

## การเปลี่ยนแปลงความยาวและมุมของเส้นกล้ามเนื้อยืดข้อเข่า หลังการออกกำลังกายแบบแรงต้านสองชนิด

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### บทคัดย่อ

**บทนำ** การปรับตัวของกล้ามเนื้อทางกายวิภาคและสรีรวิทยามีผลต่อประสิทธิภาพการทำงานประจำวันของเราอย่างมาก การเข้าใจถึงวิธีการฝึกออกกำลังกายที่มีผลต่อการปรับปรุงประสิทธิภาพกล้ามเนื้อเหล่านี้เป็นประโยชน์ในการพัฒนาความสามารถและเพิ่มประสิทธิภาพในชีวิตประจำวัน

**วัตถุประสงค์** เพื่อศึกษาผลของโปรแกรมออกกำลังกายของกล้ามเนื้อยืดข้อเข่า (knee extensor training) สองแบบในกล้ามเนื้อ Vastus Lateralis ทั้งทางกายวิภาคและสรีรวิทยา

**วิธีการศึกษา** การศึกษานี้รวมผู้เข้าร่วม 20 คน ที่มีสุขภาพแข็งแรง (อายุ =  $21.10 \pm 0.40$  ปี, ส่วนสูง =  $1.74 \pm 0.50$  เมตร, น้ำหนัก =  $69.10 \pm 11.00$  กิโลกรัม) คัดเลือกมาจากคณะวิทยาศาสตร์การกีฬา มหาวิทยาลัยบูรพา และแบ่งกลุ่มโดยสุ่มให้เข้าร่วมโปรแกรมฝึกออกกำลังกาย 2 แบบ ภายใน 6 สัปดาห์: โปรแกรมฝึกตั้งเดิมความหนักสูง (HI) หรือโปรแกรมฝึกในรูปแบบผสมความหนักสูงและความหนักน้อยร่วมกับเทคนิคการจำกัดการไหลเวียนโลหิต (MIX) ทดสอบก่อนและหลังโปรแกรมฝึกออกกำลังกาย 1 สัปดาห์ก่อนและหลังจากสิ้นสุดโปรแกรม ประเมินโดยวัดมุมของเส้นกล้ามเนื้อ (Pennation angle) และความยาวของเส้นกล้ามเนื้อ Vastus lateralis โดยรังสีแพทย์ที่ไม่ทราบโปรแกรมการออกกำลังกายของผู้ถูกศึกษา โดยใช้อัลตราซาวนด์ B-mode และประเมินความแข็งแรงของกล้ามเนื้อที่เพิ่มขึ้น (maximum strength) การวิเคราะห์ทางสถิติใช้ IBM SPSS Statistics เวอร์ชัน 20

**ผลการศึกษา** หลังจากการฝึกออกกำลังกายเป็นเวลา 6 สัปดาห์ โปรแกรมฝึก HI และ MIX ทั้งสองโปรแกรมมีผลลัพธ์ในการเพิ่มความยาวของเส้นกล้ามเนื้ออย่างมีนัยสำคัญ โดยมีขนาดเท่ากับ 12.13 มม. และ 11.81 มม. ตามลำดับ ( $p < 0.05$ ) อย่างไรก็ตาม ไม่มีการเปลี่ยนแปลงทางสถิติที่มีนัยสำคัญในมุมของเส้นกล้ามเนื้อของทั้งสองกลุ่ม ( $p > 0.05$ ) และพบว่า มีการปรับตัวทางสรีรวิทยาโดยมีการเพิ่มขึ้นของ 1 repetition maximum strength ในทั้งสองกลุ่ม คือ 12.60 กก และ 18.63 กก ตามลำดับ ( $p < 0.01$ )

**สรุปผล** ทั้งสองโปรแกรมฝึกมีประสิทธิภาพในการกระตุ้นการปรับตัวของกล้ามเนื้อทั้งทางกายวิภาคและสรีรวิทยา

**คำสำคัญ** มุมของเส้นกล้ามเนื้อ ความยาวของเส้นกล้ามเนื้อ ความแข็งแรงของกล้ามเนื้อ การออกกำลังกายแบบแรงต้าน

### ผู้นิพนธ์ที่รับผิดชอบ

อริญชัย พิษณุวงษ์

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## Change of muscular length and pennation angle after two different training programs

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### Abstract

**Introduction:** Architectural and physiological adaptations of musculature significantly influence our daily functional efficiency. Understanding how exercise training affects these adaptations provides valuable knowledge for optimizing our physical capabilities and enhancing overall performance.

