ± 0.8° more knee flexion at contact than controls across each step height ($P = .038$).

Relative EMG Onset

Onset timing at foot-step contact, as expressed by the difference between VMO and VL, did not reveal a significant interaction between group and step height ($P = .99$). Further, the onset timing at foot-step contact was not statistically significant between groups ($P = .10$) or across step heights ($P = .96$) (**TABLE**). The correlation between knee angle at contact and relative onset timing across all step heights was not significant ($r = -0.069$; $P = .34$).

Activation Magnitude Ratio

Activation magnitude ratio of the VMO and VL did not reveal a significant interaction between group and step height ($P = .09$). Further, the activation magnitude ratio was not statistically significant between groups ($P = .75$) or across step heights ($P = .58$) (**TABLE**). The correlation between knee angle at foot-step contact and activation magnitude ratio across all step heights was not significant ($r = -0.070$; $P = .33$).

Activation Duration Ratio

Activation duration ratio of the VMO and VL did not reveal a significant interaction between group and step height ($P = .87$). However, a significantly greater activity duration ratio for the PFPS group (mean ± SD, 1.15 ± 0.15) was found compared to the control group (mean ± SD, 1.0 ± 0.15) across all step heights ($P = .043$) (**TABLE**). Based on a 2-way ANOVA with repeated measures, this difference was a result of the VL being active for a significantly shorter amount of time ($P = .008$) in persons with PFPS (mean ± SD, 591 ± 119 milliseconds) compared to controls (mean ± SD, 659 ± 105 milliseconds), while the VMO activation duration was not different between groups (PFPS group mean ± SD, 632 ± 109 milliseconds; control group mean ± SD, 654 ± 111 milliseconds). The correlation between knee angle at foot-step contact and activation duration ratio across all step heights was not significant ($r = 0.011$; $P = .88$).

Knee Flexion Angle at Foot-Step Contact, Activation Onset, Magnitude Ratio, Duration Ratio, and Perceived Pain Levels During Stepping Task at Each Step Height*

	Step Height (cm)				
	8	14	20	26	32
Knee flexion (°)†‡					
PFPS	35.0 ± 7.7	49.1 ± 8.0	60.4 ± 8.2	70.4 ± 8.3	78.0 ± 8.7
Control	31.2 ± 5.8	44.9 ± 6.2	55.7 ± 5.8	64.7 ± 6.2	72.6 ± 6.2
Activation onset (ms)					
PFPS	−6.29 ± 24.9	−11.40 ± 20.67	−9.48 ± 17.45	−10.33 ± 17.06	−10.50 ± 18.26
Control	−3.30 ± 19.79	−5.58 ± 20.28	−4.54 ± 20.12	−0.38 ± 14.79	−2.82 ± 12.83
Activation magnitude ratio					
PFPS	0.80 ± 0.36	0.87 ± 0.35	0.83 ± 0.23	0.89 ± 0.32	0.88 ± 0.25
Control	0.94 ± 0.32	0.90 ± 0.35	0.95 ± 0.38	0.93 ± 0.34	0.94 ± 0.35
Activation duration ratio§					
PFPS	1.15 ± 0.43	1.06 ± 0.22	1.10 ± 0.24	1.12 ± 0.24	1.11 ± 0.18
Control	1.03 ± 0.23	0.99 ± 0.15	1.00 ± 0.17	1.00 ± 0.20	1.02 ± 0.19
Pain scores (0-10)‖					
PFPS	1.8 ± 0.3	1.7 ± 0.3	2.4 ± 0.3	2.6 ± 0.4	3.1 ± 0.5
Control	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0

Abbreviation: PFPS, patellofemoral pain syndrome.
** Values are mean ± SD. Pain score taken on a visual analog scale (range, 0-10 with 0 being no pain and 10 being maximum pain); activation onset negative value indicates that VMO preceded VL; activation magnitude ratio of less than 1.0 indicates less VMO activity relative to the VL; activation duration ratio of less than 1.0 indicates shorter VMO duration relative to VL.*
† The PFPS group had greater knee flexion angles than the control group across all step heights ($P = .038$).
‡ Greater knee flexion angle was observed with increased step height in both groups ($P<.001$).
§ The PFPS group had a greater activation duration ratio that the control group across all step heights ($P = .043$).
‖ Pain scores at step heights 26 and 32 cm were greater than for step heights of 8 and 14 cm ($P<.05$).

DISCUSSION

The purpose of this study was to compare the relative onset timing and activation ratios of the VMO and VL between subjects with and without PFPS during stair stepping, while considering the influence of knee flexion angle at foot-step contact. The results did not reveal a between-group difference in either the VMO-VL relative onset timing or VMO/VL activation magnitude ratio. However, the subjects with PFPS displayed a greater activation duration ratio. Further, relative onset timing and activation ratios (magnitude and duration) were not significantly different across step heights, with no correlation observed between knee flexion angle at foot-step contact and any of these muscle activity variables.

