Backward walking effects on activation pattern of leg muscles in young females with patellofemoral pain syndrome

Osama R Abdelraouf, Amr A Abdel-Aziem, Alaa A Ahmed, Nagui S Nassif, Ayman G Matar

Abstract

Background/Aims: Little is known regarding the activation of knee and hip muscles during backward walking in patellofemoral pain syndrome. This study examineD the effects of backward walking and forward walking on the activation of knee extensors, hip abductors, and adductors in patients with patellofemoral pain syndrome.

Methods: A total of 20 females with patellofemoral pain syndrome and 20 age-matched typically healthy female controls participated in this study. Surface electromyography from vastus medialis obliquus, vastus lateralis, gluteus medius, and adductor longus muscles were collected during forward walking and backward walking.

Findings: The patellofemoral pain syndrome group had a significantly higher normalised root mean square of the vastus medialis obliquus, vastus lateralis and gluteus medius muscles (P=0.001), without significant difference in adductor longus muscle activity during backward walking versus forward walking (P=0.098). During forward walking, the patellofemoral pain syndrome group showed significantly higher activation of adductor longus muscle (P=0.001) and significantly lower activation of the gluteus medius muscle (P=0.002) compared to the healthy group. During backward walking there was a significant increase in the vastus medialis obliquus and adductor longus muscle activity of the patellofemoral pain syndrome group compared to the control group (P=0.003, 0.001) respectively.

Conclusions: Clinicians should consider backward walking training to increase the muscle strength of knee extensors and hip abductors when developing rehabilitation programmes for patients with patellofemoral pain syndrome.

Key words: ■ Backward walking ■ Female ■ Muscular activities ■ Patellofemoral pain syndrome

Submitted: 22 November 2017; accepted following double blind peer review: 12 April 2018

Patellofemoral pain syndrome is characterised by an anterior or retropatellar pain during ascending or descending stairs, squatting and running (Wilson, 2007). Patellofemoral pain syndrome has a prevalence of 7–40% and is classified to be an overuse condition, which commonly affects highly active young people and females (Zhang et al, 2014). The risk for developing patellofemoral pain syndrome is gender-specific, with females being twice as likely to develop the condition compared to males (Boling et al, 2010). It could progress into chronic diseases such as chondromalacia patella or patellofemoral arthritis if proper treatment is not provided (Crossley, 2014).

Unfortunately, the specific aetiology of patellofemoral pain syndrome is not clearly understood (Dutton et al, 2014), with multiple risk factors reported to be associated with the development of patellofemoral pain syndrome, such as weakness of the quadriceps muscle, mal-tracking of the patella, soft tissue stiffness, and increasing the Q-angle (the angle of the knee from a frontal view) (Bolgla and Boling, 2011). Patients with patellofemoral pain syndrome have lower electromyography activity of vastus medialis obliquus to vastus lateralis ratio in comparison with typically healthy individuals. This muscular imbalance makes the vastus medialis obliquus cannot antagonise the vastus lateralis muscle that results in excessive lateral patellar tracking which causes articular surface erosion and induces pain (Powers, 2000). Additionally, recent evidence shows that proximal factors in the form of abnormal hip kinematics and hip muscle dysfunction,

Osama R Abdelraouf
Assistant professor, Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

Amr A Abdel-Aziem
Professor, Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

Alaa A Ahmed
Assistant Lecturer, Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

Nagui S Nassif
Professor, Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

Ayman G Matar
Lecturer, Department of Biomechanics, Faculty of Physical Therapy, Cairo University, Giza, Egypt

Correspondence to:
Amr A Abdel-Aziem

Email:
amralmaz@yahoo.com; amralmaz74@gmail.com

especially weakness of the hip abductors and external rotators, are linked to patellofemoral pain syndrome (Moradi et al, 2014; Davis and Powers, 2010).

Backward walking has been used recently not only for physical fitness, but also for many rehabilitation purposes in patients with knee complex affection (Hoogkamer et al, 2014). It helps to reduce stress to injured joints and increases knee extensor strength (Threlkeld et al, 1989). The neural control mechanisms of backward walking and forward walking patterns are likely to depend mostly on subcortical components (e.g. brain stem and spinal central pattern generators) (Meyns et al, 2014). The normal locomotor programme that is required to produce backward walking is different than forward walking (Thorstensson, 1986). Additionally, a simple reversal of motor patterning is not evident when switching from forward walking to backward walking (Winter et al, 1989). There was significant reduction in gait speed, stride length and cadence and longer double limb support duration during backward walking versus forward walking (Elboim-Gabyzon and Rotchild, 2017).

