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Effects of vastus medialis oblique-focused and general quadriceps strengthening exercises on Q-angle and quadriceps strength in overweight and obese females: A randomized controlled trial

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ABSTRACT

Background: Genu valgum is a condition characterized by an abnormal angling of the knee joints, causing the knees to tilt inward and the feet to rotate outward. This condition is commonly observed in overweight individuals, particularly females, due to abnormalities in body structure and muscle function, specifically in the quadriceps and vastus medialis obliquus (VMO) muscles. Such abnormalities can affect the Q-angle, and an increased Q-angle may lead to patellar instability and stress on the knee joint. Previous studies have indicated that exercises aimed at strengthening the quadriceps and VMO muscles can help reduce the Q-angle.

Objectives: This study aimed to compare the effects of VMO-focused strengthening exercises and general quadriceps strengthening exercises on the Q-angle and quadriceps strength in females with overweight and obesity.

Materials and methods: Twenty females with overweight and obesity were randomly divided into two groups of 10. The first group participated in an exercise program focused on strengthening VMO muscle, while the second group engaged in a program aimed at improving quadriceps strength. Both programs lasted for 4 weeks and were conducted 3 days a week. Measurements of the Q-angle and quadriceps muscle strength were taken one week prior to the start of the exercises and again after the completion of the 4-week program. Data were analyzed using a two-way mixed analysis of variance (ANOVA) to examine the effects of group (VMO vs. quadriceps) and time (pre- vs post-).

Results: The mixed ANOVA revealed no significant group × time interactions for Q-angle or quadriceps strength (all $p>0.05$). Both groups demonstrated similar patterns of change over time, with descriptive data indicating reductions in Q-angle and increases in quadriceps strength following the intervention.

Conclusion: Both VMO-focused and general quadriceps strengthening exercises produced similar changes in Q-angle and quadriceps strength over the 4-week intervention period. No significant differences were observed between the two exercise approaches. These results should be interpreted with caution because of the short intervention duration. Future studies employing longer training periods and more objective measures of muscle activation are warranted to better elucidate potential differences between exercise types and to strengthen the evidence base in this area.

Introduction

The quadriceps (Q) angle is definitively established by the intersection of two lines: one extends from the anterior superior iliac spine (ASIS) to the center of the patella, and the second extends from the center of the patella to the tibial tuberosity.[1] The Q-angle may be used as an indirect indicator of the line of action and loading effect of the quadriceps muscle.[2,3] The average Q angle is approximately 14 degrees for men and 17 degrees for women.[4] An increased Q-angle is often linked to genu valgum (knock knees) and represents a type of extensor mechanism malalignment. It is associated with knee joint hypermobility, patellar instability, and patellofemoral pain syndrome.[5] Additionally, recent studies have provided evidence of a relationship between being overweight or obese and skeletal abnormalities, particularly angular knee disorders.[6] As body weight increases, joint loading increases, which may contribute to an increase in Q-angle.[7] Other factors can contribute to an increased Q-angle in women. These factors include a broader pelvis, heightened femoral anteversion, knee valgus, external tibial torsion, greater ligamentous laxity, hyperpronation of the foot, patella alta, a constricted lateral patellar retinaculum, and a hypoplastic or weakened vastus medialis oblique (VMO).[8-9]

Weak quadriceps muscles can negatively impact the patellofemoral mechanism. Strengthening the quadriceps is frequently advised, as these muscles are crucial for patellar movement. The VMO not only helps extend the knee but also acts as a primary medial stabilizer of the patella. When the knee extends, the VMO pulls the patella inward because of its positioning relative to the patella.[8] The VMO is often considered a significant contributor to patellofemoral joint pain. During knee extension, the VMO exerts a medial pull on the patella and has been observed to activate later than the vastus lateralis (VL) in individuals experiencing patellofemoral pain. This delayed activation may disrupt patellar tracking, leading to lateral tracking because the VMO cannot engage in time.[10] As a result, it contributes to an increased Q-angle.[8,9] However, general quadriceps strengthening exercises tend to recruit the quadriceps muscle group globally and may not selectively enhance VMO activation relative to VL.[11]