**Objective:** This study aims to investigate the effects of two distinct knee extensor training programs on the architectural and physiological adaptations of the vastus lateralis muscle.

**Methods:** This study included 20 active and healthy participants (age = 21.10±0.40 years, height = 1.74±0.50 m, weight = 69.10± 11.00 kg), recruited from the Faculty of Sport Science, Burapha University, and randomly assigned to one of two different 6-week training programs: 1) A high-intensity strength program (HI); or 2) a mixed-intensity strength program (MIX). Pre and Post testing was conducted one week before and after the intervention completed. The vastus lateralis pennation angle and fascicle length were assessed by B-mode ultrasound imaging technique, and muscle physiological adaptation was assessed via an increase in maximum strength. The radiologist was blind to the information about which participants were assigned to which experimental group. The statistical analysis was conducted by IBM SPSS Statistics version 20.

**Results:** After 6 weeks of training, both the HI and MIX training programs resulted in a significant increase in the fascicle length of the vastus lateralis muscle, measuring 12.13 mm and 11.81 mm, respectively (both  $p < 0.05$ ). However, there was no statistically significant change observed in the pennation angle in either group ( $p > 0.05$ ). Additionally, positive physiological adaptations were observed with an increase in 1 repetition maximum strength in both groups, measuring 12.60 kg and 18.63 kg, respectively (both  $p < 0.01$ ).

**Conclusion:** Both knee extensor training programs are effective in inducing favorable architectural and physiological adaptations.

**Keywords:** Pennation angle, Fascicle length, Muscle strength, Resistance training

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### การอ้างอิง

วทันยา ใจดี รตัญญู หลงรัก ศรสุภา ลิ้มเจริญ สุธาสินี คงพร้อมสุข ชาญธรรม สุนมหาคุณ ธีร์วัช เจียรศิริกุล และ อริญชัย พิษณุวงศ์. การเปลี่ยนแปลงความยาวและมุมของเส้นกล้ามเนื้อยืดข้อเข่า หลังการออกกำลังกายแบบแรงต้านสองชนิด. บุรพาเวชสาร. 2567; 11(2): 55-71.

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## Introduction

The structural arrangement of skeletal muscles, as assessed through architectural parameters such as pennation angle and fascicle length, alongside physiological factors like muscle strength, plays an important role in human daily functional efficiency<sup>1</sup>. Pennation angle refers to the angle at which fascicles are oriented relative to the line of action of the whole muscle, affecting the force-generating capacity of the muscle. While fascicle length is the length of a bundle of muscle fibers from one end of the muscle to the other which are directly related to the number of sarcomeres in series within a muscle fiber.

A number of studies have suggested that resistance training can induce remodeling of these architectural parameters over time<sup>2,3</sup>. The evaluation of these changes commonly relies on B-mode ultrasound imaging techniques<sup>4</sup>, recognized for their reliability and cost-effectiveness in studying human skeletal muscle anatomy<sup>5-7</sup>. Previous studies have demonstrated the reliability and validity of determining fascicle length and pennation angle using B-mode ultrasound<sup>6</sup>.

Various characteristics of resistance training, including intensity, equipment and technique, can influence the extent of architectural and physiological adaptations. For example, while one study reported increases in the pennation angle in the vastus lateralis following a 14-week lower body resistance training program with a specific high-intensity 80% of one repetition maximum (1RM) training

program<sup>8</sup>, another study did not observe significant changes in the pennation angle with squatting exercises at intensities of 30-60% 1RM<sup>2</sup>. Similarly, differences in muscle fascicle length adaptations had been noted across various training variables<sup>9-11</sup>. For instance, one study found a substantial increase in the fascicle length of the vastus lateralis with sprint jump training, whereas squat training at 6RM showed no such change<sup>9</sup>. This underscores the critical role of different exercises in driving architectural adaptations.

Theoretically, there is a proposed association between fascicle length and the maximal contractile shortening velocity of muscle fibers, suggesting that longer fascicle lengths may enhance a sprinter's ability to generate high force at high velocity, for example<sup>12</sup>. Concurrently, pennation angle is linked to the force muscles can produce<sup>13</sup>; a relationship was supported by a previous study by Drazen and team, which demonstrated significant correlations between gastrocnemius fascicle length and the isokinetic torque of plantar flexors<sup>14</sup>. Consequently, examining how training programs influence these architectural adaptations can yield valuable insights for optimizing muscle training programs, relevant for both rehabilitation<sup>10</sup> and sports training contexts<sup>15-16</sup>. Therefore, this study aims to investigate and compare the effects of two distinct knee extensor training programs on the architectural and physiological adaptations of the vastus lateralis muscle.