Joshi et al (2015) reported that backward walking training is valuable in patients with patellofemoral pain syndrome. The peak patellofemoral joint reaction force was found to be lower during backward running compared to forward running at the same speed (Roos et al, 2012). Additionally, backward walking training reduced pain severity and improved functional levels when incorporated as a therapeutic regime in those patients (Saurabh, 2012). Khyatee et al (2013) reported an increased knee extensor strength after integration of backward walking into the rehabilitation protocol.

There are significant changes in the average electromyography activity of rectus femoris, hamstrings, and gastrocnemius muscles during backward walking vs forward walking (Chen et al, 2000). Backward walking involves special patterns of muscle activation that overcome the harmful compressive forces at joints such as the knee joint (Flynn and Soutas-Little, 1993). At the early stance of forward walking, there is coactivation of both flexors and extensors at the hip, knee and ankle. However, during backward walking there is activation of knee extensors and ankle plantarflexors (Thorstensson, 1986; Grasso et al, 1998). The average electromyography activity over one gait cycle was higher in backward walking vs forward walking, which increases the energy expenditure (Grasso et al, 1998). The eccentric activity and decelerating function of the quadriceps is exchanged by an isometric activity and stabilising function during single stance during backward walking (Flynn and Soutas-Little, 1993).

Although females with patellofemoral pain syndrome display a greater ipsilateral trunk lean, hip adduction (Noehren et al, 2012), excessive knee valgus (Herrington, 2014), and pronated foot (Barton et al, 2010), which create abnormal stress distribution across the patellofemoral joint (Feller et al, 2007), previous studies examined the muscle activation patterns of the hip and knee muscles during backward walking in healthy populations. There is a gap in the literature regarding the activation pattern of these muscles in individuals with patellofemoral pain syndrome during backward walking vs forward walking. Therefore, this study aimed to investigate the myoelectric activities of the vastus medialis obliquus, vastus lateralis, gluteus medius and adductor longus muscles in patients with patellofemoral pain syndrome during backward walking and forward walking, and compared them with typically healthy participants. It was hypothesised that backward walking would increase the myoelectric activities of the vastus medialis obliquus, vastus lateralis, gluteus medius and adductor longus muscles compared to forward walking.

METHODS

Participants

A total of 20 females with unilateral patellofemoral pain syndrome and 20 typically healthy females participated in this cross-sectional study. The criteria used for the diagnosis of patellofemoral pain syndrome were:

- Aged between 18 and 35 years to reduce the possibility of osteoarthritis (Cowan et al, 2001)
- Diagnosed with patellofemoral pain by a medical doctor
- Had anterior or retropatellar knee pain
- Reported that at least two of the following activities exacerbated their symptoms: prolonged sitting, ascending or descending stairs, squatting, kneeling
- Did not show clinical evidence of a current knee condition other than patellofemoral pain syndrome (Nijs et al, 2006; Song et al, 2015)
- Pain score ranged from 2–5 on the 10-cm visual analogue scale (Herrington, 2013).

The demographic characteristics of both groups are illustrated in *Table 1*.

Participants were excluded if they had clinical evidence of meniscal or ligamentous injury, patellar subluxation or dislocation, history of recent knee or any lower limb surgery, or spinal referred pain (Cowan et al, 2001). The control group included typically healthy females with no musculoskeletal or neurologic problems, no previous history of trauma or pain in the knee or surgery in the lower limb, and zero score in the 10-cm visual analogue scale regarding the patellofemoral joint.

Ethical approval

The study was conducted in accordance with the Declaration of Helsinki and approved by the Committee of Faculty of Physical Therapy, Cairo University (Approval No. P.T.REC/012/00808) and all participants signed a consent form before beginning of the study.

Assessment tool

An eight channel portable myomonitor IV EMG System (Delsys Inc, Boston) was used to measure the myoelectric activities of the vastus medialis obliquus, vastus lateralis, gluteus medius and adductor longus during forward walking and backward walking. Each channel is connected to a 41 x 20 x 5 mm single differential electrode, with two silver contacts bars and 10 mm inter-electrode spacing for optimal signal detection and consistency. For the vastus medialis obliquus and vastus lateralis muscle electrode placement, a reference line connecting the anterior superior iliac spine to the centre of the patella was determined while the participant sat with their legs fully extended, and the trunk and thighs at right angle with the tested knee slightly flexed. The vastus medialis obliquus electrode was placed approximately 4 cm proximal and medial to the superomedial border of the patella in a 50–55° angle to the reference line. The vastus lateralis electrode was placed at approximately 10 cm proximal to the superolateral border of the patella oriented at 15–20° to the reference line (Miao et al, 2015). The adductor longus muscle electrode was placed on the anteromedial aspect of the thigh in the proximal one third of the distance between the symphysis pubis and the adductor tubercle of the femur with the participant lying supine (Aminaka et al, 2011), while the gluteus medius muscle electrode was placed at proximal one third of the distance between the iliac crest and the greater trochanter (Song et al, 2015) and the reference electrode was placed over the tibial tuberosity.

