



Original Article

Comparative Evaluation of Core and Knee Extensor Mechanism Muscle Activation Patterns in a Stair Stepping Task in Healthy Controls and Patellofemoral Pain Patients

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ABSTRACT

Background: Patellofemoral pain (PFP) is a common affliction and complex clinical entity. Deficit in neuromotor control of the core may be a remote contributing factor to the development of PFPS. Comparative evaluation of core and extensor mechanism muscle activation patterns between healthy group and patients involved by patellofemoral pain syndrome (PFPS) in a stair stepping task is the aim of this study.

Methods: In this non-randomized interventional study fifteen males with PFPS and fifteen asymptomatic controls participated. Electromyographic (EMG) activity of Vastusmedialisobliquus (VMO), Vastuslateralis (VL), Gluteus medius (GMED), Gluteus Maximus (GMAX), Internal oblique (IO) and Erector spinae (ES) were recorded and EMG onsets were assessed in both stepping up (SU) and down (SD). The time of foot contact determined by a foot switch.

Results: During SU: Onset times of all muscles except, VL and ES in the controls were significantly less than PFPS group ($P<0.05$). In PFPS group the temporal sequence of ES, VL and VMO were different from control groups. During SD: Onset times of all muscles except, GMAX and ES in the control group were significantly less than PFP group ($P<0.05$). The sequence of muscle activity in both healthy and PFP groups were the same.

Conclusion: Our findings are in line with previous researches about the effects of core on function and control of lower extremity. Activation patterns of core and vasti muscles are different between control and PFPS group during stair stepping task. Designing exercises to correct inappropriate timing of core muscles may have a role in management of PFPS and it needs more future researches.

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Introduction

Patellofemoral pain syndrome (PFPS) is a common affliction affecting both athletes and general populations, especially in activities required repetitive lower limb loading [1]. 25% of knee athletic injuries that are treated

in the sport medicine clinics were related to PFPS [2].

Dye et al. named this syndrome black hole of orthopedics due to its unknown reason [3]. Although the development of PFPS is multi-factorial, abnormal tracking of the patella has been accepted as a most contributing factor. One proposed mechanism for abnormal patellar tracking is reduced control of quadriceps muscle in PFPS [4, 5]. This could be explained either by a delayed activity of Vastusmedialisobliquus (VMO) relative to Vastuslateralis (VL) or reduced force production capabilities of VMO

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relative to VL [4-6].

Patellar tracking is result of an interaction between function of near and remote muscles, passive structures and the neuromotor control systems [7]. Instability and reduced core strength has been implicated as being contributory to increase risk of lower extremity injuries. Exercise targeting the hip, Pelvis and trunk musculatures benefit individual with PFPS by improving strength and motor control of these regions [8, 9]. Since stability of trunk and pelvis is essential for limbs movement [8, 10], pelvic asymmetry in frontal plane and anterior pelvic tilt might result in lower limb injury. Therefore, pelvic asymmetry would be a predictive factor for knee injury or pathology [8-13].

Although, several researchers have suggested that knee joint could be considered as one of the victims of core instability and impaired trunk neuromuscular control [13], few studies have evaluated the effect of core and trunk neuromuscular control in individuals with PFPS. Some investigators have studied the activation timing of VM and gluteal muscles during stair climbing using electromyography (EMG). However, the results of these studies in the field of motor control are inconsistent [7, 14, 15].

Brindle et al. and Cowan et al. demonstrated a delayed EMG activity of gluteus medius (GM) relative to VM muscle in people with PFPS [7, 14]. In contrast, Boling et al. found no significant difference between GM and VM onset times in subjects with PFPS [15]. Furthermore most studies were done on relationship between motor control of GM and VM muscles with PFPS. But to date, little objective data are available that provide adequate rationale for control role of other core muscles that check pelvic in other planes.

Considering that, altered neuromotor control of the core have been proposed as a remote contributing factor to the development of PFPS [16] and in respect to stair negotiation is one of the most common painful activities in patients with PFPS [17, 18], and stepping exercise is suggested for intermediate and final phases of rehabilitation in PFPS [19], the purpose of this study was to identify the core and vasti temporal activation pattern in stair negotiation using EMG.

Methods

Fifteen males with PFPS and fifteen asymptomatic controls in a convenient sampling took part in this non-randomized interventional study. Subjects were matched in variables such as age, height and weight, and body mass index. The subjects in PFPS group with unilateral knee pain were included if they had anterior or retro patellar knee pain on at least, two of the following activities: prolonged sitting, climbing stairs, squatting, running and jumping. Also they were included if they had pain on patellar palpation, symptoms for at least 1 month, BMI between 18.5-24.9, an average pain level of 3 cm or less on a 10-cm visual analog scale (VAS) and insidious onset of symptoms unrelated to a traumatic event. All participants were aged 40 years or less to reduce the possibility of osteoarthritic changes in the patellofemoral

joint. Subjects should be score more than 10 on Functional Index Questionnaire (FIQ) provided that subject was able to step up stairs without taking rails.