Our findings are consistent with previous studies that have demonstrated no difference in onset timing[7,17,24,28] and activation magnitude ratio[5,28,29,34] of the VMO and VL between individuals with and without PFPS. This study is the first to systematically test VMO and VL relative onset timing and activation magnitude ratios across various step heights and knee flexion angles. Our findings indicate that the relative activity of the VMO and VL are not dependent on the knee flexion angle during stair stepping, suggesting that discrepancies in literature pertaining to quadriceps timing and activation may be attributed to methodological differences other than knee flexion angle or step height (eg, muscle activity onset detection algorithm).[16,22]

The increased activation duration ratio observed in the subjects with PFPS compared to the control group resulted from a reduction in total onset time of the VL relative to the VMO. That is, the control subjects displayed similar activation duration of the VMO and VL during the stepping task, while the subjects with PFPS showed an early cessation of the VL. As both groups performed the task at a constant cadence (96 steps per minute), the change in VL activation duration can not be attributed to different stepping speeds as suggested by Brindle et al.[7] Further, the similarity in activation onset times between the 2 groups indicates that the reduction in VL activation time occurred toward the end of the stepping task, with a corresponding knee flexion angle of less than 20°. As this phase of stepping corresponds to a small knee extension moment,[27] the significance of this early VL cessation to functional performance may be questioned. Rather, the increased activation duration ratio present in the subjects with PFPS may be related to other kinematic changes previously observed in subjects with PFPS, such as femoral and tibial rotation or knee valgus.[25]

The PFPS group demonstrated mean (±SD) knee flexion angles that averaged 4.7° ± 0.8° greater than those of the control group at each step height. Subject height does not appear to account for this difference due to similarities in subject height between groups. Furthermore, post hoc analysis revealed that there was no correlation between subject height and knee flexion angle in either group at any step height (r = 0.00 to −0.10, $P>.05$). Altered knee joint position sense[3] and/or corticomotor adaptations[23] proposed to accompany PFPS may account for the different knee angles observed between groups. However, other investigations have found no difference in knee flexion angle between individuals with and without PFPS during stair ascent.[6,13,24,27] A possible explanation for the opposing results may be attributed to the task used in each study. While prior studies have utilized a reciprocal step-over pattern, this study utilized a reciprocal step-up/step-down pattern. Even though the point of reference for all studies was foot-step contact during stair ascent, the requirements of the step-up/step-down task may have resulted in different movement patterns than in a step-over task. For example, the difference in knee flexion angle may have resulted from changes in foot placement on the step and the center of pressure location at the time of foot-step contact. Comparing the hip and ankle kinematics and kinetics in addition to the knee during these 2 stepping tasks may provide more insight regarding a shift in stepping strategy. Likewise, pelvis and trunk compensations may influence stepping patterns at the knee in patients with PFPS[6,25] and warrant further investigation.

The subjects within the PFPS group indicated greater perceived knee pain at the 2 highest step heights (26 and 32 cm). This increase in pain with higher step height can not be explained by changes in the VMO and VL relative onset timing or activation ratios, as all were unaffected by step height. Conversely, the presence of increased pain with higher step height did not affect onset timing or activation ratios. The increased pain at the higher step heights may result from greater knee flexion angles and knee extensor moments required of the higher steps. Both knee flexion angle and knee extensor moment have been found to increase linearly with step height in noninjured subjects,[26] likely leading to an increase in patellofemoral joint compressive forces.

CONCLUSION

Step height during stair ascent does not appear to alter VMO and VL relative onset timing or activation in individuals with PFPS, despite an increase in reported knee pain at the higher step heights. Although subjects with PFPS displayed greater knee flexion angles at foot-step contact than subjects without PFPS, relative onset timing and activation magnitude ratio of the VMO and VL did not differ between individuals in the 2 groups. The presence of delayed or inhibited VMO activation relative to VL among persons with PFPS is not supported by the results of this study.

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REFERENCES

1. Alrowayeh HN, Sabbahi MA. Vastus medialis H-reflex reliability during standing. *J Clin Neurophysiol.* 2006;23:79-84.
2. Alrowayeh HN, Sabbahi MA, Etnyre B. Soleus and vastus medialis H-reflexes: similarities and differences while standing or lying during varied knee flexion angles. *J Neurosci Methods.* 2005;144:215-225.
3. Baker V, Bennell K, Stillman B, Cowan S, Crossley K. Abnormal knee joint position sense in individuals with patellofemoral pain syndrome. *J Orthop Res.* 2002;20:208-214.
4. Basmajian J. *Biofeedback: Principles and Practice for Clinicians.* Baltimore, MD: Williams & Wilkins; 1989.
5. Boucher JP, King MA, Lefebvre R, Pepin A.