Procedure

All participants received a brief orientation about the nature and significance of the study, equipment and tasks to be performed. Since backward walking is an unaccustomed task for most people, a Biodex Gait trainer (Biodex Medical Systems, Inc, Shirley, NY) was used to familiarise the participants with backward walking before testing. The participant was instructed to hold the handrails then the speed of the gait trainer was increased slowly till reaching 3 km/hour with hands free. Before electromyography electrode placement, the skin was shaved when needed and cleaned with isopropyl alcohol 70% to remove excess oils and debris. Electrodes were fixed to the skin with the use of Delsys adhesive electrode interface, which promotes a high-quality electrical connection between the sensor bars and the skin, minimising motion artifacts.

The maximum voluntary isometric contraction measurement was recorded for each of the tested muscles. This was necessary to allow between-participant comparisons through normalising the electromyography activity during the performed task to the maximum voluntary isometric contraction. Three trials were performed for each muscle; each was maintained for 6 seconds and there was a 30-second rest period between trials to avoid possible fatigue (Bolgla et al, 2011). Verbal encouragement and visual feedback were used to ensure that maximum effort was provided through the whole measuring process.

Table 1. Demographic characteristics of participants

	Patellofemoral pain syndrome group Mean, standard deviation	Control group Mean, standard deviation	*P* value
Age (years)	21.4, 2.32	20.30, 1.33	0.106
Weight (kg)	65.10, 10.60	63.70, 6.91	0.660
Height (m)	1.62, 0.07	1.63, 0.06	0.624
Body mass index (kg/m^2)	24.92, 3.83	24.04, 2.44	0.438

P>0.05 means non-significant difference

Regarding the vastus medialis obliquus and vastus lateralis muscles, the participant was seated at the edge of the plinth with both hips and knees flexed to 900, with both upper limbs kept beside the trunk and used for stabilisation. While the researcher's hand was placed 2.5 cm above the medial malleolus to provide resistance to knee extension, the participant was then instructed to extend her knee and push against the applied resistance as hard as possible for 6 seconds (*Figure 1*). To measure the maximum voluntary isometric contraction of the adductor longus muscle, the participant was instructed to squeeze a medium sized ball placed between both knees as hard as possible for 6 seconds while seated on a chair with both feet resting on the floor and holding onto the chair with both hands (*Figure 2*).

For the gluteus medius muscle, the participant assumed a side lying position on the untested limb, which was flexed at the hip and knee joints for stability and comfort. A belt was used to fix the pelvis to the testing table to minimise possible compensations. The upper (tested) limb rested on a pillow with the knee joint in full extension and hip in a neutral position. The examiner's hand provided manual resistance above the participant's knee, then the participant was instructed to push the limb upward in abduction for 6 seconds (*Figure 3*).

Electromyography recording for the forward walking trials was conducted by asking the participant to walk on the Biodex Gait trainer. The speed was increased gradually until reaching the predetermined testing speed (3km/hour), then electromyography acquisition was triggered from the host laptop. Three forward walking trials were performed each for 30

Figure 1. Recording the maximum voluntary isometric contraction of the vastus medialis obliquus and vastus lateralis muscles

