The Effect of Exercise on the Architecture of Vastus Medialis Oblique: An Ultrasound Investigation

Abstract

Introduction

The vastus medialis oblique (VMO) is thought to be implicated in patellofemoral pain (PFP), and weakness in this portion of the vastus medialis muscle may lead to PFP. Management includes physiotherapy to strengthen the VMO. Although this intervention has been shown to be effective, the effects on the architecture of the muscle have not been investigated. This study aims to determine the changes in VMO architecture following a program of strengthening exercises.

Materials and Methods

Twenty-one male participants underwent an initial ultrasound scan to measure the fibre angle and the insertion level of the VMO on the patella. Each subject then undertook a 6-week quadriceps strengthening program; the scan and measurements were then repeated.

Results

A significant increase in VMO fibre angle and insertion length was observed. Average fibre angle increased by 5.24°; average insertion length increased by 2.7 mm. There was found to be a significant negative correlation between the initial values and the degree of change. Pearson's coefficient of correlation for measurements of patella length taken before and after exercise was 0.921, indicating a high degree of reliability. There was a significant positive correlation between fibre angle change and declared level of compliance ($R^2 = 0.796$).

Conclusions

The results reported here indicate that physiotherapy leads to a significant change in VMO morphology. Given the inverse correlation noted between initial architectural parameters and the degree of change, we suggest that patients who would benefit most from physiotherapy can be identified in clinic using a simple ultrasound technique.

Keywords: vastus medialis; ultrasound; patellofemoral pain; muscle architecture.

INTRODUCTION

Patellofemoral Pain (PFP) is a common condition defined by anterior or retro-patellar knee pain exacerbated by movements such as climbing, prolonged sitting and squatting. PFP is most often seen in young, athletic individuals, and predominantly in females. Estimates of its prevalence vary from 3% - 40% of the population (Callaghan and Selfe, 2007) and it has been reported to affect 20% of the student population (Cowan et al., 2001). PFP is often a diagnosis of exclusion once other pathological processes have been ruled out; it is often present in the absence of pathology.

Patellar maltracking or malalignment may be related to the pathophysiology of PFP (Katchburian et al., 2003). In the normal knee, the patella should track across the centre of the trochlea of the femur during flexion and extension (Raimondo et al., 1998); deviation from this path places uneven stress on the patellofemoral joint and surrounding tissues, causing PFP (Wilson, 2007).

While the quadriceps femoris as a group are principally extensors of the knee joint, the vastus medialis and vastus lateralis also have a role in patellar stability. The distal, oblique portions of both these muscles insert to some degree onto the patella, hence providing the means for a medial or lateral pull on the patella during extension (Amis, 2007). It is during the first 20° of angulation that the balance of soft tissue structures is particularly important, for it is at this point that the pull of the medial and lateral structures determines the position of the patella. Following the initial 20°, the patella becomes engaged in the trochlea of the femur and hence the bony architecture of the femur takes over responsibility for its position (Wilson, 2007).

During powered extension, the force of the quadriceps acts along the femoral axis (i.e. an oblique line from the anterior superior iliac spine [ASIS] to the apex of the patella), while the patella tendon is in line with the tibia (effectively vertical). The angle so created (the Q angle: approximately 12° in males and 17° in females) results in a lateral pull on the patella that is resisted by the deep lateral facet of the trochlea (Amis et al., 2003). This resistance, however, is only present once the patella is engaged in the trochlea; at other times the distal, oblique portion of the vastus medialis becomes important in counteracting this lateral pull and maintaining normal patellar tracking.

There is controversy over whether the vastus medialis should be considered to be a single muscle, or divided into two separate muscles, the vastus medialis obliquus (VMO) and the vastus medialis longus (VML) (e.g. Lieb and Perry, 1968; Hubbard et al., 1997; Glenn and Samojla, 2002; Peeler et al., 2005; Skinner and Adds, 2012). Some authors have even suggested that it should be divided into three parts (Thiranagama, 1990; Lefebvre et al., 2006). While the issue of whether the VMO should be considered as a separate muscles remains unresolved; what is beyond doubt is that the distal fibres of the vastus medialis are angled more obliquely with respect to the femoral axis than the proximal fibres, and it has been hypothesised that weakness in this portion of the muscle may be a contributory factor in PFP (Souza and Gross, 1991). It has also been suggested that an imbalance in response time between vastus medialis and vastus lateralis may contribute to patellar maltracking and hence, to PFP (Voight and Wieder, 1991; Raimondo et al., 1998).

Physiotherapy is currently the first line of treatment for PFP, frequently concentrating on VMO or quadriceps strengthening, with results from one study showing a significant alleviation of pain following physical therapy (Crossley et al., 2002). Despite this, the evidence to support such management is limited and mainly based on scientific theory. It is theorised that physical therapy causes morphological changes in the VMO which can increase its force, preventing mal-tracking and thus reducing anterior knee pain (Chiu et al., 2012).

Such physiotherapy revolves around attempting to develop a set of exercises that activate the VMO. Studies have compared the use of open-chain kinetic exercises (OCKE) and closed-chain kinetic exercises (CCKE), with varied results (Tang et al., 2001; Witvrouw et al., 2004; Irish et al., 2010). However, OCKE are thought to favour VMO activation over the other quadriceps muscles (Cerny, 1995; Karst and Jewett, 1993), and are commonly used in clinical practice (Mason et al., 2011) and are therefore the exercises of choice for this study.