Quadriceps femoris muscle activity in patellofemoral pain syndrome. *Am J Sports Med.* 1992;20:527-532.
6. Brechter JH, Powers CM. Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait Posture.* 2002;16:115-123.
7. Brindle TJ, Mattacola C, McCrory J. Electromyographic changes in the gluteus medius during stair ascent and descent in subjects with anterior knee pain. *Knee Surg Sports Traumatol Arthrosc.* 2003;11:244-251.
8. Cesarelli M, Bifulco P, Bracale M. Study of the control strategy of the quadriceps muscles in anterior knee pain. *IEEE Trans Rehabil Eng.* 2000;8:330-341.
9. 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.
10. Cowan SM, Hodges PW, Bennell KL, Crossley KM. Altered vastii recruitment when people with patellofemoral pain syndrome complete a postural task. *Arch Phys Med Rehabil.* 2002;83:989-995.
11. Crossley K, Bennell K, Green S, Cowan S, McConnell J. Physical therapy for patellofemoral pain: a randomized, double-blinded, placebo-controlled trial. *Am J Sports Med.* 2002;30:857-865.
12. Crossley KM, Cowan SM, Bennell KL, McConnell J. Knee flexion during stair ambulation is altered in individuals with patellofemoral pain. *J Orthop Res.* 2004;22:267-274.
13. Crossley KM, Cowan SM, McConnell J, Bennell KL. Physical therapy improves knee flexion during stair ambulation in patellofemoral pain. *Med Sci Sports Exerc.* 2005;37:176-183.
14. Devereaux MD, Lachmann SM. Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. *Br J Sports Med.* 1984;18:18-21.
15. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng.* 1983;105:136-144.
16. Hodges PW, Bui BH. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalogr Clin Neurophysiol.* 1996;101:511-519.
17. Karst GM, Willett GM. Onset timing of electromyographic activity in the vastus medialis oblique and vastus lateralis muscles in subjects with and without patellofemoral pain syndrome. *Phys Ther.* 1995;75:813-823.
18. Lam PL, Ng GY. Activation of the quadriceps muscle during semisquatting with different hip and knee positions in patients with anterior knee pain. *Am J Phys Med Rehabil.* 2001;80:804-808.
19. Lin F, Wang G, Koh JL, Hendrix RW, Zhang LQ. In vivo and noninvasive three-dimensional patellar tracking induced by individual heads of quadriceps. *Med Sci Sports Exerc.* 2004;36:93-101.
20. MacIntyre DL, Robertson DG. Quadriceps muscle activity in women runners with and without patellofemoral pain syndrome. *Arch Phys Med Rehabil.* 1992;73:10-14.
21. McConnell J. The management of chondromalacia patellae: a long-term solution. *Aust J Physiother.* 1986;32:215-223.
22. Morey-Klapsing G, Arampatzis A, Bruggemann GP. Choosing EMG parameters: comparison of different onset determination algorithms and EMG integrals in a joint stability study. *Clin Biomech (Bristol, Avon).* 2004;19:196-201.
23. On AY, Uludag B, Taskiran E, Ertekin C. Differential corticomotor control of a muscle adjacent to a painful joint. *Neurorehabil Neural Repair.* 2004;18:127-133.
24. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *J Orthop Sports Phys Ther.* 2003;33:639-646.
25. 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; discussion 956-967.
26. Riener R, Rabuffetti M, Frigo C. Stair ascent and descent at different inclinations. *Gait Posture.* 2002;15:32-44.
27. Salsich GB, Brechter JH, Powers CM. Lower extremity kinetics during stair ambulation in patients with and without patellofemoral pain. *Clin Biomech (Bristol, Avon).* 2001;16:906-912.
28. Sheehy P, Burdett RG, Irrgang JJ, VanSwearingen J. An electromyographic study of vastus medialis oblique and vastus lateralis activity while ascending and descending steps. *J Orthop Sports Phys Ther.* 1998;27:423-429.
29. Souza DR, Gross MT. Comparison of vastus medialis obliquus: vastus lateralis muscle integrated electromyographic ratios between healthy subjects and patients with patellofemoral pain. *Phys Ther.* 1991;71:310-316; discussion 317-320.
30. Tang SF, Chen CK, Hsu R, Chou SW, Hong WH, Lew HL. Vastus medialis obliquus and vastus lateralis activity in open and closed kinetic chain exercises in patients with patellofemoral pain syndrome: an electromyographic study. *Arch Phys Med Rehabil.* 2001;82:1441-1445.
31. Voight ML, Wieder DL. Comparative reflex response times of vastus medialis obliquus and vastus lateralis in normal subjects and subjects with extensor mechanism dysfunction. An electromyographic study. *Am J Sports Med.* 1991;19:131-137.
32. 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.
33. Witvrouw E, Sneyers C, Lysens R, Victor J, Bellemans J. Reflex response times of vastus medialis oblique and vastus lateralis in normal subjects and in subjects with patellofemoral pain syndrome. *J Orthop Sports Phys Ther.* 1996;24:160-165.
34. Worrell T, Connelly S, Hilvert J. VMO: VL ratios and torque comparisons at four angles of knee flexion. *J Sport Rehab.* 1995;4:264-272.