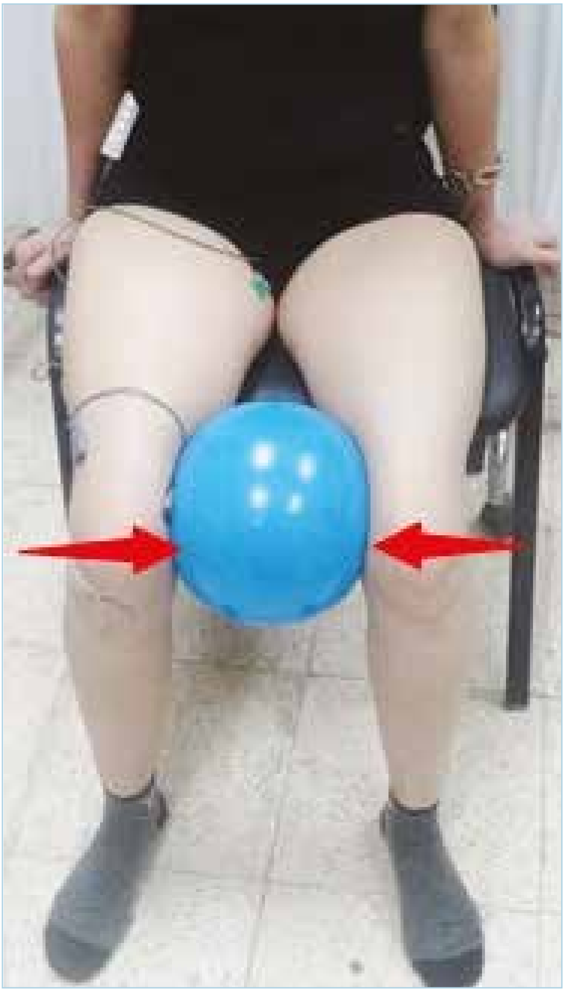

Figure 2. Recording the maximum voluntary isometric contraction of the adductor longus muscle

seconds. The participant was given a rest period of 60 seconds, then the belt direction was reversed. The same protocol of forward walking was followed during backward walking (*Figure 4*). The participant was instructed to report any dizziness, increased pain or discomfort. The order of forward walking and backward walking trials was random to avoid the learning effect. Data was sampled at 1000 Hz, filtered with 20–450 Hz band pass filter. The root mean square value was calculated for the three trials of maximum voluntary isometric contraction, forward walking and backward walking for the four tested muscles. The average root mean square values of the three trials of maximum voluntary isometric contraction, forward walking and backward walking were then calculated and normalised according to the following equation: Normalised root mean square = [(Average root mean square during activity/Average root mean square of maximum voluntary isometric contraction) x100].

Data analysis

Data were analysed using Statistical Package for the Social Sciences version 20.0. The sample size was determined using power analysis statistical test. The data were screened for normality assumption and homogeneity of variance. This exploration was done as a prerequisite for parametric calculations of the analysis of difference. The Shapiro-Wilk test showed that the data were normally distributed.

Multivariate analysis of variance was used to compare the normalised root mean square values (%) of the vastus medialis obliquus, vastus lateralis, gluteus medius and adductor longus in both walking directions within each group and between groups. Multiple pairwise comparison tests with subsequent Bonferroni adjustment were conducted to detect the source of significance for each of the dependent variables. The family-wise alpha level was set at 0.05. The independent t-test was conducted to detect any significant difference in the baseline characteristics (age, weight, height, and body mass index) between both groups. The data were represented as mean ± standard deviation.

RESULTS

There was no significant difference between both groups in terms of age, weight, height, and body mass index (P=0.106, 0.660, 0.624, 0.438), respectively, as shown in *Table 1*. Regarding the effect of walking direction, the patellofemoral pain syndrome group showed a significant increase in electromyography activity of the vastus medialis obliquus, vastus lateralis and gluteus medius muscles (P=0.001), without significant increase in the adductor longus muscle (P=0.098) during backward walking versus

Figure 3. Recording the maximum voluntary isometric contraction of the gluteus medius muscle muscles

Figure 4. Walking trial

forward walking. The percentage of increase of the vastus medialis obliquus muscle normalised root mean square mean value was 100.36% during backward walking versus forward walking. Additionally, the percentage of increase of the normalised electromyography activity of the vastus lateralis muscle during backward walking was 50.27%. The normalised root mean square mean value of gluteus medius muscle increased during backward walking by 27.89% versus forward walking, as shown in *Table 2*.

During backward walking, there was a significant increase in the electromyography activity of the vastus medialis obliquus and adductor longus muscle of the patellofemoral pain syndrome group compared to the control group (*P*=0.003, 0.001) respectively, there was no significant difference in the electromyography activity of the vastus lateralis, and gluteus medius muscle between both groups (*P*=0.900, 0.169) respectively. During forward walking, there was no significant difference in the electromyography activity of both the vastus medialis obliquus and vastus lateralis muscle between both groups (*P*=0.449, 0.768) respectively. The gluteus medius normalised root mean square mean value was significantly lower in the patellofemoral pain syndrome group compared to the control group (*P*=0.002). However, the adductor longus muscle showed a significant increase in electromyography activity in the patellofemoral pain syndrome group compared to the control group (*P*=0.001).

DISCUSSION

The findings of this study revealed a significant increase in the electromyography activities of the vastus medialis obliquus, vastus lateralis and gluteus medius muscles, without significant difference in adductor longus muscle activity during backward walking versus forward walking of the patellofemoral pain syndrome group. The increased electromyography activity of knee extensors, hip abductors, and adductors may be linked to the increased cortical activation during backward walking, as there is increasing oxygenated hemoglobin concentration in the supplementary motor area, precentral gyrus, and the superior parietal lobule during backward walking versus forward walking (Kurz et al, 2012). This could be explained by the findings of Shibuya et al (2014), who found a direct relation between cortical activation indicated by the levels of oxygenated haemoglobin and the amplitude of the electromyography activity.