## Materials and methods

### Study design

The study was a randomized controlled trial designed to investigate changes in muscle pennation angle, and fascicle length as well as muscle strength, resulting from two strength training programs: 1) A high-intensity strength program (HI); and 2) a mixed-intensity strength program (MIX). The random grouping was done using the website <https://www.randomlists.com> by assigning numbers 1-20 to the participants and letting the program randomly determine which numbers would be in the HI group or the MIX group. The sample size calculation was based on parameter values from a previous study that conducted a similar test with two groups to observe muscle adaptation results (PMID: 31260419). Using the inputs of effect size = 0.75,  $\alpha$  level = 0.05 and power = 0.80, the calculation was performed using the Test-family F-test MANOVA: Repeated measures, within-between interaction, with number of groups = 2 and number of measurements = 2. This resulted in an initial n of 17. The researcher then added a 20% dropout rate, resulting in a total n of 20 participants.

The study employed an experimental design comprising two experimental groups, with standardized controls for factors such as volume, exercise order, execution pattern, repetition tempo, and rest intervals. Eligibility criteria required participants to have no prior structured resistance training experience to minimize experience-related biases.

Furthermore, all resistance training sessions were closely monitored by a certified personal trainer within a controlled setting. Baseline testing included muscle pennation angle and fascicle length assessment via ultrasound imaging technique and 1 repetition maximum testing via a knee extension machine. This study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of the Burapha University Ethics Committee (IRB3-083/2566).

### Participants

Inclusion criteria included students from the Sport Science Faculty who had no functional limitations, with no history of substance use affecting muscle architecture and muscle strength, as well as no resistance training experience. A general health screening was conducted by a physician, and informed consent was obtained from all participants.

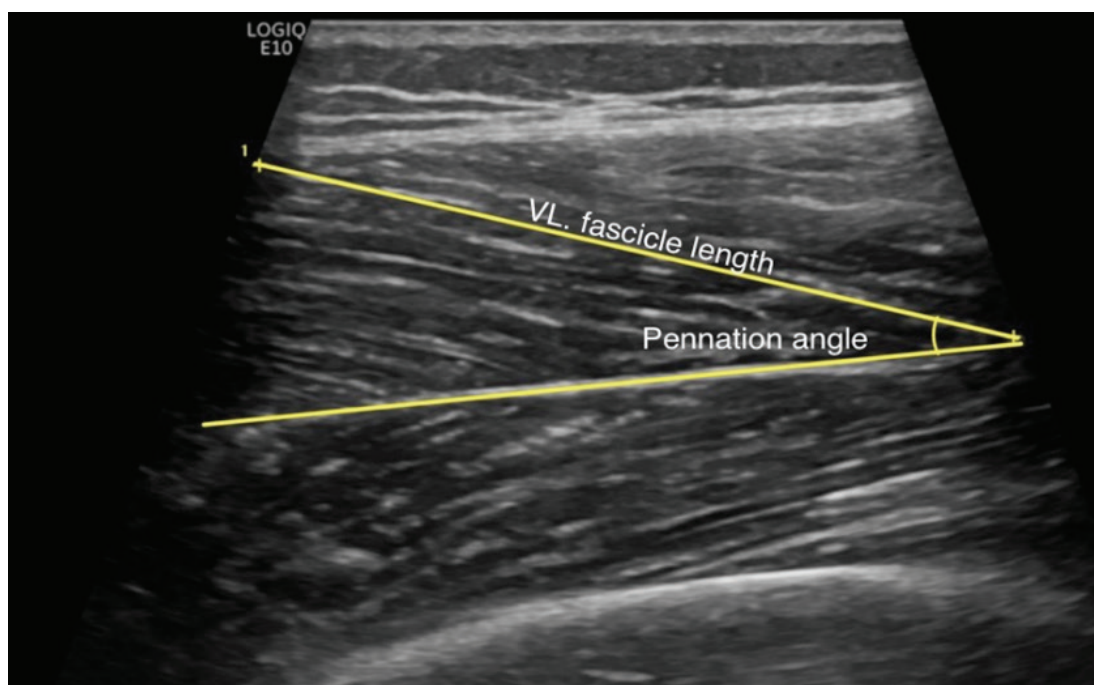
Twenty healthy males (age =  $21.10 \pm 0.40$  years, height =  $1.74 \pm 0.50$  m, weight =  $69.10 \pm 11.00$  kg) from 3<sup>rd</sup>- year sport-science majors were recruited to this study. Sample size was calculated by a priori power analysis using G\*power with an effect size = 0.75,  $\alpha$  = 0.05, power = 0.80 plus with 20% dropout rate. The input parameter was adopted from a previous study which employed a similar experimental design<sup>17</sup>. This proactive approach ensured sufficient statistical power to detect meaningful effects within the study population. Participants were randomly assigned to either the HI (n=10) or MIX (n=10) group using the