Ultrasound is a safe, non-invasive technique that has been shown to be both effective and accurate in assessing VMO architecture (Engelina et al. 2014(a), Engelina et al. 2014(b)). The parameters that were assessed in this study were the maximum VMO fibre angle, the length of the patella, and the insertion length of the VMO, i.e. the length of the medial border of the patella into which the VMO inserts, from which the insertion ratio (insertion length/patella length) can be calculated and expressed as a percentage. After undergoing an initial ultrasound scan, participants were asked to undertake a 6-week program of standardised, home-based quadriceps strengthening exercises, after which they were scanned again. The aim of the study was to assess the effects of exercise on the fibre angle and level of insertion on the patella of the VMO.

MATERIALS AND METHODS

Twenty-one male volunteers participated in this study. Informed consent was obtained, and the study received ethical approval from the local Research Ethics Committee. The age, weight, height, ethnicity and Tegner activity score of all participants were recorded (Table 1). The Tegner Scoring system is a commonly used, validated method of grading a subject's activity level from 0 – 10, where a score of 10 signifies very strenuous sporting or work-related activity (Tegner and Lysholm, 1985).

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Exclusion criteria were applied as follows, to exclude from the study any athletic subjects and any subjects with pre-existing knee pathology:

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The subject was positioned supine, with legs relaxed and knees extended. A holder was placed under the ankles to ensure that the knees were immobilised. Three measurements were recorded in each procedure: patella length, insertion length and VMO fibre angle. The methodology used here follows previous studies in which the ultrasound technique has been shown to be statistically robust and accurate (Lin et al., 2008; Jan et al., 2009, Engelina et al., 2014a; Engelina et al., 2014b, Benjafield et al., 2015).

To record the patella length, the superior and inferior borders of the patella were palpated. The superior border of the patella (the base) and the apex were marked with a marker pen. Using a 30cm ruler, parallel horizontal lines were drawn through each point, marking the borders of the patella. The vertical length of the patella between the apex and the superior border was then measured using digital callipers with a resolution of 0.01mm (Fig. 1a).

In order to establish the femoral axis, one end of a 1-metre steel ruler, with a resolution of 1 mm, was positioned at the lateral edge of the subject's anterior superior iliac spine (ASIS) with the other end passing through the apex of the patella. While the subject held the proximal end of the ruler in place, a straight line approximately 10 cm in length was drawn along the femoral axis from the patellar apex towards the ASIS (Fig. 1b).

FIGURE 1

Ultrasound method

A small amount of ultrasound transmission gel was applied to the subject's skin. The probe was placed lightly (to avoid distorting the underlying tissues) on the medial aspect of the knee, at the level of the inferior border of the patella. The probe was then moved proximally until the fibres of the VMO were visible on the ultrasound screen. The probe was then rotated until the fibres of the VMO were seen running parallel to each other on the screen. Using a marker pen, a point was placed on the subject's skin on each side of the probe (Fig.2a). The probe was removed and a line was drawn through these two points and extended to intersect the femoral axis, thus representing the angle of the VMO fibres with respect to the femoral axis (Fig. 2b). The angle was measured using a protractor with a resolution of 1 degree. All measurements before and after the exercise program were taken by the same operator.

FIGURE 2

The probe was then replaced on the medial aspect of the knee at the superior patellar border, and moved distally until the VMO muscle fibres were no longer visible. The position of the probe was again marked on the subject's skin. This point represents the lower limit of the VMO; the vertical distance between this point and the superior patellar border represents the *insertion length*, i.e. the length of the patella onto which the VMO is inserted. The *insertion ratio* was calculated by dividing the insertion length by the patellar length and representing the value as a percentage.

Physiotherapy program

Two open-chain kinetic exercises (OCKE) were used in this study. Participants were asked to undertake these exercises every second day for a period of 6 weeks, and to record their compliance. These exercises were chosen as they are standard practice in Physiotherapy treatment for PFP. They are easy to perform, do not require any equipment, and can be performed at home, all of which are important considerations for physiotherapists treating PFP. Furthermore, due to the non-athletic nature of the participants it was possible to induce muscle fatigue with these simple exercises, (this would be harder in an athletic population). These exercises have been used in previous investigations into PFP treatment, and have demonstrated therapeutic positive effects, (Witvrouw et al., 2000).

Exercise 1: knee extensions

Participants were asked to lie supine and place a rolled towel or pillow underneath their knees, to create a slight bend in the joint. From a relaxed position with their ankle resting on the floor, participants were asked to fully extend their knee, hold for 10 seconds, then return to the resting position, repeating until the first signs of fatigue.

Exercise 2: isometric quadriceps contractions

Participants remained in a supine position, with the towel or pillow beneath their ankles. No movement was to take place during the exercise; participants were asked to consciously tense their quadriceps muscle for 10 seconds, relax and repeat until the onset of fatigue.

After the 6-week exercise program, participants were re-scanned in exactly the same fashion as before. The same measurements were taken, and the differences between the initial and subsequent measurements were calculated.

Assessment of compliance

Participants were asked to keep a diary during the exercise program to record their level of compliance. Compliance was then expressed as a percentage, and plotted against fibre angle change.

Intra-rater reliability study

To assess the reliability of the measurements, intra-rater reliability was assessed by measuring the parameters of one subject's knee on 4 separate occasions. The subject was not a participant in the exercise program, so no change in muscle architecture was expected.

Statistical Analysis

The change in initial and final VMO fibre angle, and change in initial and final insertion length and insertion ratio were calculated. A paired t-test was used to evaluate the significance of any changes. Pearson's coefficient of correlation was calculated for the measurements of patella length before and after exercise in order to assess measurement reliability. The change in relation to initial values, and in relation to the participants' declared level of compliance, were also compared.