It has been proposed that quadriceps strengthening exercises and sports participation may alter Q-angle magnitude.[12] Exercises that concentrate on activating the VMO are highlighted to balance the VMO:VL firing ratio, aiming to correct the patellar tracking pattern, which may reduce the Q-angle.[8] A study found that strengthening exercises for the quadriceps effectively decreased the Q-angle.[13] However, previous studies have lacked information regarding the comparison between quadriceps strengthening and VMO strengthening exercises. Therefore, this study compared the effects of VMO strengthening exercises and quadriceps strengthening exercises on the Q-angle and quadriceps strength in females with overweight and obesity. General quadriceps strengthening enhances

overall knee extensor strength and function; however, it falls short in addressing the medial-lateral quadriceps imbalance, thus providing limited impact on patellar maltracking or the Q-angle. In contrast, training that focuses on the VMO specifically targets medial knee stabilization, which can improve patellar tracking and dynamic knee alignment.[14-17]

Moreover, in theory, increasing VMO activation or force production can alter the Q-angle over 4 weeks because the Q-angle has a dynamic component influenced by muscle forces.[11] The VMO exerts a medial stabilizing force on the patella, counteracting the lateral pull of the vastus lateralis. Enhanced VMO recruitment shifts the resultant quadriceps force vector medially, improving patellar tracking and reducing lateral displacement.[18] Neuromuscular adaptations occurring within 3-4 weeks can modify motor control and reduce dynamic knee valgus, thereby altering the functional alignment of the extensor mechanism.[17] Additionally, changes in patellar position affect surface landmark measurements, leading to a measurable reduction in Q-angle despite no change in bony anatomy.[19]

Although the VMO is anatomically part of the quadriceps femoris, it plays a distinct functional role in providing medial stabilization of the patella and contributes to patellofemoral alignment.[20] Selective VMO-focused exercises are therefore commonly prescribed to enhance neuromuscular control and correct lateral patellar tracking, particularly in individuals with altered knee mechanics.[21,22] Given that a higher Q-angle in females, especially in overweight and obese individuals, has been associated with altered knee biomechanics and patellofemoral loading[23], it was hypothesized that both exercise programs would lead to positive changes in Q-angle and quadriceps strength.

Furthermore, it was hypothesized that VMO-focused training would be more effective in improving Q-angle compared with general quadriceps strengthening.

Materials and methods

Study design and participants

This study was a randomized controlled trial (RCT). The G-Power 3.1 program (University of Düsseldorf, Düsseldorf, Germany) was used to calculate the required sample size for a repeated-measures ANOVA with a within-between interaction. With a significance level of 0.05, power of 80%, and an effect size of 0.4 based on a previous study[24], the analysis indicated that a total sample size of 16 participants was required. However, to mitigate the risk of participant drop-out, this randomized controlled trial (RCT) included a total of 20 participants who met the following inclusion criteria: 1) females aged between 18 and 25 years, 2) a body mass index (BMI) 23-24.9 kg/m^2 for overweight and ≥25 kg/m^2 for obesity[25], 3) a Q-angle exceeding 17 degrees on both sides, and 4) no participation in structured lower limb exercise or sports activities of moderate to vigorous intensity for at least three months prior to the test (light activities such as daily walking were permitted). The study excluded individuals who had: 1) a history of lower limb or lower back injuries or surgeries within the six months preceding the test, and 2) any knee joint-related pathology, including ligament injuries, meniscus tears, muscle strains, or inflammation of the quadriceps tendon.

Intraclass correlation coefficient (ICC)

The intraclass correlation coefficient (ICC) was employed to assess the intra-rater reliability of three researchers in measuring Q-angle and quadriceps muscle strength. Both measurements were conducted on the same day with 10 volunteers and were repeated 24 hours later. The resulting data were analyzed to calculate the ICC. The investigator with an ICC value closest to 1 was chosen to carry out the measurements. A minimum acceptable ICC value of 0.70 was established.[26] The analysis revealed ICC values of 0.7 for the Q-angle assessments and 0.8 for the quadriceps muscle strength evaluations, respectively.