Subjects from either group were excluded from participation if they had: (1) any history of pathology or disorder which might interfere with the kinetics or kinematics of trunk, hip, knee and ankle such as neuromuscular or central nervous system diseases that would impair gait (for example: vertigo). (2) Orthopedic problems for instance: A history of knee, ankle, hip and spine surgery, previous experience with patellar or hip dislocation/subluxation, history or clinical evidence of lower extremity, pelvis and spine fracture, meniscus or ligament injury, patellar tendon pathology, osteoarthritis, disc herniation or referred pain from the spine, any low back pain or sacroiliac dysfunction in the past 6 months, postural abnormality such as scoliosis, genu varum/valgum, flat foot or pes cavus, leg length asymmetry for more than 1 cm (3) Systemic diseases such as rheumatoid arthritis and diabetes.

Also, the professional athletes (exercise more than 2 hours a day or every other day) were excluded.

The study protocol was approved by Ethics Committee of the Tehran University of Medical Sciences and Health Services. Informed consent was obtained from all the participants.

Kinesiological EMG of Vastus medialis obliquus (VMO), Vastus lateralis (VL), anterior portion of the Gluteus medius (GMED), Gluteus Maximus (GMAX), Internal oblique (IO) and Erector spinae (ES) were recorded using surface electrodes (Silver/silver chloride) with an inter-electrode distance of 20 mm [20].

Electrode locations set as follows:

VMO - approximately 4 cm superior to and 3 cm medial to the superomedial patellar margin and orientated 55 degrees to the vertical [21].

VL - 10 cm superior and 6-8 cm lateral to the superior border of the patella and angled 15 degrees to the vertical [22].

GMED - 5 cm posterior to anterior superior iliac spine and 3-4 cm inferior to iliac crest [24].

GMAX - at the midpoint of a line running from the inferior lateral angle of the sacrum to the greater trochanter [23].

IO - 2 cm inferior and medial to the anterior superior iliac spine [24].

ES - on the erector spinae muscles in the L4 level and parallel to plumb axis of the spine [25].

Ground electrode was located on the right wrist of the participants over the radial styloid process.

Eight channels EMG system and foot switch (Blue myo, KYA Company, Iran) were used to record electromyographic activity and the time of foot contact with the step respectively. The muscle onset was determined relative to the moment of foot contact [7].

The stair- stepping task consisted of ascending and descending 2 steps (one foot on each step). Each step was 20 cm in height, 80 cm in width, with no handrails. Depth of first and second step was 30 cm and 60 cm respectively. Participants stood on the floor facing the stairs and 20

cm away from edge of the first step. The stair stepping task was performed barefooted while arms hanged at the side of the body. The patients were instructed to start ascending the steps immediately after hearing the audio signal of the X note timer, at their maximum self-selected speed with the involved lower extremity. Subjects in the control group started the stair stepping task with the same leg (right or left) as their counterpart match in the PFPS group [1, 7, 18, 26, 27].

The stair stepping down task was performed in the same way as stepping up but the subjects stood on the second step and 5 cm away from its edge.

Before data collection, subjects performed three practice trials of step up and down to familiarize with the task. Then, the subjects performed 3 test trials with 30 seconds of rest between each trial in order to prevent fatigue [1].

Sequence of ascending and descending the stairs were determined randomly by the examiner and mean of data in 3 test trials was used for analysis.

EMG data were sampled at 1000 Hz and full-wave rectified, then band-pass filtered between 20-500 Hz. Also, Foot switch signal was sampled at 1000 Hz. Using Matlab codes, the onset latency was determined by the temporal distance between the onset of foot switch signal and the point at which the amplitude of EMG activity reached 3 SDs above the baseline level and stayed for more than 30 milliseconds [28]. The determined onset by the computer algorithm was checked visually in the form of rectified, unfiltered EMG signal to detect noise and artifacts on analysis.

Statistical Analysis

Since results of Kolmogorov-Smirnov test show normal distribution curve, parametric methods were used. Independent t-test was used to compare muscle onset

between control and patients groups on ascending and descending stairs. One-way analysis of variance with repeated measures was used in order to determine the sequence of muscle activation during stair negotiation.