RESULTS

Anthropometric data

The anthropometric data for the 21 participants of the study are summarised in Table 1. The average age was 22.6 years.

	Age (yrs)	Weight (kg)	Height (m)	BMI	Tegner Score
Mean ±SD	22.57 ± 1.86	74.71 ± 8.6	1.78 ± 0.07	24.29 ± 2.36	3.19 ± 0.98
Range	19 – 26	59 – 95	1.62 – 1.86	18.41 – 27.68	1 – 5

TABLE 1. Anthropometric data of the study participants

VMO angle change

The mean initial VMO angle was 62.24°, increasing to 67.48° after the exercise program, an average change of 5.24° ($p < 0.001$) (Table 2).

	VMO angle (°) (initial)	VMO angle (°) (final)	VMO angle change (°)
Mean ± SD	62.24 ± 5.72	67.48 ± 5.21	5.24 ± 2.84
Range	54-75	59-78	-1 – 12
P-value			<0.001

TABLE 2. VMO fibre angle before and after exercise program

Insertion Length & Insertion Ratio Change

The average initial insertion length was 21.77 mm. This increased to 24.46 mm after exercise, an average change of 2.69 mm ($p < 0.001$) (Table 3a).

The average initial insertion ratio was 43.53%, which increased to 48.78% after exercise, an average increase of 5.25% ($p < 0.001$) (Table 3b).

(a)	Insertion length (initial) (mm)	Insertion length (final) (mm)	Insertion length change (mm)
Mean ± SD	21.77 ± 4.93	24.46 ± 4.21	2.69 ±3.23
Range	12.97-34.9	19.10-39.35	-3.68-11.53
P-value			<0.001

(b)	Insertion ratio (initial) (%)	Insertion ratio (final) (%)	Insertion ratio change (%)
Mean ± SD	43.53 ± 6.74	48.78 ± 6.10	5.25 ±6.59
Range	28.90-55.55	37.78-64.17	-6.66-25.23
P-value			<0.001

TABLE 3a and 3b. Insertion length (a) and insertion ratio (b) before and after the exercise program. Mean (SD), range and P value.

Correlation between initial VMO angle and magnitude of angle change

A moderate inverse correlation ($R^2 = -0.419$) was found between initial fibre angle and the magnitude of the change observed in the fibre angle after physical therapy (Fig. 3). Thus, participants with a smaller initial angle showed a greater change

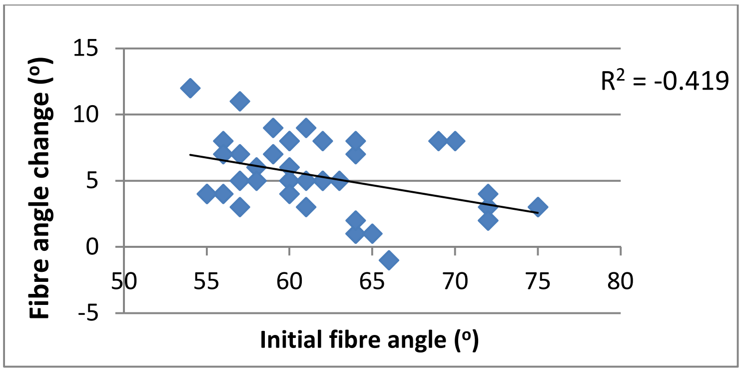

FIGURE 3. Correlation between initial fibre angle and fibre angle change

Correlation between initial insertion length and insertion length change

A weak inverse correlation ($R^2 = 0.2842$) was found between the initial insertion length and the insertion length change after physical therapy (Fig. 4). Again, the greatest change was seen in subjects with small initial values.

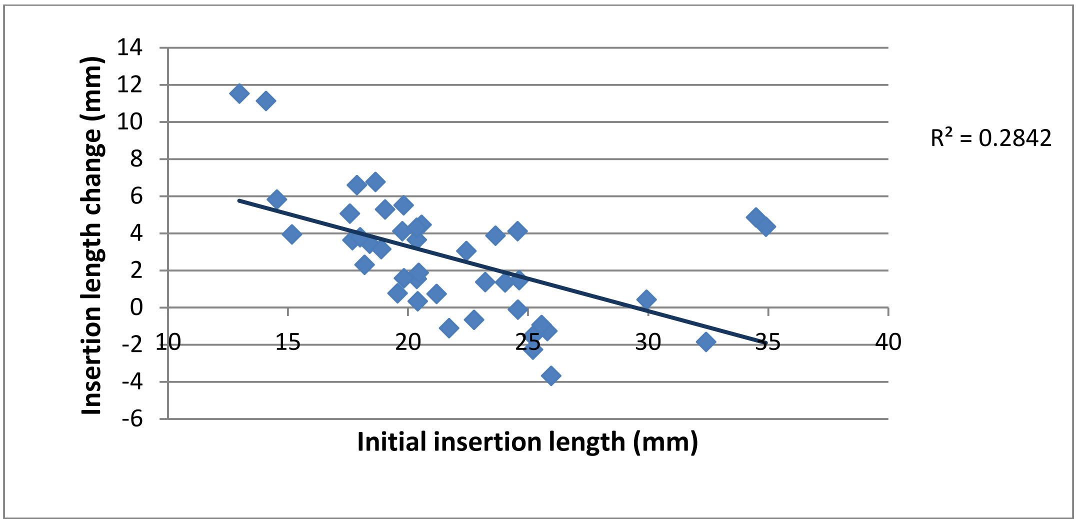

FIGURE 4. Correlation between initial insertion length and insertion length change.