Outcome measurements

Q-angle

The Q angle was measured using a full-circle universal manual goniometer while the subject stood in an erect weight-bearing position. The anterior superior iliac spine (ASIS), the midpoint of the patella (identified by palpating the superior and inferior borders and marking the midpoint along its longitudinal axis), and the tibial tuberosity were identified and marked. The axis of the goniometer was positioned at the midpoint of the patella, and the arms were adjusted to align with the line connecting the ASIS to the tibial tuberosity. The small angle indicated on the goniometer was recorded as the Q angle.[27]

Quadriceps muscle strength

The volunteer was seated on a bed, with their legs elevated off the ground. The tester stood in front of the volunteer and used a handheld dynamometer (HHD) to assess quadriceps strength. The volunteer was instructed to perform a maximal isometric contraction against the tester and hold the position for five seconds. Each test was conducted three times, with the volunteer resting for 15 seconds between measurements to prevent muscle fatigue. Quadriceps strength was recorded in kilograms, and the results were averaged.[28]

Quadriceps strengthening exercise

Double-legged squat

The volunteer positioned themselves with their feet shoulder-width apart and hands clasped in front of their chest. They then bent their knees to lower into a squat, ensuring both knees formed a 90-degree angle and their thighs remained parallel to the floor. Afterward, they stood back up, which counted as

one repetition. Aim to perform 10 repetitions per set, completing a total of 2 sets with a 1-minute rest allowed between sets.[29,30]

Forward lunge

The volunteer stood with feet shoulder-width apart and maintained an upright posture. The participant then stepped forward with their right foot, bending both knees to a 90-degree angle. The volunteer then pushed through their feet and returned to the starting position, completing one repetition. This process was repeated with the left foot for a total of 30 repetitions, which constituted one set. The exercise was performed for two sets, with a 1-minute rest between sets.[30,31]

Single-leg squat to chair

The volunteer stood with feet shoulder-width apart, placing the right foot slightly in front of the left. They shifted their weight onto the left foot, turning the right foot outward while keeping the heel on the ground. With hands clasped in front of their chest, they maintained an upright posture throughout the stance. The volunteer then shifted weight to the left foot, pushed the hips back, and bent the left knee to lower into a seated position. Simultaneously, they extended the right leg forward and drove through the left foot to elevate their hips and body back up. This counted as one repetition. The volunteer completed 10 repetitions for one set and performed a total of 2 sets. Next, they switched sides by placing the right foot behind and using it to support their weight.[30]

Double-legged wall squat

The participant stood with feet shoulder-width apart and engaged their core to maintain contact with the wall. They then lowered their body until their knees bent to approximately 90 degrees, ensuring both thighs remained parallel to the floor. The back stayed in contact with the wall throughout the movement. The participant held this position for 15-20 seconds, which counted as one repetition. They completed 5 repetitions per set and performed 2 sets overall.[29,30]

VMO strengthening exercise

VMO straight leg raise

The volunteer lay on their back with legs extended straight and engaged the right thigh as they slowly lifted the leg off the ground. They then rotated the leg outward so that the toes pointed 45 degrees to the side before lowering it back to the starting position. This counted as one repetition. The volunteer completed ten repetitions for one set and performed two sets, with a 1-minute rest between sets. After finishing with the right leg, the participant switched to the left leg and repeated the exercise.[32,33]

VMO activation

The participant sat upright in a chair, with their knees bent and feet flat on the floor. A medicine ball, measuring 45 cm in diameter, was positioned between their knees. The participant was instructed to squeeze their hips and gently press the inner sides of their knees against the ball. This action constituted one repetition. They completed 10 repetitions per set, performing a total of 2 sets.[33,34]

VMO strengthening squat

The volunteer positioned themselves with their back against the wall, slightly bending their knees and hips while holding a ball securely between the inner sides of their knees. They then lowered their body until their knees were bent at approximately 90 degrees, maintaining the squeeze on the ball. At this point, their thighs were parallel to the floor, and their knees did not extend beyond their toes. The participant then returned to the starting position, which counted as one repetition. The participant performed 10 repetitions per set, completing 2 sets overall.[33,35]