Results

Onset times of all muscles except VL and ES in the control group were significantly less than PFPS group during ascending stairs (Table 1). In addition, sequence of activity of ES, VL and VMO in PFPS group was different from control groups during stair ascending. (Table 2).

Onset times of all muscles except GMAX and ES in the control group were significantly less than PFPS group during descending stairs (Table 1). There was no significant difference between the two groups with regard to sequence of muscle activation during descending stairs (Table 2 and Figures 1 and 2).

Discussion

Our results showed that, during ascending stair, VMO, GMED, VL and GMAX muscles in the control group activated significantly before their counterparts in the PFPS group.

Also, during stair descending, VMO, GMED, VL and IO in the control group activated significantly earlier than their counterparts in the PFPS group. Individuals with PFPS also, displayed a delay onset of muscle activation relative to the control groups in both stair stepping up and down.

Based on our results, in the control group, the core muscles were activated before foot contact with the step in order to provide stability of kinetic chain and resist against its imposed perturbation. Our finding is consistent

Table 1: Comparison of muscle onset time between PFPS and control groups during stair stepping task

	Stepping Up			Stepping Down		
	CONTROL (Mean±SD)	PFPS (Mean±SD)	P	CONTROL (Mean±SD)	PFPS (Mean±SD)	P
VMO	-114.69±13.45	-89.39±38.04	0.026*	-211.84±61.17	-151.20±67.14	0.015*
VL	-102.16±20.03	-106.76±38.38	0.685	-182.84±43.10	-126.17±93.18	0.041*
GMED	-87.26±85.67	15.60±35.89	0.001*	-123.20±57.17	-30.26±58.37	0.001*
GMAX	-90.60±87.87	4.13±32.03	0.001*	-152.00±108.29	-93.26±46.42	0.064
IO	-236.20±119.46	-156.50±89.09	0.048*	-371.20±142.11	-271.06±66.28	0.020*
ES	-128.53±128.97	-107.00±92.38	0.603	-317.66±227.91	-227.33±111.98	0.179

Table 2: comparison of onset time of muscles during stair stepping task in both groups

		VM	VL	GMED	GMAX	IO	ES
Step Up	Control	* , †, ℓ -114.69±13.45	* , ¥, ¶ -102.16±20.03	† , ¥, ∅ -87.26±85.67	ϕ -90.60±87.87	ℓ, ¶, ∅, ϕ, ψ -236.20±119.46	ψ -128.53±128.97
	PFPS	* , †, ‡, ℓ -89.39±38.04	* , ¥, ∆ -106.76±38.38	† , ¥, ∞, ∅, λ 15.60±35.89	‡, ∆, ∞, ϕ, ж 4.13±32.03	ℓ, ∅, ϕ -156.50±89.09	λ, ж -107.00±92.38
Step Down	Control	* , †, ℓ -211.84±61.17	* , ¥, ¶, ff -182.84±43.10	† , ¥, ∅, λ -123.20±57.17	ϕ, ж -152.00±108.29	ℓ, ∅, ¶, ϕ -371.20±142.11	λ, ж, ff -317.66±227.91
	PFPS	†, ‡, ℓ, £ -151.20±67.14	¥, ¶, ff -126.17±93.18	† , ¥, ∞, ∅, λ -30.26±58.37	‡, ∞, ϕ, ж -93.26±46.42	ℓ, ¶, ∅, ϕ -271.06±66.28	£, □, λ, ж -227.33±111.98

*P<0.05 VMO vs VL; † P<0.05 VMO vs GMED; ‡ p< 0.05 VMO vs GMAX; ℓ P< 0.05 VMO vs IO; £ P<0.05 VMO vs ES; ¥ P<0.05 VL vs GMED; ¶ P<0.05 VL vs IO; ff P<0.05 VL vs ES; ∆ P<0.05 VL vs GMAX; ∅ P<0.05 GMED vs IO; λ P<0.05 GMED vs ES; ∞ P<0.05 GMED vs GMA; ϕ P<0.05 GMAX vs IO; ж P<0.05 GMAX vs ES; ψ P<0.05 IO vs ES