Intra-rater reliability study

The coefficient of variation for the patella length, VMO angle and insertion length were 0.01, 0.02 and 0.01 respectively, confirming that the readings were reliable (Table 4).

	Mean	Standard Deviation (SD)	Coefficient of variation (CV)	Variance
Patella length (mm)	50.0	0.5	0.01	0.24
VMO fibre angle (°)	63.5	0.6	0.02	0.33
VMO insertion length (mm)	20.7	0.4	0.01	0.17

TABLE 4. Results of the intra-rater reliability study

Compliance

There was found to be a highly significant positive correlation between fibre angle change and declared level of compliance (R^2 = 0.796, Fig. 5). The average compliance was 67.69%, with a range between 30-150% (one participant completed the exercise program more often than the prescribed amount).

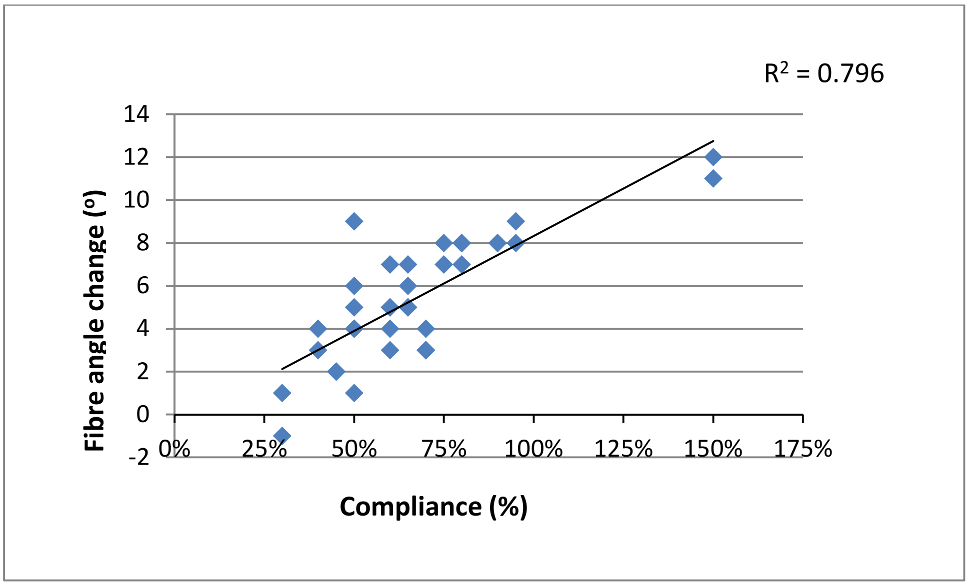

FIGURE 5. Fibre angle change in relation to compliance

Reliability

Pearson's coefficient of correlation on the measurements of patella length before and after the exercise program was found to be 0.921, indicating a high degree of operator reliability.

DISCUSSION

Twenty-one young, asymptomatic males took part in this study. Initial ultrasound scans showed an average VMO angle of 62.24° (range 54°-75°) and insertion length of 21.77 mm (range 12.97-34.9 mm). After a 6-week program of exercises, the average VMO angle increased to 67.48° (range 59°-78°), and insertion length increased to 24.46 mm (19.1-39.35 mm): an average angle change of 5.24° and insertion length change of 2.69 mm. The changes were found to be highly statistically significant.

A negative correlation was found between the initial VMO angle and the magnitude of the change in fibre angle after exercise: a smaller initial angle yielded a greater change ($p < 0.05$). Similarly, the degree of insertion length change in relation to the initial insertion length was also found to have a negative correlation: a smaller initial insertion length yielded a greater change. The degree of change between insertion lengths and VMO angle were also positively correlated ($p < 0.05$). Unsurprisingly, a significant positive correlation was found between compliance and VMO angle/insertion length change.

VMO strengthening exercises are commonly prescribed for PFP patients and have shown considerable symptomatic benefit (Crossley et al., 2002). The strengthening of the VMO will in theory cause a stronger medial pull on the patella thus preventing malalignment, easing the stresses around the patellofemoral joint, and hence alleviating pain. Although there is no direct evidence that these exercises selectively recruit the VMO, due to the morphology of the trochlea, (with its steeper more pronounced lateral inclination) it is the VMO that has the capability to alter the position of the patella. Therefore, although these exercises are not targeting the VMO in isolation, itis highly unlikely that any of the other quadriceps muscles would have the capacity to alter the position of the patella to such a degree that it could change the observed architecture of the VMO, though we do accept that this may be a potential limitation in studies of this type. It is, we suggest, most likely that the changes in architecture observed and measured in the VMO result, not from incidental effects of the other quadriceps, but from the exercise program itself. While the symptomatic benefits of these measures have been investigated, the morphological changes in the VMO have not.

Previous investigations in cadaveric specimens have reported fibre angles of the VMO ranging from 28°-70° (Reider et al., 1981; Scharf et al., 1985; Weinstabl et al., 1989; Nozic et al., 1997; Hubbard et al., 1997; Skinner and Adds, 2012). However data from asymptomatic *in vivo* investigations are limited. A study by Benjafield et al. (2015) on subject groups with differing activity levels found an average VMO fibre angle of 67.8° for athletic groups (Tegner score > 7), and 53.6° for sedentary groups (Tegner score < 3). The average VMO fibre angle of 62.24° reported here before exercise is within the expected range as the study was limited to subjects with a Tegner score of 5 or less.