Bridge with ball between knees

The volunteer lay on their back with both knees bent and feet flat on the floor, hands resting beside the body, and a ball positioned between the knees. They lifted their hips and held the position for 5 seconds while squeezing the ball, then returned to the starting position. This counted as one repetition. Participants performed 10 repetitions per set, completing 2 sets overall.[33,36]

Procedure

The study received approval from the University of Phayao Human Ethics Committee (HREC-UP-HSST 1.2/098/67) and adhered to the Declaration of Helsinki. The protocol was sanctioned by the Thai Clinical Trials Registry (TCTR20240723014). All participants provided written informed consent before testing. Researcher 1 randomly assigned participants to either the VMO or quadriceps group using the drawing-lots of method. Researchers 2 and 3 measured all baseline data, Q-angle, and quadriceps muscle strength at the start of the study. The assessment researchers were not aware of the group allocation. Volunteers were instructed not to discuss their group activities with the assessment staff. The quadriceps group performed quadriceps strengthening exercises, while the VMO group performed VMO strengthening exercises 3 times a week for 4 weeks. The participants completed the exercise programs under the supervision of Researcher 1 during each session at the physiotherapy clinic, School of Allied Health Sciences, University of Phayao. The Q-angle and quadriceps muscle strength were reassessed after 4 weeks of the exercise programs by Researchers 2 and 3, who remained blinded to the group allocation (Figure 1).