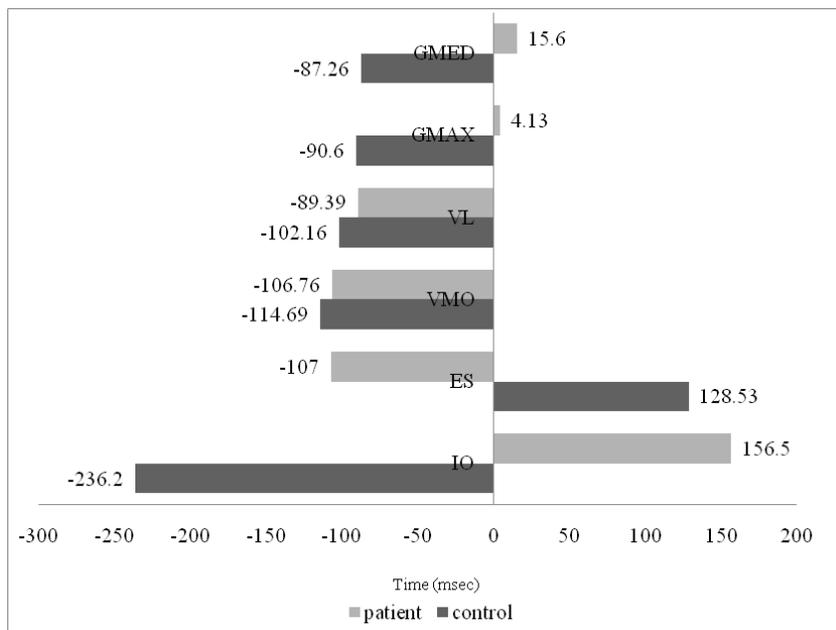


Figure 1: mean latency (onset time) and sequence of muscle activation for both group during stepping up.

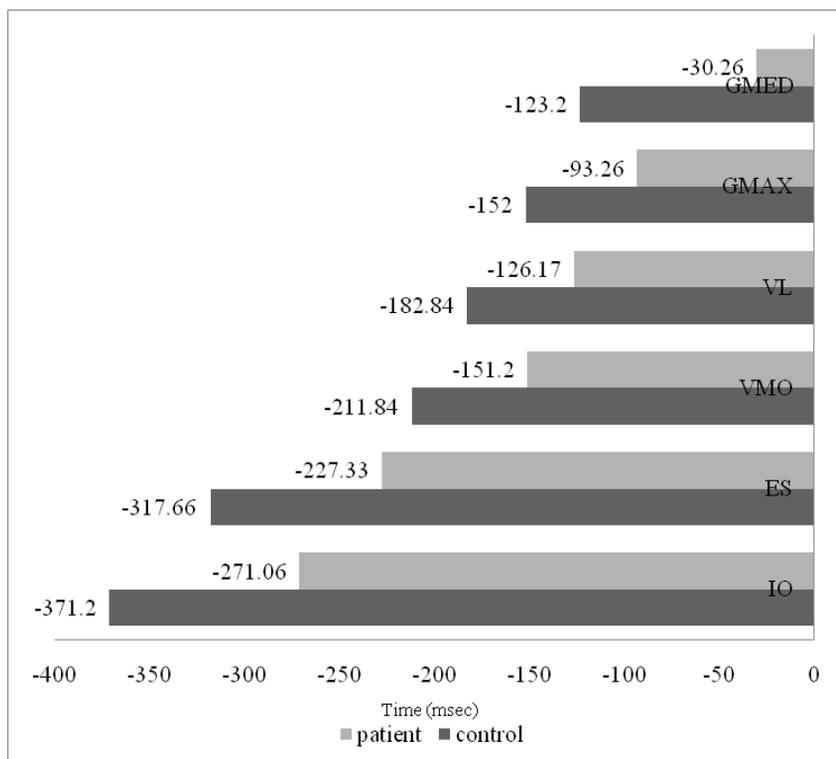


Figure 2: mean latency (onset time) and sequence of muscle activation for both group during stepping down.

with those of previous studies [14, 29, 30].

Cresswell et al. demonstrated that, prior to a predictable perturbation, immediate activation of core muscles (transverse abdominis, obliquus abdominis internus, obliquus abdominis externus, rectus abdominis and erector spinae) provide trunk stability [31]. This result also confirmed our finding.

In PFPS group GMAX and GMED demonstrated more delayed activity during ascending stair and their onset time occurred after heel strike. This finding concurs with previous research by Cowan et al. and Brindle et al. however differ from the finding of Boling et al. they report no significant difference in GMED onset time between

control and PFPS groups [7, 14, 15].

This is the first study which evaluates core muscle EMG activity in conjunction with quadriceps activity during a stair-stepping task, making it hard to compare our result with previous investigations. Alteration in motor control and onset time of core muscles was reported in patients with low back pain [32, 33]. Because, in this study, participants had no low back pain and knee was the site of pathology, difference in the onset of core muscles is a considerable finding.

Delay activation of core muscles in individuals with PFPS might be an adaptive or compensatory strategy due to change in knee motor control or may be a proximal

factor for the development of PFPS. As a result of the cross-sectional design of this study the mechanism of delayed core muscle activity cannot be established.