The increased knee extensor electromyography activity may be attributed to changing the type of activation during backward walking. Backward walking is considered as a time-reversed copy of forward walking, where the forward walking stance

Table 2. The normalised root mean square values for muscles during forward walking and backward walking

	Patellofemoral pain syndrome group Mean, standard deviation			Control group Mean, standard deviation		
Muscles	**Forward walking**	**Backward walking**	***P* value**	**Forward walking**	**Backward walking**	**P value**
Vastus medialis obliquus	25.36, 6.75	50.88, 9.42	0.001*	27.45, 7.15	42.54, 10.79	0.001*
Vastus lateralis	26.49, 8.39	39.80, 11.46	0.001*	25.49, 8.16	39.38, 13.70	0.001*
Gluteus medius	30.58, 5.49	40.26, 7.06	0.001*	39.28, 11.08	44.10, 10.11	0.085
Adductor longus	65.30, 8.17	71.17, 9.53	0.098	43.16, 10.83	52.31, 14.72	0.011*

**means significant difference (P<0.05)*

phase starts with heel strike and ends with toes contact while the backward walking stance starts with toes contact and ends with heel off. This means that the knee joint angular displacement curve is reversed during the backward walking stance phase. During forward walking, the knee has undergone flexion just after heel strike during loading response. In contrast, during backward walking the knee joint is initially flexed at the toes contact then it continues to extend during the most of the stance phase (Lee et al, 2013).

This reversal of knee joint kinematics leads to changing the type of quadriceps muscle activation. The early knee flexion during forward walking is controlled by the eccentric activation of the knee extensors to provide shock absorption in response to ground impact (Neumann, 2010). However, during backward walking the knee extension during the early stance is achieved by a concentric contraction of the quadriceps muscle to prevent the descent of the body's centre of gravity and propel the body backward (Lee et al, 2013). The conversion of eccentric quadriceps activation during forward walking to concentric activation during backward walking may explain the increased vastus medialis obliquus, and vastus lateralis muscles electromyography activities found during backward walking.

Another possible explanation for the increased vastus medialis obliquus and vastus lateralis muscle activity is the leg stiffening mechanism adopted in response to knee instability during backward walking. According to Katsavelis et al (2010), the knee's reduced range of motion during backward walking may be a natural response to the greater instability encountered during this walking pattern. They also added that forward walking and backward walking may not differ in terms of a simple reversal. Moreover, the increased muscular activities during backward walking might have led to an increase in the magnitude of variability that was observed at the knee joints.

Regarding the patellofemoral pain syndrome group, the increased electromyography activity of the vastus medialis obliquus and vastus lateralis muscle may be attributed to pain reduction during backward walking. Patients with anterior knee pain demonstrated greater quadriceps muscle inhibition with higher pain levels (Surer et al, 1998). Pain levels significantly reduced in patients with patellofemoral pain syndrome after 4 weeks of a backward walking training programme (Saurabh, 2012); therefore, it can be assumed that increased quadriceps activation during backward walking may be because of the reduction of quadriceps inhibition from pain (Saurabh, 2012). The increased vastus medialis obliquus and vastus lateralis muscle activities in the control group are consistent with the findings of Grasso et al (1998), who found that the electromyography activity of vastus lateralis muscle was higher in healthy subjects during backward walking compared to that recorded during forward walking. Moreover, Han (2005) reported increased electromyography activity levels of the vastus medialis obliquus and vastus lateralis muscles in backward walking versus forward walking at all tested treadmill inclines.

The greater activation of the gluteus medius muscle during backward walking may be an attempt to provide more control during this unstable gait pattern. The supporting function of a muscle during walking is defined by its contribution to the vertical acceleration of the centre of gravity against gravity. During forward walking, the gluteus medius muscle is considered as one of the main supporting muscles during single limb support (Anderson and Pandy, 2003). Moreover, during backward walking there is increased gluteus medius muscle contribution to the vertical acceleration of the centre of gravity during the single limb support interval compared to forward walking (Jansen et al, 2012). This may imply that the supporting function of gluteus medius during single limb support is greater during backward walking, which requires a higher level of muscular activity.

In relation to the pelvic motion during backward walking, there is a reduction in pelvis stability during backward walking vs forward walking (Wu et al, 2015). Thus, based on Katsavelis et al (2010) suggestion, greater muscular activation is required to minimise joint displacement during the unstable backward walking pattern; this slight decrease in pelvic motion may be the product of the increased activity of gluteus medius muscle. This finding could explain the non-significant increase in gluteus medius muscle activity in the control group. The non-significant increase in the gluteus medius muscle electromyography activity in the control group agrees with the findings of Masumoto et al (2007), who found a non-significant increase in the gluteus medius muscle electromyography activity during backward walking vs forward walking on an underwater treadmill, although the measuring environment is different.