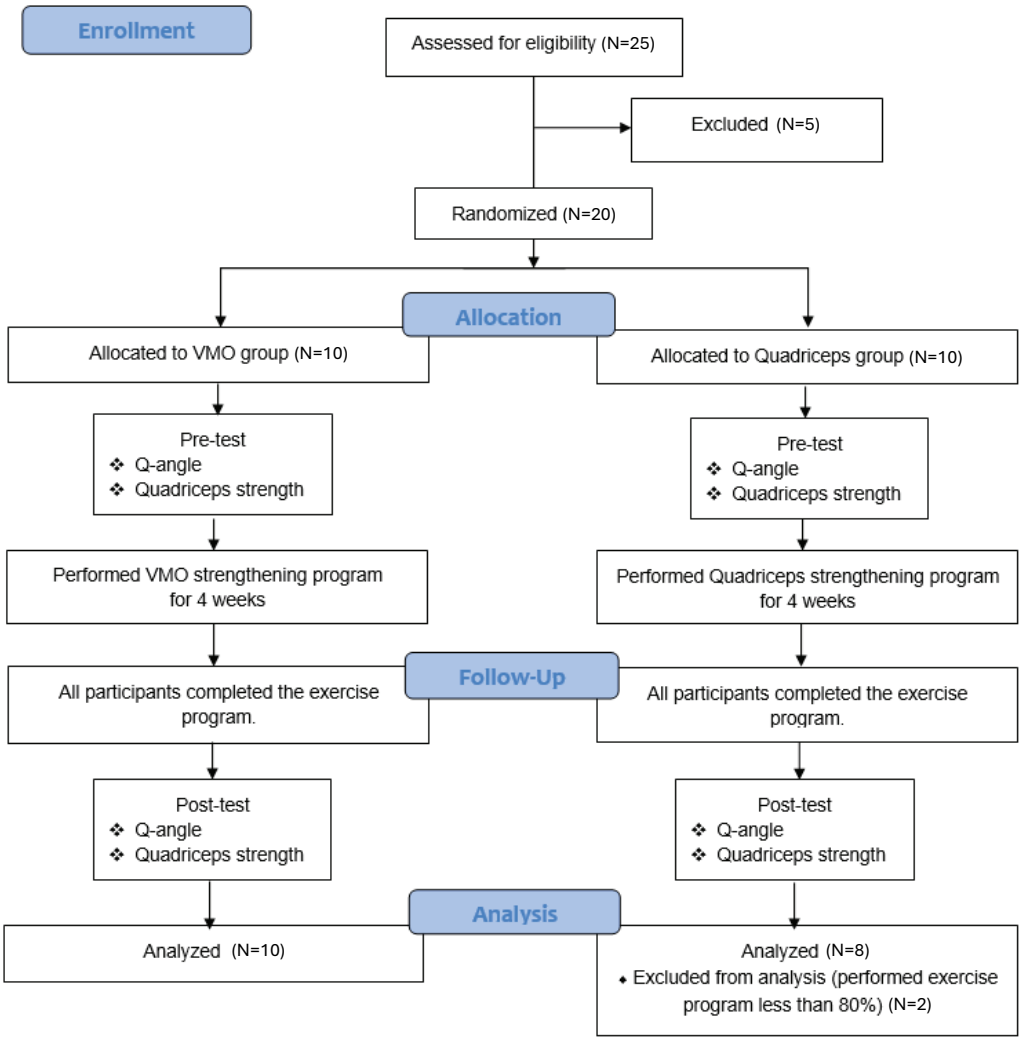

Figure 1. Consort flow diagram of the operational procedures and data collection.

Statistical analysis

The data were analyzed using SPSS statistical package version 25 (SPSS Inc., Chicago, IL). All baseline data were presented as mean ± standard deviation (SD). Normality of the data was confirmed using the Shapiro–Wilk test, which showed that all variables followed a normal distribution ($p>0.05$). To examine significant differences in baseline data between groups, an independent t-test was utilized. The dependent variables were analyzed using a two-way mixed ANOVA on two factors, which were one between-subjects factor (group) with two levels (groups: VMO, Quadriceps) and one within-subjects factor (time) with two levels (time: pre-, post-). A significance level was set at $p<0.05$. Descriptive percentage changes were calculated for each outcome to illustrate the magnitude and direction of change within each group. These descriptive data were not subjected to inferential statistical testing.

Results

A total of 20 participants who met the inclusion criteria were recruited for the study. However, during follow-up in the final week, 2 participants in the quadriceps group completed less than 80 percent of the total exercise sessions. Consequently, they were excluded from statistical analysis. The baseline characteristics of the participants are outlined in Table 1, which indicates no significant differences between the groups across all baseline measures. Table 2 presents the within- and between-group analysis of pre- and post-test Q-angle and quadriceps muscle strength in the VMO and general quadriceps training groups. The mixed-design analysis showed no statistically significant group × time interaction effects for right Q-angle, left Q-angle, right quadriceps strength, or left quadriceps strength (all $p>0.05$), indicating that changes over time did not differ significantly between the two intervention groups. Figure 2 presents descriptive percentage changes in Q-angle and quadriceps strength for both groups following the intervention. Overall, both groups showed reductions in Q-angle and increases in quadriceps strength; however, these values are reported descriptively only and were not subjected to inferential statistical comparison.

Table 1. Baseline characteristics of the participants (N=18)

Characteristics	VMO group (N=10)	Quadriceps group (N=8)	*p* value
Age (year)	20.00±1.33	20.13±1.55	0.86
Weight (kg)	75.84±10.51	84.44±14.88	0.17
Height (cm)	161.55±5.44	164.50±3.82	0.21
BMI (kg/m^2)	28.99±3.14	31.26±5.71	0.34
Rt Q-angle (°)	19.22±1.84	19.48±1.18	0.73
Lt Q-angle (°)	19.33±1.45	20.73±1.31	0.05
Rt Quadriceps strength (kg)	14.53±4.42	17.64±3.91	0.14
Lt Quadriceps strength (kg)	15.08±5.53	15.24±1.94	0.94

Note: BMI: body mass index, Rt: right, Lt: left.

Table 2. Mean±SD of the pre- and post-test Q-angle and quadriceps muscle strength in the VMO (N=10) and quadriceps (N=8) groups.