Sequence of Muscle Activation in Control Group during Stair Negotiation

In the healthy group sequence of muscle activation were IO, ES, VMO, VL, GMAX and GMED respectively during both phases of stair stepping. Significant difference was found between onset time of IO and other muscles during both phase of stair stepping. However, there was no significant difference between ES and IO onset times. This means that co-contraction of ES and IO might provide core stability. This finding is consistent with the results of previously mentioned studies indicating contraction of TrA and IO prior to perturbation providing postural stability [10, 35]. Several studies revealed that in healthy subjects IO and TrA contribute to spinal stability by either increasing intra-abdominal pressure (IAP) or by increasing tension in the thoracolumbar fascia (TLF) thus increasing spinal stiffness for inter-segmental control [34].

It has been suggested that the IO pre-activation plays an important role in providing core stability. Hodges et al. reported TrA and IO activation prior to increase in IAP [36]. Increase in IAP lead to increase in tension in the TLF and has been suggested to contribute to increased stability of the spine [32].

According to Belen'Kii, the central nervous system (CNS) can provide postural adjustments in advance of predictable perturbations to the body [37]. It could be suggested that nervous system controls spinal stability anticipating the moment of foot contact to the step through activating abdominal and paravertebral muscles.

On the other hand, ES muscle onset time, had the second rank during stair stepping task. Contraction of this muscle prior to movement of the lower extremity contributes to the stability of proximal part of kinetic chain, in addition their activation prior to internal or external perturbations provide trunk stability [10, 32].

Early "Feed-forward" activation of ES is considered to contribute to either control of center of mass displacement or control of acceleration during stepping down [34].

Feed forward trunk muscle activity has been proposed to control the orientation of the trunk in accordance with control center of mass [37].

In this study, there was no significant difference between onset times of Vasti during stair stepping. This result might indicate synchronized VMO and VL activity. Our result is consistent with previous studies which have demonstrated concurrent activity of Vasti muscles during various tasks in healthy group [5, 38, 39]. Moreover Cowan et al. reported that pain free subjects show simultaneous activity of Vasti during stair stepping [38].

VMO was the third muscle which activated during stair descent. The EMG onset of VMO occurred significantly earlier than VL. In the normal population it is proposed that recruitment of VMO should occur prior to the VL to ensure optimal patellar tracking [21].

Grabner stated that the medial components of the quadriceps have a smaller cross-sectional area than

their lateral counterparts and it may be necessary for VMO to be recruited earlier than the VL in order to overcome the larger lateral forces [40]. Our finding about sequence of activation of the medial and lateral components of quadriceps concurs with result of previous researches [5, 7, 14, 15].

Our results showed that onset of activity of the medial and lateral components of the quadriceps group occurred significantly prior to gluteal muscles in both phases of stair stepping task. This result is similar to those reported by Brindle et al. and Boling et al. [15, 16].

Astables 2 and 3 show, in healthy group, GMED and GMAX EMG onsets were almost simultaneous. Co-contraction of these muscles may provide hip stability during stair stepping.

Sequence of Muscle Activation in PFPS Group during Stair Negotiation

In patient group sequence of muscle activation were IO, ES, VL, VMO, GMAX and GMED respectively during ascending phase of stair stepping. However in this group sequence of muscle activation during descent phase were IO, ES, VMO, VL, GMAX and GMED respectively.

Onset of IO EMG occurred significantly before VMO, GMED and GMAX muscles during both phase of stair stepping. The earlier onset of IO can be due to role of this muscle in providing core stability as stated previously. No significant difference in onset time was found between IO and ES muscles. It could be suggested that both muscles activated at the same time in order to establish stability. Previous researches have shown that trunk muscle co-contraction was associated with an increase in trunk stiffness [41, 42].

The EMG onset of ES occurred significantly prior to gluteal muscles during ascending phase. In descending phase onset time of ES was not only before gluteal muscles but also before VMO muscle. In PFPS group simultaneous activation of ES and VMO can be attributed to change in motor control or adaptive strategies.

In ascent phase of stair stepping onset time of VL was significantly earlier than VMO, GMAX and GMED. Result of this experiment indicated anticipatory activity of Vasti before foot contact to the step in PFPS group, but VMO onset of activity occurred after that of VL. This may reflect change in preplanned strategy used by the CNS to control the patella. This finding is consistent with those of several previous studies [15, 21, 43].

In our study no difference was found between EMG onset of VL and VMO during descent phase in subject with PFPS. This results contrast with results of Cowan et al. and Boling et al. [5, 15]. The reasons for this discrepancy may be due to different speed of stair stepping task. In two previous studies subjects ascend and descend the stairs at a rate of 96 steps per minute, while in present study participants performed stair stepping task at self-selected speed.