aforementioned research randomizer program to prevent bias. Although the training process cannot be blind, the radiologist is blind to the information about which participants are assigned to which experimental group.

### Muscle architectural assessments

In accordance with established recommendations<sup>4</sup>, the study utilized a B-mode ultrasonography device (LOGIQ E10 Series, GE Healthcare, USA) with a linear probe operating at a frequency range of 2-9 MHz. Ultrasound imaging was conducted one week before and one week after the training intervention. Imaging data was collected from the vastus lateralis muscle at 30% length of

femur, as identified anatomically from the greater trochanter to the lateral epicondyle of the femur. Standardized positioning and technique were maintained throughout the imaging process to minimize variability. Muscle pennation angle (PA) was determined as the angle between the fascicle and the deep aponeurosis, while fascicle length (FL) was determined as the length of the fascicular path spanning from the superficial to the deep aponeuroses, as observed on the ultrasound images<sup>18</sup> (Figure 1). Both fascicular length and pennation angle were measured by a subspecialist radiologist with 5-years experience in diagnostic radiology and 2-years experience in advanced diagnostic body imaging.



**Figure 1** Example image of the vastus lateralis muscle fascicle length and the pennation angle of a random participant

### Muscle strength test

The dynamic strength test as 1 repetition maximum (1RM), was conducted under the supervision of the researcher. 1RM was assessed by finding the greatest load each participant could lift for one time, with proper form, through a full range of motion. All strength testing procedures were strictly controlled. For leg extension exercises, the participants sat on the leg extension machine (Body Solid, USA), where they moved the load from a

starting point (knee flexion approximately at 90 degree) to full knee extension (0 degree of knee flexion), one time per attempt. The load would be gradually increased following each successful attempt in order to increase the intensity for the next attempt. If the repetition was unsuccessfully completed, the load was decreased. The process continued until the maximum load the participant could lift for 1 repetition was obtained. The recovery period of each attempt was 4 minutes.



**Figure 2** Knee extension machine (Body Solid, USA)

### Knee extensor training programs

Two programs were used in this study. While the current high-intensity strength program (HI) can be effective for strength and muscle gains, it may present challenges in terms of injury risk for certain populations, susceptibility to mental fatigue, and potentially suboptimal improvements in endothelial function, as compared to lower intensities<sup>39-40</sup>. For these reasons, we developed the new mixed-intensity strength program (MIX) containing both high and low intensities to reduce the potential drawbacks.

In the first two weeks of the high-intensity strength program (HI) participants performed only three sets of knee extension training using the knee extension machine (Body Solid, USA), using an external load at 70% of 1RM. Repetitions were performed to failure in every training set. The exercises were performed with a fixed repetition tempo of 2 seconds for concentric phase and 2 seconds of eccentric phase. Participants took a 60-second rest between sets. Participants needed to perform every repetition with a full range of

motion. The training volume set was increased to 6 sets in week 4 and 5, and 8 sets in week 5 and 6. In the mixed-intensity strength program (MIX), participants performed two sets of high-intensity training at 70% of 1RM, and one set of low intensity training at 30% of 1RM. The low intensity set was combined with a practical blood flow restriction (pBFR) technique. This pBFR was achieved by using elastic wraps (Grizzly Fitness, USA) fastened at the proximal portion of the legs, set tightly enough to achieve 40% of the perceived arterial occlusion pressure (AOP). Participants were familiarized to learn about their perceived AOP levels using a pneumatic cuff (H+Cuff, USA) before the study began. This technique was shown in previous studies to enhance muscle adaptations<sup>19,20</sup>. The training volume set was increased to 3 sets of each intensity in the third and fourth weeks, and then to 4 sets in the fifth and sixth weeks. The training sessions occurred once per week consistently throughout the training program. All other training variables remained consistent across both groups. Details are illustrated in Table 1.