	Group × Time (interaction)						
	Group	Pre-test	Post-test	95% CI	F	*p* value	Partial η^2
Rt Q-angle (°)	VMO	19.22±1.84	16.20±2.01	-3.11 (-7.34-2.00)	0.58	0.47	0.076
	Quadriceps	19.48±1.18	17.92±2.67	-1.81 (-5.96-2.35)			
Lt Q-angle (°)	VMO	19.33±1.45	17.15±2.47	-0.16 (-4.52-4.21)	0.001	0.95	0.000
	Quadriceps	20.73±1.31	18.29±1.72	-1.92 (-6.54-2.70)			
Rt Quadriceps strength (kg)	VMO	14.53±4.42	18.35±4.75	-0.26 (-1.86-1.33)	1.13	0.32	0.139
	Quadriceps	17.64±3.91	20.16±3.17	-1.72 (-4.05-0.62)			
Lt Quadriceps strength (kg)	VMO	15.08±5.53	17.94±5.05	-1.40 (-2.80-0.00)	0.80	0.40	0.103
	Quadriceps	15.24±1.94	19.86±3.94	-1.14 (-3.33-1.05)			

Note: Q: quadriceps, VMO: vastus medialis oblique, Rt: right, Lt: left.

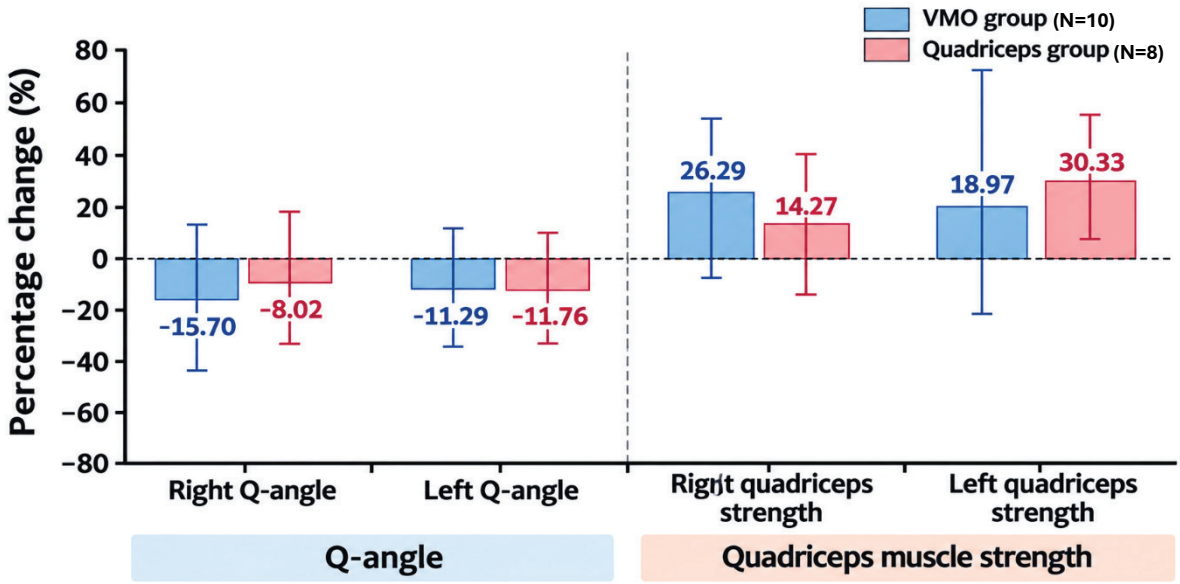

Figure 2. Descriptive percentage changes in Q-angle and quadriceps muscle strength.

Discussion

The present study examined the effects of a 4-week vastus medialis oblique (VMO)-focused exercise program compared with general quadriceps strengthening on Q-angle and quadriceps muscle strength. The mixed ANOVA showed no significant group × time interaction for any outcome variable, indicating that neither intervention was statistically superior to the other in changing Q-angle or quadriceps strength. The associated partial eta-squared values were small to moderate, suggesting limited between-group effect sizes. Therefore, the primary hypothesis was not supported, as no significant between-group differences were observed.