The exercise program in this study consisted of two open-chain kinetic exercises that have been shown to be effective in PFP treatment (Mason et al., 2011). A study of OCKE on the quadriceps by Mikkelsen et al. (2000) showed an increase in power and functionality, however the effect of such exercises on muscle morphology has not hitherto been investigated.

Strengthening programs of as little as 6 weeks have been shown to cause a significant increase in both muscle bulk and strength (Rasch and Moorehouse, 1957). Muscle hypertrophy will tend to increase pennation angles, allowing more of the contractile tissue to insert onto the tendon and hence enable greater muscle power (Jones and Rutherford, 1987; Kawakami et al., 1993). Given that strengthening exercises are designed to target the VMO, its action in medially stabilising the patella should be potentiated, thereby providing symptomatic relief where PFP is caused by patellar malalignment.

In the study reported here, the average VMO fibre angle increased from 62.24° to 67.48° following a six-week exercise program. Our results show that VMO-specific exercises can have a significant effect on the fibre angle. We also found a significant inverse correlation between the initial fibre angle and the magnitude of the post-exercise change. Participants with smaller initial angles showed the greatest change, with greater initial angles experiencing the least change. These results suggest that patients with smaller initial values may derive greater benefits from VMO-targeted physical therapy. A study by Jan et al. (2009) reported that patellofemoral pain syndrome (PFPS) patients had significantly lower VMO fibre angles than asymptomatic subjects, which further strengthens the likelihood that, in PFP sufferers, a demonstrable change in muscle morphology can be achieved by following a therapeutic exercise regime. Furthermore, Barton et al. (2015) comment that PFP is multimodal and that quadriceps exercises should work for some patients. The investigation reported here presents a way of potentially identifying which patients would be more suitable candidates for quadriceps exercises

The average VMO insertion ratio (i.e. the proportion of the medial border of the patella into which the VM inserts) in non-pathological knees has been variously reported as 44% (Roberts et al., 2007), 51% (Holt et al., 2008) and 58% (Engelina et al., 2014b). In our study group, the initial insertion ratio was 43.53%, which is at the lower end of the scale, but in line with values of 39.5% and 43% in sedentary and athletic individuals respectively, reported by Benjafield et al. (2015). After six weeks of exercise, the average insertion ratio had increased significantly, to 48.78%. This can be explained by an increase in muscle volume causing its insertion to extend distally. This increased insertion ratio will cause the VMO to act with greater force on the patella, enhancing its action as a medial stabiliser.

As with the fibre angle, the increase in insertion length was more pronounced in subjects with small initial values. These results suggest that it might be most beneficial to target VMO training on those patients with smaller initial VMO parameters. It has been reported that PFPS sufferers had smaller insertion ratios and fibre angles than the healthy control group (Jan et al., 2009), though the data on fibre angles are less clear and there is some overlap between fibre angles seen in PFPS and non-pathological knees (Engelina et al., 2014b). The results reported here suggest that it would be beneficial to screen patients using ultrasound, before recommending VMO strengthening exercises to those patients with low initial values. Work is on-going to further elucidate the effects of different types of exercise on the architecture of the VMO, and to what extent the effect is maintained once the exercises have been stopped.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the volunteers who kindly agreed to take part in this study. The authors have no conflicts of interest to declare.

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A significant increase in VMO fibre angle and insertion length was observed. Average fibre angle increased by 5.24°; average insertion length increased by 2.7 mm. There was found to be a significant negative correlation between the initial values and the degree of change. Pearson's coefficient of correlation for measurements of patella length taken before and after exercise was 0.921, indicating a high degree of reliability. There was a significant positive correlation between fibre angle change and declared level of compliance (R^2 = 0.796).

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FIGURE 1

Ultrasound method

A small amount of ultrasound transmission gel was applied to the subject's skin. The probe was placed lightly (to avoid distorting the underlying tissues) on the medial aspect of the knee, at the level of the inferior border of the patella. The probe was then moved proximally until the fibres of the VMO were visible on the ultrasound screen. The probe was then rotated until the fibres of the VMO were seen running parallel to each other on the screen. Using a marker pen, a point was placed on the subject's skin on each side of the probe (Fig.2a). The probe was removed and a line was drawn through these two points and extended to intersect the femoral axis, thus representing the angle of the VMO fibres with respect to the femoral axis (Fig. 2b). The angle was measured using a protractor with a resolution of 1 degree. All measurements before and after the exercise program were taken by the same operator.

FIGURE 2

The probe was then replaced on the medial aspect of the knee at the superior patellar border, and moved distally until the VMO muscle fibres were no longer visible. The position of the probe was again marked on the subject's skin. This point represents the lower limit of the VMO; the vertical distance between this point and the superior patellar border represents the *insertion length*, i.e. the length of the patella onto which the VMO is inserted. The *insertion ratio* was calculated by dividing the insertion length by the patellar length and representing the value as a percentage.

Physiotherapy program

Two open-chain kinetic exercises (OCKE) were used in this study. Participants were asked to undertake these exercises every second day for a period of 6 weeks, and to record their compliance. These exercises were chosen as they are standard practice in Physiotherapy treatment for PFP. They are easy to perform, do not require any equipment, and can be performed at home, all of which are important considerations for physiotherapists treating PFP. Furthermore, due to the non-athletic nature of the participants it was possible to induce muscle fatigue with these simple exercises, (this would be harder in an athletic population). These exercises have been used in previous investigations into PFP treatment, and have demonstrated therapeutic positive effects, (Witvrouw et al., 2000).