The increased electromyography activity of the adductor longus muscle that was found in the control group during backward walking may be used to provide additional stability (Katsavelis et al, 2010). The inability to see the walking direction during backward walking makes the subject more cautious and calls for additional stabilising mechanisms. The lack of visual information asks the nervous system to reload the available sensory feedback that is normally used to correct the stepping pattern, which needs additional neural computational resources to assess the available sensory feedback to control the stepping pattern of backward walking (Kurz et al, 2012). In animal models, during the backward walking there is a strict demand for coordination in the lower extremity motor synergies for proper foot placement that occurs as a result of the absence of peripheral visual feedback that is normally used to increase the accuracy of foot placement (Reynolds and Day, 2005).

The significant increase in the electromyography activity of adductor longus of patellofemoral pain syndrome group compared to healthy group may be attributed to alteration in lower limb mechanics between both groups (Moradi et al, 2014; Davis and Powers, 2010). However, this postulation could not be supported or refuted because of the lack of associated kinetic and kinematic analysis. Additionally, no previous studies have addressed either the frontal plane lower limb kinetics and kinematics or the adductor longus muscle activity during backward walking in healthy or affected populations. Unfortunately, reviewing the literature revealed scarcity in studies that explored the adductor longus muscle activity in patients with patellofemoral pain syndrome. However, Aminaka et al (2011) reported that during stair climbing, patients with patellofemoral pain syndrome showed prolonged activation of the adductor longus muscle compared to the typically healthy group.

Recently, Mahaki et al (2017) reported that the pattern of muscle activity of backward walking has a poor relationship to those of forward walking. These data do not support a simple reversal of spinal central pattern generators. They reported that a phase shift in the muscle activation pattern of approximately 60% occurred. This shift may represent a different control between two walking modes. Indeed, there is a different spinal mechanism that controls the forward walking and backward walking. Their findings could explain the differences between forward walking and backward walking of healthy and patellofemoral pain syndrome groups.

Limitations

The results of this study should be considered in the light of its limitations. Surface electromyography has its limitations regarding the dynamic nature of walking. The lower limb angular displacement results in possible displacement of the electrode, which may have affected the recorded signal (Farina et al, 2001). In addition, crosstalk from nearby adductors might have influenced the electromyography activity of the adductor longus muscle. This could not be avoided using surface electrodes owing to the close anatomical proximity of hip adductors. Although performing kinetic and kinematic analysis was out of the scope of this study, the lack of such information interfered with the ability to justify some of the present findings. Finally, this study was conducted on young females, so the generalisation of the results on the male population should be studied. Future research is required to evaluate the effect of backward walking training on lower limb kinetics, and kinematics during functional tasks in patients with patellofemoral pain syndrome. Additional research should also include the effect of backward walking training on patellar alignment in patellofemoral pain syndrome patients with and without patellar subluxation. Further research is required to evaluate the effect of backward walking training on hip abductors/adductors strength ratios in patients with patellofemoral pain syndrome.

CONCLUSIONS

Backward walking was found to improve the activation of the commonly weakened knee extensors and hip abductors, particularly the vastus medialis obliquus and adductor longus muscle in patients with patellofemoral pain syndrome. Accordingly, physiotherapists should consider backward walking training to increase hip abductor and knee extensor muscle strength when developing rehabilitation programmes for patients with patellofemoral pain syndrome. **IJTR**

Conflict of interests: none declared.

Acknowledgements: We would like to acknowledge the participants of our study.

Aminaka N, Pietrosimone BG, Armstrong CW, Meszaros A, Gribble PA. Patellofemoral pain syndrome alters neuromuscular healthy and kinetics during stair ambulation. J Electromyogr Kinesiol. 2011;21(4):645–651. https://doi.org/10.1016/j.jelekin.2011.03.007

Anderson FC, Pandy MG. Individual muscle contributions to support in normal walking. Gait Posture. 2003;17(2):159–169. https://doi.org/10.1016/S0966-6362(02)00073-5

Barton C, Bonanno D, Levinger P, Menz H. Foot and ankle characteristics in patellofemoral pain syndrome: a case control and reliability study. J Orthop Sports Phys Ther. 2010;40(5):286–296. https://doi.org/10.2519/jospt.2010.3227

Bolgla L, Malone T, Umberger B, Uhl T. Comparison of hip and knee strength and neuromuscular activity in subjects with and without patellofemoral pain syndrome. J Orthop Sports Phys Ther. 2011;6(4):285–296.