Effects on Q-angle

Both groups showed reductions in right and left Q-angle over the intervention period, although no significant between-group differences were observed. The small partial eta-squared values observed for Q-angle outcomes further indicate that the between-group effect size was trivial to small, implying limited practical significance despite observable numerical improvements. This suggests that general quadriceps strengthening may be as effective as VMO-specific training in influencing Q-angle. From a biomechanical perspective, Q-angle is influenced not only by VMO activation but also by global lower limb alignment, including femoral internal rotation, tibial torsion, pelvic width, and hip muscle strength.[11,37] Therefore, it is unlikely that isolated VMO strengthening alone would produce substantial structural changes in Q-angle.

Furthermore, Q-angle is traditionally considered a relatively static anatomical measure, particularly in adults, and large structural changes are not expected over short intervention periods.[38,39] This may explain why the magnitude of change observed in the present study was small and not statistically different between groups. Previous research has similarly reported limited effects of short-term exercise interventions on Q-angle, even when neuromuscular improvements are evident.[40,41]

Effects on quadriceps muscle strength

Both intervention groups demonstrated increases in quadriceps muscle strength, with no significant differences between the VMO and general quadriceps groups. However, the moderate partial eta-squared values for right and left quadriceps strength indicate small-to-moderate effect sizes, suggesting the intervention had a meaningful impact on muscle performance, even without statistically significant group differences. This aligns with the principle of training specificity, whereby any repeated knee extensor loading is likely to induce neural and muscular adaptations in the quadriceps as a whole.[42] Early strength gains, particularly within the first 4-6 weeks, are predominantly attributed to neural adaptations rather than hypertrophy.[43] This supports the notion that the observed increases in strength may reflect increased motor unit recruitment and improved neuromuscular coordination rather than true structural muscle growth.

Importantly, the lack of between-group differences suggests that selectively targeting the VMO may not confer additional benefits for overall quadriceps strength compared with general strengthening exercises. This is consistent with electromyographic studies showing that selective activation of the VMO independent of the vastus lateralis is difficult to achieve during functional exercises.[44,45] Consequently, general quadriceps strengthening may be sufficient for improving knee extensor performance in clinical populations.

Given that the vastus medialis obliquus (VMO) is anatomically part of the quadriceps femoris muscle group, general quadriceps strengthening may inherently activate the VMO, which could partly explain the absence of significant between-group differences observed in this study.[45,46]

Was the intervention duration sufficient?

A key consideration in interpreting these findings is whether the 4-week intervention period was sufficient to induce meaningful biomechanical or structural adaptations. Muscle hypertrophy and tendon or alignment-related changes typically require longer training durations, often exceeding 6-8 weeks.[47,48] Therefore, the short duration of the intervention may have limited the potential for detecting larger between-group differences, particularly in Q-angle, which reflects structural alignment rather than purely neuromuscular control.

Previous studies investigating patellofemoral biomechanics commonly employ intervention periods of 6–12 weeks or longer and report more substantial functional improvements.[41,49] It is therefore plausible that the present study was underpowered in both sample size (Type II error) and intervention duration to detect small-to-moderate between-group effects.

Training intensity and load

In addition to duration, the training intensity and mechanical loading may also have influenced the outcomes. While the exercise program was likely sufficient to stimulate improvements in quadriceps strength through neural mechanisms, it may not have provided adequate mechanical stimulus to elicit meaningful structural remodeling of the quadriceps muscle or patellofemoral joint alignment.[48,50] Structural changes in muscle and connective tissue depend on progressive overload, sufficient training volume, and high mechanical tension, which are critical for inducing hypertrophy and altering musculoskeletal properties.[42,48] Consequently, although participants demonstrated functional improvements, the training load may have been insufficient to generate detectable

changes in static Q-angle, which is strongly influenced by bony alignment and long-term neuromuscular adaptations.[11]

Exploratory between-group percentage changes

Figure 2 presents the descriptive percentage changes in Q-angle and quadriceps muscle strength following the 4-week intervention in both groups. Overall, both the VMO and quadriceps groups demonstrated reductions in Q-angle and increases in quadriceps strength, indicating improvements in lower limb alignment and muscle performance.

For Q-angle, both groups showed comparable decreases bilaterally. The VMO group exhibited a mean reduction of -15.70% on the right and -11.29% on the left, while the quadriceps group showed reductions of -8.02% and -11.76%, respectively. These findings suggest that both exercise programs were associated with modest improvements in patellofemoral alignment, with slightly greater reductions in the VMO group on the right.