Exercise 1: knee extensions

Participants were asked to lie supine and place a rolled towel or pillow underneath their knees, to create a slight bend in the joint. From a relaxed position with their ankle resting on the floor, participants were asked to fully extend their knee, hold for 10 seconds, then return to the resting position, repeating until the first signs of fatigue.

Exercise 2: isometric quadriceps contractions

Participants remained in a supine position, with the towel or pillow beneath their ankles. No movement was to take place during the exercise; participants were asked to consciously tense their quadriceps muscle for 10 seconds, relax and repeat until the onset of fatigue.

After the 6-week exercise program, participants were re-scanned in exactly the same fashion as before. The same measurements were taken, and the differences between the initial and subsequent measurements were calculated.

Assessment of compliance

Participants were asked to keep a diary during the exercise program to record their level of compliance. Compliance was then expressed as a percentage, and plotted against fibre angle change.

Intra-rater reliability study

To assess the reliability of the measurements, intra-rater reliability was assessed by measuring the parameters of one subject's knee on 4 separate occasions. The subject was not a participant in the exercise program, so no change in muscle architecture was expected.

Statistical Analysis

The change in initial and final VMO fibre angle, and change in initial and final insertion length and insertion ratio were calculated. A paired t-test was used to evaluate the significance of any changes. Pearson's coefficient of correlation was calculated for the measurements of patella length before and after exercise in order to assess measurement reliability. The change in relation to initial values, and in relation to the participants' declared level of compliance, were also compared.

RESULTS

Anthropometric data

The anthropometric data for the 21 participants of the study are summarised in Table 1. The average age was 22.6 years.

	Age (yrs)	Weight (kg)	Height (m)	BMI	Tegner Score
Mean ±SD	22.57 ± 1.86	74.71 ± 8.6	1.78 ± 0.07	24.29 ± 2.36	3.19 ± 0.98
Range	19 – 26	59 – 95	1.62 – 1.86	18.41 – 27.68	1 – 5

TABLE 1. Anthropometric data of the study participants

VMO angle change

The mean initial VMO angle was 62.24°, increasing to 67.48° after the exercise program, an average change of 5.24° ($p < 0.001$) (Table 2).

	VMO angle (°) (initial)	VMO angle (°) (final)	VMO angle change (°)
Mean ± SD	62.24 ± 5.72	67.48 ± 5.21	5.24 ± 2.84
Range	54-75	59-78	-1 – 12
P-value			<0.001

TABLE 2. VMO fibre angle before and after exercise program

Insertion Length & Insertion Ratio Change

The average initial insertion length was 21.77 mm. This increased to 24.46 mm after exercise, an average change of 2.69 mm ($p < 0.001$) (Table 3a).

The average initial insertion ratio was 43.53%, which increased to 48.78% after exercise, an average increase of 5.25% ($p < 0.001$) (Table 3b).

(a)	Insertion length (initial) (mm)	Insertion length (final) (mm)	Insertion length change (mm)
Mean ± SD	21.77 ± 4.93	24.46 ± 4.21	2.69 ±3.23
Range	12.97-34.9	19.10-39.35	-3.68-11.53
P-value			<0.001

(b)	Insertion ratio (initial) (%)	Insertion ratio (final) (%)	Insertion ratio change (%)
Mean ± SD	43.53 ± 6.74	48.78 ± 6.10	5.25 ±6.59
Range	28.90-55.55	37.78-64.17	-6.66-25.23
P-value			<0.001

TABLE 3a and 3b. Insertion length (a) and insertion ratio (b) before and after the exercise program. Mean (SD), range and P value.

Correlation between initial VMO angle and magnitude of angle change

A moderate inverse correlation ($R^2 = -0.419$) was found between initial fibre angle and the magnitude of the change observed in the fibre angle after physical therapy (Fig. 3). Thus, participants with a smaller initial angle showed a greater change

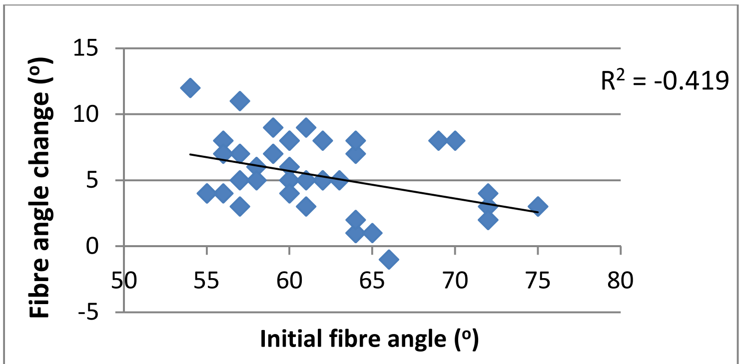

FIGURE 3. Correlation between initial fibre angle and fibre angle change

Correlation between initial insertion length and insertion length change

A weak inverse correlation ($R^2 = 0.2842$) was found between the initial insertion length and the insertion length change after physical therapy (Fig. 4). Again, the greatest change was seen in subjects with small initial values.