Bolgla LA, Boling MC. An update for the conservative management of patellofemoral pain syndrome: a systematic review of the literature. Int J Sports Phys Ther. 2011;6(2):112–125.

Boling M, Padua D, Marshall S et al. Gender differences in the incidence and prevalence of patellofemoral pain syndrome. Scand J Med Sci Sports. 2010;20(5):725–730. https://doi.org/10.1111/j.1600-0838.2009.00996.x

Chen L, Su F, Chiang P. Kinematic and EMG analysis of backward walking on treadmill. Proc 22nd Ann EMBS Inter Conf. 2000;23–28.

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(2):183–189. https://doi.org/10.1053/apmr.2001.19022

Crossley KM. Is patellofemoral osteoarthritis a common sequela of patellofemoral pain? Br J Sports Med. 2014;48(6):409–410. https://doi.org/10.1136/bjsports-2014-093445

Davis IS, Powers CM. Patellofemoral pain syndrome: proximal, distal, and local factors-international research retreat. J Orthop Sports Phys Ther. 2010;40(3):A1–A16. https://doi.org/10.2519/jospt.2010.0302

Dutton R, Khadavi M, Fredericson M. Update on rehabilitation of patellofemoral pain. Curr Sports Med Rep. 2014;13(3):172–178. https://doi.org/10.1249/JSR.0000000000000056

Elboim-Gabyzon M, Rotchild S. Spatial and temporal gait characteristics of elderly individuals during backward and forward walking with shoes and barefoot. Gait Posture. 2017;52:363–366. https://doi.org/10.1016/j.gaitpost.2016.12.007

Farina D, Merletti R, Nazzaro M, Caruso I. Influence of joint angle on EMG variables in leg and thigh muscles. IEEE Eng Med Biol Mag. 2001;20(6):62–71.

Feller JA, Amis AA, Andrish JT et al. Surgical biomechanics of the patellofemoral joint. Arthroscopy. 2007;23(5):542–553. https://doi.org/10.1016/j.arthro.2007.03.006

Flynn TW, Soutas-Little RW. Mechanical power and muscle action during forward and backward running. J Orthop Sports Phys Ther. 1993;17(2):108–112. https://doi.org/10.2519/jospt.1993.17.2.108

Grasso R, Bianchi L, Lacquaniti F. Motor patterns for human gait: backward versus forward locomotion. J Neurophysiol. 1998;80(4):1868–1885. https://doi.org/10.1152/jn.1998.80.4.1868

Han SW. The effect of forward walking and backward walking on quadriceps muscles with treadmill inclination: surface electromyographic analysis. Phys Ther Kor. 2005;12(1):63–70.

Herrington L. Effect of a SERF strap on pain and knee-valgus angle during unilateral squat and step landing in patellofemoral patients. J Sport Rehabil. 2013;22(1):27–32. https://doi.org/10.1123/jsr.22.1.27

Herrington L. Knee valgus angle during single leg squat and landing in patellofemoral pain 263 patients and controls. Knee. 2014;21(2):514–517. https://doi.org/10.1016/j.knee.2013.11.011

Hoogkamer W, Meyns P, Duysens J. Steps forward in understanding backward gait: from basic circuits to rehabilitation. Exerc Sport Sci Rev. 2014;42(1):23–29. https://doi.org/10.1249/JES.0000000000000000

Jansen K, De Groote F, Massaad F et al. Similar muscles contribute to horizontal and vertical acceleration of center of mass in forward and backward walking: implications for neural healthy. J Neurophysiol. 2012;107(12):3385–3396. https://doi.org/10.1152/jn.01156.2011

Joshi S, Vij JS, Singh SK. Retrowalking: a new concept in physiotherapy and rehabilitation. Int J Sci Res. 2015;4(10):152–156.

Katsavelis D, Mukherjee M, Decker L, Stergiou N. Variability of lower extremity joint kinematics during backward walking in a virtual environment. Nonlinear Dynamics Psychol Life Sci. 2010;14(2):165–178.

Khyatee N, Kanchan M, Guptar S. Retrotreadmill walking as a rehabilitative tool in knee pain and quadriceps insufficiency. Inter J Res Sci Techno. 2013;2(4):1–8.