For quadriceps strength, both groups showed substantial percentage increases. The VMO group showed increases of 26.29% (right) and 18.97% (left), whereas the quadriceps group demonstrated increases of 14.27% (right) and 30.33% (left). The large standard deviations indicate considerable inter-individual variability in training responses, particularly for muscle strength outcomes.

Importantly, these data are descriptive and should be interpreted in conjunction with the mixed ANOVA results, which showed no statistically significant group × time interactions. Therefore, although both groups exhibited changes, Figure 2 supports the conclusion that the magnitude of change was broadly comparable between interventions over the 4-week period, rather than indicating superiority of one program over the other.

Limitations

Several limitations should be acknowledged. Firstly, the small sample size limited statistical power to detect between-group differences, particularly group × time interaction effects, and increased the risk of Type II error. Secondly, the short intervention duration (4 weeks) may have been insufficient to induce meaningful structural or biomechanical adaptations. Thirdly, the absence of a non-exercise control group restricts causal inference, as observed changes may reflect learning effects or natural variability. Fourthly, using static Q-angle as an outcome measure may not fully capture dynamic knee mechanics during functional activities. Finally, the specific participant population (young overweight/obese females) limits the generalizability of the results to other groups.

Future study

Future studies should include a larger sample size and a longer training period to determine whether VMO-focused and general quadriceps strengthening exercises produce different effects over time. A non-exercise control group should also be included to better determine whether the observed changes are related to the exercise programs. In addition, dynamic knee alignment and VMO and VL muscle activity should be assessed to provide more information than static Q-angle measurement alone. Longer-term follow-up may also help determine whether changes in Q-angle and quadriceps strength are maintained after the intervention.

Practical implications

The findings suggest that both VMO-focused and general quadriceps strengthening exercises may reduce Q-angle and increase quadriceps strength over a short-term period (4 weeks). However, the study found no statistically significant differences between interventions, suggesting neither approach clearly outperformed the other within this timeframe. From a clinical perspective, these results imply that clinicians may have flexibility in exercise prescription, and both targeted and general strengthening programs could be considered as part of early-phase rehabilitation. Nevertheless, given the exploratory nature of the study, small sample size, short intervention duration, and lack of a control group, interpret these implications cautiously. The present findings should not be generalized to longer-term rehabilitation programs, and further studies with larger samples and extended follow-up periods are required before definitive clinical recommendations can be made.

Conclusion

Both VMO-focused and general quadriceps strengthening exercises were associated with within-group decreases in Q-angle and increases in quadriceps muscle strength; however, no statistically significant differences were observed between interventions. These findings suggest that neither approach clearly outperformed the other over the 4-week period. Given the small sample size, short intervention duration, and absence of a control group, the results should be interpreted as preliminary, and further adequately powered studies are required to confirm these findings. Future studies incorporating longer intervention periods and neuromuscular measures, such as EMG onset timing or assessments of muscle morphology, may provide deeper insights into the differential effects of VMO-focused versus general quadriceps training.

Ethical approval

The study obtained approval from the University of Phayao Human Ethics Committee (HREC-UP-HSST 1.2/098/67) and complied with the Declaration of Helsinki. The protocol was authorized by the Thai Clinical Trials Registry (TCTR20240723014).

Declaration of generative AI and AI-assisted technologies

ChatGPT (OpenAI) was used to assist with English language editing and improve the clarity of the manuscript. Grammarly was used to check grammar, spelling, and language. All content was reviewed and approved by the authors, who take full responsibility for the final manuscript.

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Conflict of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Somruthai Poomsalood: conceptualization, methodology, visualization, validation, data analysis, writing-English original draft; **Panida Hanphitakphong:** data analysis, result summary; **Palagon Udomkichpagon** and **Chatchadaporn Jaiyen:** investigation, writing-reviewing and editing; **Chayanid Wongchanta, Natthaphon Chanrak** and **Vasita Cheeprem:** data collection, methodology.

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