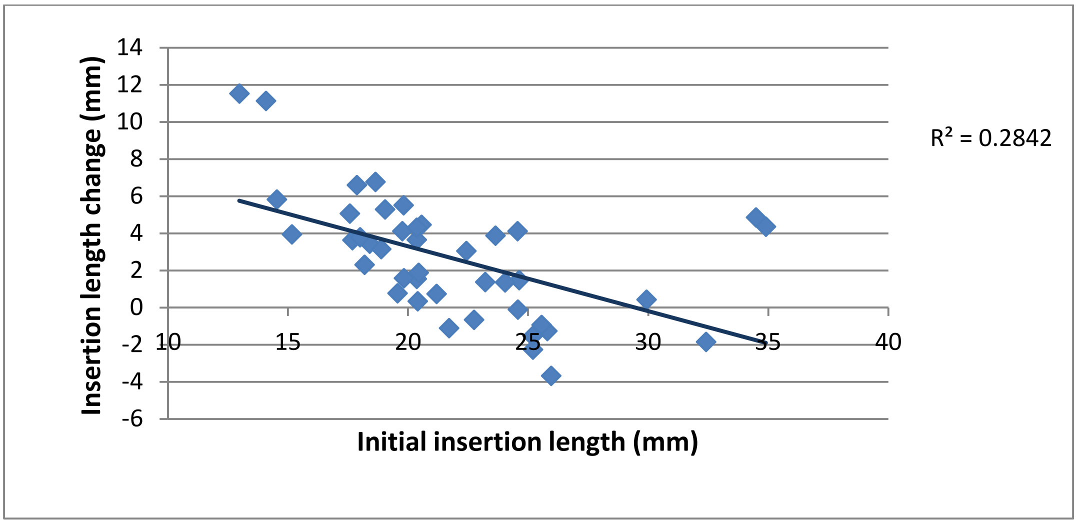

FIGURE 4. Correlation between initial insertion length and insertion length change.

Intra-rater reliability study

The coefficient of variation for the patella length, VMO angle and insertion length were 0.01, 0.02 and 0.01 respectively, confirming that the readings were reliable (Table 4).

	Mean	Standard Deviation (SD)	Coefficient of variation (CV)	Variance
Patella length (mm)	50.0	0.5	0.01	0.24
VMO fibre angle (°)	63.5	0.6	0.02	0.33
VMO insertion length (mm)	20.7	0.4	0.01	0.17

TABLE 4. Results of the intra-rater reliability study

Compliance

There was found to be a highly significant positive correlation between fibre angle change and declared level of compliance (R^2 = 0.796, Fig. 5). The average compliance was 67.69%, with a range between 30-150% (one participant completed the exercise program more often than the prescribed amount).

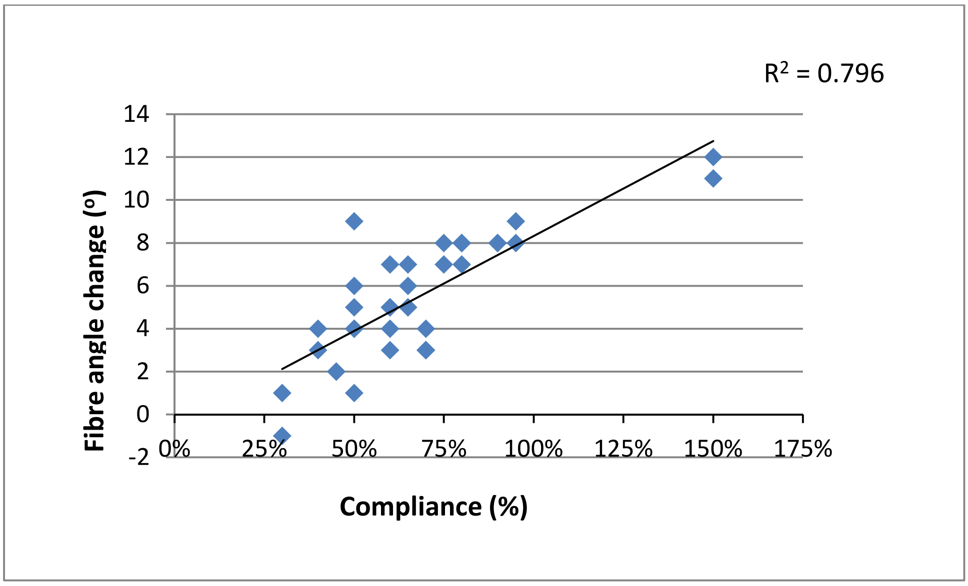

FIGURE 5. Fibre angle change in relation to compliance

Reliability

Pearson's coefficient of correlation on the measurements of patella length before and after the exercise program was found to be 0.921, indicating a high degree of operator reliability.

DISCUSSION

Twenty-one young, asymptomatic males took part in this study. Initial ultrasound scans showed an average VMO angle of 62.24° (range 54°-75°) and insertion length of 21.77 mm (range 12.97-34.9 mm). After a 6-week program of exercises, the average VMO angle increased to 67.48° (range 59°-78°), and insertion length increased to 24.46 mm (19.1-39.35 mm): an average angle change of 5.24° and insertion length change of 2.69 mm. The changes were found to be highly statistically significant.

A negative correlation was found between the initial VMO angle and the magnitude of the change in fibre angle after exercise: a smaller initial angle yielded a greater change ($p < 0.05$). Similarly, the degree of insertion length change in relation to the initial insertion length was also found to have a negative correlation: a smaller initial insertion length yielded a greater change. The degree of change between insertion lengths and VMO angle were also positively correlated ($p < 0.05$). Unsurprisingly, a significant positive correlation was found between compliance and VMO angle/insertion length change.