On the other hand, in both stepping up and down, GMAX onset time was significantly earlier than GMED. In addition, Souza et al. demonstrated altered GMAX motor control in patients with PFPS and reported an

increased GMAX EMG when compared to pain free controls during stepping down [44]. These findings suggest a tendency in subjects with PFPS to use hip strategy more than healthy group.

Pain and Change in Motor Strategy

People with PFPS were found to have different motor strategy in stepping up relative to asymptomatic individuals. Change in motor programming as a result of pain may lead to change in motor strategy. This finding of an alteration in motor strategy concurs with previous researches by Matre et al. and Derbyshire et al. [45, 46].

Afferent inputs related to mechanoreceptors, which are present in skin, muscle and joint provide necessary information related to motor control and stability. Painful stimulus could disrupt the function of sensory receptors and thereby affecting motor strategy [47]. Findings of Gill and Callaghan consistent with hypothesis of this study [48].

Cowan et al. reported an altered motor control of both anterior and posterior portions of GM in individual with PFPS [7]. Findings of Cowan et al. agree with the result from the present study.

Biomechanical Outcomes of Altered Motor Strategy

Decreased core stability result from altered activity pattern of the muscles may lead to excessive motion of trunk in various planes and may affect pelvic posture and lower limb mechanics. The trunk and hip stabilizers may pre-activate to compensate trunk motion and control lower limb postures. Reduced pre-activation of the trunk and hip stabilizers may lead to excessive displacement of trunk in frontal plane and increased load to the knee. Decreased core stability and muscular synergism of the trunk and hip stabilizers may increase the injury secondary to lack of control of the center of mass [49].

Result of present study show change in activity pattern of core muscle in patient group, for example individuals in PFPS group demonstrated later onset of GMAX and GMED. Impairment of the neuromotor control of the GMED and GMAX can result in contralateral dropping of the pelvis, adduction and internal rotation of the hip, greater valgus force vector at the knee, altered tracking of patellofemoral joint, thereby contributing to patellofemoral joint pain [8, 14, 50]. Therefore latency in function of these muscles in weight acceptance of stance phase during stair stepping task need to be considered. Studies show that abductor muscles by a concentric contraction raised the pelvis on the contralateral side during stair climbing [51].

In our study, onset latency of GMAX and GMED were transferred from before foot contact with ground to after foot contact with ground, thus can impair posture and motor control.

It could be suggested that activity of muscles before foot contact with ground that act as an external perturbation necessary to provide stability of trunk and lower limb in weight acceptance phase. Otherwise excessive displacement of trunk similar to an inverted pendulum may lead to exertion of abnormal forces to the knee and

in prolonged time lead to PFPS. A number of studies have reported excessive displacement of trunk in patients with PFPS during stair climbing. Dierks et al. reported that excessive displacement of the trunk in to the affective limb may have been an adaptive strategy used to compensate neuromotor control of muscles related to stabilizing the pelvis such as hip abductors [52]. In this study, kinematic of movement were not evaluated, therefore further study is needed to identify possible changes in trunk movement.

Altered Motor Strategy in Patients with PFPS

Few studies have investigated the comparison of motor strategies between healthy and patients with PFPS. Nadeau et al. demonstrated that patients with anterior knee pain presenting increase in hip extensor moment during gait. Increase in hip extensor moment can be considered as a strategy used by PFPS subjects to compensate decrease in knee extensor moment. These authors stated that PFPS subjects used hip strategy during gait [53].

Souza reported increase GMAX EMG in PFPS subjects when compared to pain-free control during descent phase of stair stepping task [44]. This finding is in agreement with previously results indicating tendency of motor control system of patient individuals to use of hip strategy.

In our study, finding of a delay in GMED relative to GMAX in subjects with PFPS provide support for other studies that suggested use of hip strategy in individual with anterior knee pain [53].

According to present study, it can be mentioned that besides regain of strength of knee extensor moment and appropriate timing of VMO muscles, clinician should incorporate exercises to correct inappropriate timing of GMAX and GMED muscles in to rehabilitation program.

This study demonstrated a link between PFPS and altered core muscle activity which signifies attention to biomechanics and motor control of knee and core muscles as an important target in rehabilitation of patients with PFPS.

Conclusion

The result of our investigation indicate that activation patterns of core and vasti muscles are different between pain free control and PFPS group during stair stepping task. Exercises to correct inappropriate timing of core muscles may have a role in management of PFPS.

Conflict of Interest: None declared.