Kurz MJ, Wilson TW, Arpin DJ. Stride-time variability and sensorimotor cortical activation during walking. NeuroImage. 2012; 59(2):1602–1607. https://doi.org/10.1016/j.neuroimage.2011.08.084

Lee M, Kim J, Son J, Kim Y. Kinematic and kinetic analysis during forward and backward walking. Gait Posture. 2013;38(4):674–678. https://doi.org/10.1016/j.gaitpost.2013.02.014

Mahaki M, De Sá E Souzab GS, Mimar R, Vieira MF. The comparison of ground reaction forces and lower limb muscles correlation and activation time delay between forward and backward walking. Gait Posture. 2017;58:380–385. https://doi.org/10.1016/j.gaitpost.2017.08.039

Masumoto K, Takasugi S, Hotta N, Fujishima K, Iwamoto Y. A comparison of muscle activity and heart rate response during backward and forward walking on an underwater treadmill. Gait Posture. 2007;25(2):222–228. https://doi.org/10.1016/j.gaitpost.2006.03.013

Meyns P, Molenaers G, Desloovere K, Duysens J. Interlimb coordination during forward walking is largely preserved in backward walking in children with cerebral palsy. Clin Neurophysiol. 2014;125(3):552–561. https://doi.org/10.1016/j.clinph.2013.08.022

Miao P, Xu Y, Pan E, Liu H, Wang C. Vastus medialis obliquus and vastus lateralis activity during a double-leg semisquat with or without hip adduction in patients with patellofemoral pain syndrome. BMC Musculoskel Disord. 2015;16(1):289–299.

Moradi Z, Akbari M, Ansari N, Emrani A, Mohammadi P. Strength of hip muscle groups in sedentary women with patellofemoral pain syndrome. J Back Musculoskelet Rehabil. 2014;27(3):299–306. https://doi.org/10.3233/BMR-130447

Neumann DA. Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation. 2nd edn. St. Louis, MO: Mosby Elsevier; 2010.

Nijs J, Van Geel C, Van der Auwera C, Van de Velde B. Diagnostic value of five clinical tests in patellofemoral pain syndrome. Man Ther. 2006;11(1):69–77. https://doi.org/10.1016/j.math.2005.04.002

Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. Clin Biomech. 2012;27(4):366–371. https://doi.org/10.1016/j.clinbiomech.2011.10.005

Powers CM. Patellar kinematics, part I: the influence of vastus muscle activity in subjects with and without patellofemoral pain. Phys Ther. 2000;80(10):956–964.

Reynolds RF, Day BL. Visual guidance of the human foot during a step. J Physiol. 2005;569(Pt 2):677–684. https://doi.org/10.1113/jphysiol.2005.095869

Roos PE, Barton N, van Deursen RW. Patellofemoral joint compression forces in backward and forward running. J Biomech. 2012;45(9):1656–1660. https://doi.org/10.1016/j.

jbiomech.2012.03.020
Saurabh KS. Effect of retro-treadmill ambulation training in patellofemoral pain patients. Physiother Occup Ther J. 2012;5(2):59–64.
Shibuya K, Kuboyama N, Tanaka J. Changes in ipsilateral motor cortex activity during a unilateral isometric finger task are dependent on the muscle contraction force. Physiol Meas. 2014;35(3):417–428. https://doi.org/10.1088/0967-3334/35/3/417
Song CY, Huang HY, Chen SC, Lin JJ, Chang AH. Effects of femoral rotational taping on pain, lower extremity kinematics, and muscle activation in female patients with patellofemoral pain. J Sci Med Sport. 2015;18(4):388–393. https://doi.org/10.1016/j.jsams.2014.07.009
Surer E, Herzog W, Souza KD, Bray R. Inhibition of the quadriceps muscles in patients with anterior knee pain. J Appl Biomech. 1998;14(4):360–373. https://doi.org/10.1123/jab.14.4.360
Threlkeld AJ, Horn TS, Wojtowicz GM, Rooney JG, Shapiro R. Pilot study: kinematics, ground reaction force, and muscle balance produced by backward running. J Orthop Sports Phys Ther. 1989;11(2):56–63. https://doi.org/10.2519/jospt.1989.11.2.56
Thorstensson A. How is the normal locomotor program modified to produce backward walking? Exp Brain Res. 1986;61(3):664–668.
Wilson T. The measurement of patellar alignment in patellofemoral pain syndrome: are we confusing assumptions with evidence? J Orthop Sports Phys Ther. 2007;37(6):330–341. https://doi.org/10.2519/jospt.2007.2281
Winter DA, Pluck N, Yang JF. Backward walking: a simple reversal of forward walking? J Mot Behav. 1989;21(3):291–305. https://doi.org/10.1080/00222895.1989.10735483
Wu Y, Xiao F, Gu DY. Local dynamic stability of the trunk segments and lower extremity joints during backward walking. Conf. Proc. IEEE Eng Med Biol Mag. 2015;34(3):5303–5306.
Zhang F, Wang J, Wang F. Comparison of the clinical effects of open and closed chain exercises after medial patellofemoral ligament reconstruction. J Phys Ther Sci. 2014;26(10):1557–1560. https://doi.org/10.1589/jpts.26.1557