**Table 1** Knee extensor training programs via knee extension exercises

Duration HI	(n=10)	MIX (n=8)
1 <sup>st</sup> -2 <sup>nd</sup> week	• 3 sets at 70% 1RM	• 2sets at 70%1RM • 1sets at 30%1RM + pBFR
3 <sup>rd</sup> -4 <sup>th</sup> week	• 6 sets at 70% 1RM	• 3sets at 70%1RM • 3sets at 30%1RM + pBFR
5 <sup>th</sup> -6 <sup>th</sup> week	• 8 sets at 70% 1RM	• 4sets at 70%1RM • 4sets at 30%1RM + pBFR

**Note: Training variables:** 60-second rest between sets; 2-second concentric phase; 2-second eccentric phase; full range of motion; repetition to failure; one session/week.

Abbreviation: HI = High-intensity strength program, MIX = Mixed-intensity strength program, pBFR = practical blood flow restriction technique, 1RM = 1 repetition maximum.

### Statistical analysis

The statistical analysis was calculated to investigate and compare the effects of two different knee extensor training programs on muscle architectural and physiological adaptations. The Shapiro-Wilk test was used to analyze the distribution of data. Descriptive statistics were calculated to summarize baseline characteristics of both groups and one-way ANOVA was employed to compare baseline variables between groups. Levene's test was used to assess the homogeneity of variances. Changes in the vastus lateralis muscle pennation angle and fascicle length, and dynamic 1RM strength from baseline to post-test, were calculated and two-way repeated measured ANOVA was calculated to compare the effects between groups (HI vs. MIX), Times (Pre vs. Post) were also factored in. Effect sizes were calculated using the following

formula: mean change/pooled SD<sup>21</sup>, with interpretations based on conventional criteria of effect sizes as small ( $d > 0.2$ ), medium ( $d > 0.5$ ) and large ( $d > 0.8$ ). Statistical analyses were performed using IBM SPSS Statistics version 20, with a significance level set at  $\alpha = 0.05$ .

### Results

Table 2 displays the baseline characteristics of the participants. Initially, 20 participants were recruited, but 2 dropped out during the study—one due to knee injury after playing another sport and the other due to loss of interest—leaving 8 participants in the MIX group and 10 participants in the HI group for final analysis. Statistical analysis revealed no significant differences in participant characteristics between the two groups at baseline ( $p > 0.05$ ).

**Table 2** Participant's characteristics at baseline

Variables	HI (n=10)	MIX (n=8)	F	p-value
Age (years)	21.25±0.70	21±0	1.27	0.28
Height (m)	1.73±0.55	1.74±0.53	0.01	0.93
Body weight (kg)	68.50±11.40	69.50±11.90	0.43	0.52
Pennation angle (degree)	15.55±5.03	14.51±3.15	0.30	0.62
Fascicle length (mm)	71.98±10.76	74.01±10.31	0.16	0.69
1RM (kg)	64.70±8.92	70.00±18.05	0.67	0.43

**Note:** Data were presented as mean ± standard deviation. Abbreviation; HI = High-intensity strength program, MIX = Mixed-intensity strength program, 1RM = 1 repetition maximum.

A significant main time effect was found for only the vastus lateralis muscle fascicle length ( $F_{[1,16]} = 19.39$ ,  $p = 0.00$ ,  $\eta^2_p = 0.55$ ) and 1RM strength ( $F_{[1,16]} = 54.50$ ,  $p = 0.00$ ,  $\eta^2_p = 0.77$ ). No significant main time effect to the

vastus lateralis muscle pennation angle was observed ( $p = 0.05$ ). However, no main effect group or interaction was revealed ( $p > 0.05$ ) for all pennation angles, fascicle lengths and 1RMs (Table 3).