VMO strengthening exercises are commonly prescribed for PFP patients and have shown considerable symptomatic benefit (Crossley et al., 2002). The strengthening of the VMO will in theory cause a stronger medial pull on the patella thus preventing malalignment, easing the stresses around the patellofemoral joint, and hence alleviating pain. Although there is no direct evidence that these exercises selectively recruit the VMO, due to the morphology of the trochlea, (with its steeper more pronounced lateral inclination) it is the VMO that has the capability to alter the position of the patella. Therefore, although these exercises are not targeting the VMO in isolation, it is highly unlikely that any of the other quadriceps muscles would have the capacity to alter the position of the patella to such a degree that it could change the observed architecture of the VMO, though we do accept that this may be a potential limitation in studies of this type. It is, we suggest, most likely that the changes in architecture observed and measured in the VMO result, not from incidental effects of the other quadriceps, but from the exercise program itself. While the symptomatic benefits of these measures have been investigated, the morphological changes in the VMO have not.

Previous investigations in cadaveric specimens have reported fibre angles of the VMO ranging from 28°-70° (Reider et al., 1981; Scharf et al., 1985; Weinstabl et al., 1989; Nozic et al., 1997; Hubbard et al., 1997; Skinner and Adds, 2012). However data from asymptomatic *in vivo* investigations are limited. A study by Benjafield et al. (2015) on subject groups with differing activity levels found an average VMO fibre angle of 67.8° for athletic groups (Tegner score > 7), and 53.6° for sedentary groups (Tegner score < 3). The average VMO fibre angle of 62.24° reported here before exercise is within the expected range as the study was limited to subjects with a Tegner score of 5 or less.

The exercise program in this study consisted of two open-chain kinetic exercises that have been shown to be effective in PFP treatment (Mason et al., 2011). A study of OCKE on the quadriceps by Mikkelsen et al. (2000) showed an increase in power and functionality, however the effect of such exercises on muscle morphology has not hitherto been investigated.

Strengthening programs of as little as 6 weeks have been shown to cause a significant increase in both muscle bulk and strength (Rasch and Moorehouse, 1957). Muscle hypertrophy will tend to increase pennation angles, allowing more of the contractile tissue to insert onto the tendon and hence enable greater muscle power (Jones and Rutherford, 1987; Kawakami et al., 1993). Given that strengthening exercises are designed to target the VMO, its action in medially stabilising the patella should be potentiated, thereby providing symptomatic relief where PFP is caused by patellar malalignment.

In the study reported here, the average VMO fibre angle increased from 62.24° to 67.48° following a six-week exercise program. Our results show that VMO-specific exercises can have a significant effect on the fibre angle. We also found a significant inverse correlation between the initial fibre angle and the magnitude of the post-exercise change. Participants with smaller initial angles showed the greatest change, with greater initial angles experiencing the least change. These results suggest that patients with smaller initial values may derive greater benefits from VMO-targeted physical therapy. A study by Jan et al. (2009) reported that patellofemoral pain syndrome (PFPS) patients had significantly lower VMO fibre angles than asymptomatic subjects, which further strengthens the likelihood that, in PFP sufferers, a demonstrable change in muscle morphology can be achieved by following a therapeutic exercise regime. Furthermore, Barton et al. (2015) comment that PFP is multimodal and that quadriceps exercises should work for some patients. The investigation reported here presents a way of potentially identifying which patients would be more suitable candidates for quadriceps exercises

The average VMO insertion ratio (i.e. the proportion of the medial border of the patella into which the VM inserts) in non-pathological knees has been variously reported as 44% (Roberts et al., 2007), 51% (Holt et al., 2008) and 58% (Engelina et al., 2014b). In our study group, the initial insertion ratio was 43.53%, which is at the lower end of the scale, but in line with values of 39.5% and 43% in sedentary and athletic individuals respectively, reported by Benjafield et al. (2015). After six weeks of exercise, the average insertion ratio had increased significantly, to 48.78%. This can be explained by an increase in muscle volume causing its insertion to extend distally. This increased insertion ratio will cause the VMO to act with greater force on the patella, enhancing its action as a medial stabiliser.

As with the fibre angle, the increase in insertion length was more pronounced in subjects with small initial values. These results suggest that it might be most beneficial to target VMO training on those patients with smaller initial VMO parameters. It has been reported that PFPS sufferers had smaller insertion ratios and fibre angles than the healthy control group (Jan et al., 2009), though the data on fibre angles are less clear and there is some overlap between fibre angles seen in PFPS and non-pathological knees (Engelina et al., 2014b). The results reported here suggest that it would be beneficial to screen patients using ultrasound, before recommending VMO strengthening exercises to those patients with low initial values. Work is on-going to further elucidate the effects of different types of exercise on the architecture of the VMO, and to what extent the effect is maintained once the exercises have been stopped.

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Figure Legends

Figure 1 a. The superior and inferior borders of the patella were marked and measured;

b. the femoral axis (ASIS to apex of patella) was marked.

Figure 2 a. A mark was made on each side of the probe;

b. a line was drawn through the points and extended to the femoral axis. The VMO angle was then measured.

Figure 3. Correlation between initial VMO fibre angle and fibre angle change after physiotherapy

Figure 4. Correlation between initial insertion length and insertion length change after physiotherapy

Figure 5. Correlation between fibre angle change (°) and declared level of compliance

Tables and table legends

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Range	28.9 – 55.55	37.78 – 64.17	-6.66 – 25.23
P-value			<0.001

Table 3a and b. Insertion length (a) and insertion ratio (b) before and after exercise program.

Mean(SD), range and P value.

	Mean	Standard deviation (SD)	Coefficient of variation (CV)	Variance
Patella length (mm)	50.0	0.5	0.01	0.24
VMO fibre angle (°)	63.5	0.6	0.02	0.33
VMO insertion length (mm)	20.7	0.4	0.01	0.17

Table 4. Results of the intra-rater reliability study