References

1. Cowan SM, Crossley KM. Does gender influence neuromotor control of the knee and hip? *Journal of Electromyography and Kinesiology* 2009;19(2):276-82.
2. Devereaux M, Lachmann S. Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. *British journal of sports medicine* 1984;18(1):18-21.
3. Dye SF, Stabily HU, Biedert RM, Vaupel GL. The mosaic of pathophysiology causing patellofemoral pain: Therapeutic implications. *Operative Techniques in Sports Medicine* 1999;7(2):46-54.
4. Stensdotter A-K, Hodges P, Öhberg F, Häger-Ross C. Quadriceps EMG in open and closed kinetic chain tasks in women with patellofemoral pain. *Journal of motor behavior* 2007;39(3):194-202.

5. Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Delayed onset of electromyographic activity of vastusmedialisobliquus relative to vastuslateralis in subjects with patellofemoral pain syndrome. *Archives of physical medicine and rehabilitation*2001;82(2):183-9.
6. Powers CM. Rehabilitation of patellofemoral joint disorders: a critical review. *Journal of Orthopaedic & Sports Physical Therapy*1998;28(5):345-54.
7. Cowan SM, Crossley KM, Bennell KL. Altered hip and trunk muscle function in individuals with patellofemoral pain. *British journal of sports medicine*2009;43(8):584-8.
8. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IM. Core stability measures as risk factors for lower extremity injury in athletes. *Medicine & Science in Sports & Exercise*2004;36(6):926-34.
9. Mascal CL, Landel R, Powers C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *Journal of Orthopaedic & Sports Physical Therapy*2003;33(11):647-60.
10. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Physical Therapy*1997;77(2):132-42.
11. Ireland ML. The female ACL: why is it more prone to injury? *Orthopedic Clinics of North America*2002;33(4):637-51.
12. Tanaka K, Miyashita K, Urabe Y, Ijiri T, Takemoto Y, Ishii Y, et al. Characteristics of trunk lean motion during walking in patients with symptomatic knee osteoarthritis. *The Knee*2008;15(2):134-8.
13. Zazulak B, Cholewicki J, Reeves NP. Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *Journal of the American Academy of Orthopaedic Surgeons*2008;16(9):497-505.
14. Brindle TJ, Mattacola C, McCrory J. Electromyographic changes in the gluteus medius during stair ascent and descent in subjects with anterior knee pain. *Knee Surgery, Sports Traumatology, Arthroscopy*2003;11(4):244-51.
15. Boling MC, Bolgla LA, Mattacola CG, Uhl TL, Hosey RG. Outcomes of a weight-bearing rehabilitation program for patients diagnosed with patellofemoral pain syndrome. *Archives of physical medicine and rehabilitation*2006;87(11):1428-35.
16. Fulkerson JP. Diagnosis and treatment of patients with patellofemoral pain. *The American journal of sports medicine*2002;30(3):447-56.
17. Vack HJ, Nielsen DH, Shurp DG. Kinetic patterns during stair ascent in patients with transtibial amputations using three different prostheses. *JPO: Journal of Prosthetics and Orthotics*1999;11(3):57-62.
18. Brechter JH, Powers CM. Patellofemoral joint stress during stair ascent and descent in persons with and without patellofemoral pain. *Gait & posture*2002;16(2):115-23.
19. Brask B, Lueke RH, Soderberg GL. Electromyographic analysis of selected muscles during the lateral step-up exercise. *Physical Therapy*1984;64(3):324-9.
20. De Luca CJ. The use of surface electromyography in biomechanics. *Journal of applied biomechanics*1997;13:135-63.
21. Cowan SM, Hodges PW, Bennell KL. Anticipatory activity of vastuslateralis and vastusmedialisobliquus occurs simultaneously in voluntary heel and toe raises. *Physical Therapy in Sport*2001;2(2):71-9.
22. Kendal FP, McCreary EK. *Muscle testing and function with Posture and Pain*. 5th ed. Philadelphia: Lippincott Williams & Wilkins; 2005
23. Hungerford B, Gilleard W, Hodges P. Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. *Spine*2003;28(14):1593-600.
24. Marshall P, Murphy B. The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. *Journal of Electromyography and Kinesiology*2003;13(5):477-89.
25. Hodges P, Cresswell A, Thorstensson A. Preparatory trunk motion accompanies rapid upper limb movement. *Experimental Brain Research*1999;124(1):69-79.
26. Salsich GB, Brechter JH, Powers CM. Lower extremity kinetics during stair ambulation in patients with and without patellofemoral pain. *Clinical Biomechanics*2001;16(10):906-12.
27. Grenholm A, Stensdotter A-K, Häger-Ross C. Kinematic analyses during stair descent in young women with patellofemoral pain. *Clinical Biomechanics*2009;24(1):88-94.
28. Peter Konard. *The ABC of EMG: a practical introduction to Kinsiological Electromyography*. 1st ed. Noraxon INC: 2005,42.
29. Lyons K, Perry J, Gronley JK, Barnes L, Antonelli D. Timing and relative intensity of hip extensor and abductor muscle action during level and stair ambulation. An EMG study. *Physical Therapy*1983;63(10):1597-605.
30. Soderberg GL, Dostal WF. Electromyographic study of three parts of the gluteus medius muscle during functional activities. *Physical therapy*1978;58(6):691-6.
31. Cresswell A, Oddsson L, Thorstensson A. The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research*1994;98(2):336-41.
32. Richardson CA, Hodges PW, Hides J. *Therapeutic exercise for lumbopelvic stabilization. A Motor Control Approach for the Treatment and Prevention of Low Back Pain*. 2nd ed. Philadelphia: Churchill Livingstone; 2004.
33. Boyling JD, Jull GA, Twomey LT. *Grieve's Modern Manual Therapy. The vertebral column*. 3rd ed. Churchill Livingstone; 2004
34. Hodges PW, Richardson CA. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. *Archives of physical medicine and rehabilitation*1999;80(9):1005-12.
35. Gibson J, McCarron T. Feedforward muscle activity: an investigation into the onset and activity of internal oblique during two functional reaching tasks. *Journal of Bodywork and Movement Therapies*2004;8(2):104-13.
36. Tsao H, Hodges PW. Immediate changes in feedforward postural adjustments following voluntary motor training. *Experimental brain research*2007;181(4):537-46.
37. Aruin AS, Latash ML. Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research*1995;103(2):323-32.
38. Cowan SM, Bennell KL, Hodges PW, Crossley KM, McConnell J. Simultaneous feedforward recruitment of the vasti in untrained postural tasks can be restored by physical therapy. *Journal of Orthopaedic Research*2003;21(3):553-8.
39. Karst GM, Willett GM. Onset timing of electromyographic activity in the vastusmedialis oblique and vastuslateralis muscles in subjects with and without patellofemoral pain syndrome. *Physical Therapy*1995;75(9):813-23.
40. Grabiner M, Koh T, Miller G. Fatigue rates of vastusmedialis oblique and vastuslateralis during static and dynamic knee extension. *Journal of orthopaedic research*1991;9(3):391-7.
41. Lee PJ, Rogers EL, Granata KP. Active trunk stiffness increases with co-contraction. *Journal of Electromyography and Kinesiology*2006;16(1):51-7.
42. Kavcic N, Grenier S, McGill SM. Determining the stabilizing role of individual torso muscles during rehabilitation exercises. *Spine*2004;29(11):1254-65.
43. Santos E, Bessa S, Lins C, Marinho A, Silva K, Brasileiro J. Electromyographic activity of vastusmedialisobliquus and vastuslateralis muscles during functional activities in subjects with patellofemoral pain syndrome. *Brazilian Journal of Physical Therapy*2008;12(4):304-10.
44. Souza RB. *The Influence of Hip and Femur Kinematics on Patellofemoral Joint Dysfunction*: ProQuest; 2008.
45. Matre DA, Sinkjaer T, Svensson P, Arendt-Nielsen L. Experimental muscle pain increases the human stretch reflex. *Pain*1998;75(2):331-9.
46. Derbyshire SW, Jones AK, Gyulai F, Clark S, Townsend D, Firestone LL. Pain processing during three levels of noxious stimulation produces differential patterns of central activity. *Pain*1997;73(3):431-45.
47. Barrack Lephart SM, Fu FH. *proprioception and neuromuscular control in joint stability*. Human Kinetics; 2000.
48. Gill KP, Callaghan MJ. The measurement of lumbar proprioception in individuals with and without low back pain. *Spine*1998;23(3):371-7.
49. Myer GD, Chu DA, Brent JL, Hewett TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clinics in sports medicine*2008;27(3):425-48.

50. Piva SR, Goodnite EA, Childs JD. Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *Journal of orthopaedic & sports physical therapy* 2005;35(12):793-801.
51. Nadeau S, McFadyen BJ, Malouin F. Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? *Clinical Biomechanics* 2003;18(10):950-9.
52. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *Journal of orthopaedic & sports physical therapy* 2008;38(8):448-56.
53. Nadeau S, Gravel D, Hebert LJ, Arsenault AB, Lepage Y. Gait study of patients with patellofemoral pain syndrome. *Gait & posture* 1997;5(1):21-7.