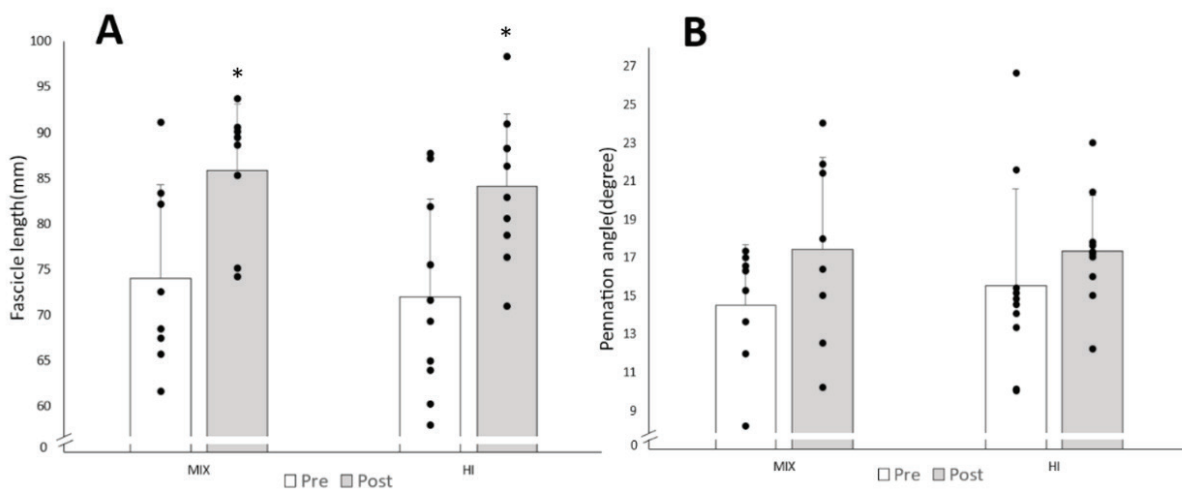
**Table 3** Changes in muscle architectures and physiology

Variables	HI (n=10)				MIX (n=8)				Effect <i>p</i>		
	Pre	Post	$\Delta$ (95%CI)	<i>d</i>	Pre	Post	$\Delta$ (95%CI)	<i>d</i>	Group	Time	Interaction
	Mean $\pm$ S.D.	Mean $\pm$ S.D.			Mean $\pm$ S.D.	Mean $\pm$ S.D.					
PA <sub>VL</sub> (degree)	15.55 $\pm$ 5.03	17.34 $\pm$ 2.90	1.79 (-1.71;5.29)	.44	14.51 $\pm$ 3.15	17.41 $\pm$ 4.82	2.90 (-.78;6.57)	0.71	.76	.05	.62
FL <sub>VL</sub> (mm)	71.98 $\pm$ 10.76	84.11 $\pm$ 7.92*	12.13 (3.28;20.98)	1.28	74.01 $\pm$ 10.31	85.83 $\pm$ 7.28*	11.81 (3.31;20.32)	1.32	.59	.00	.95
1RM (kg)	64.70 $\pm$ 8.92	77.30 $\pm$ 12.79 <sup>†</sup>	12.60 (8.15;17.05)	1.13	70.00 $\pm$ 18.05	88.63 $\pm$ 27.04 <sup>†</sup>	18.63 (9.02;28.23)	0.81	.31	.00	.17

**Note:** Data were presented as mean  $\pm$  standard deviation. Abbreviation: HI = High-intensity strength program, MIX = Mixed-intensity strength program, PA = Pennation angle, FL = Fascicle length, 1RM = 1 repetition maximum, VL = Vastus lateralis muscle. \*  $p < .05$  compared to Pre, <sup>†</sup>  $p < .01$  compared to Pre.

Specifically, significant increases in vastus lateralis muscle fascicle length, as assessed by ultrasound imaging, was observed at 16.85% ( $p = 0.01$ ;  $CI_{95\%} = 3.28$  to 20.98;  $d = 1.28$ ) and 15.97% ( $p = 0.01$ ;  $CI_{95\%} = 3.31$  to

20.32;  $d = 1.32$ ) in the HI and MIX groups, respectively (Figure 3). Furthermore, 1RM was significantly increased in both groups for 19.47% ( $p = 0.00$ ;  $CI_{95\%} = 8.15$  to 17.05;  $d = 1.13$ ) and 26.61% ( $p = 0.00$ ;  $CI_{95\%} = 9.02$  to 28.23;  $d = .81$ ), respectively.



**Figure 3** Vastus lateralis muscle fascicle length (A) and pennation angle (B) from Pre to Post intervention. Each participant was depicted by a black dot that indicated individual variation. Data were represented as mean with a standard deviation error bar. \* Indicates significant differences from Pre for each group ( $p < .05$ )

## Discussion

The main findings of this study were 1) both high-intensity and mixed-intensity strength programs resulted in a significant increase in fascicle length ( $p < .05$ ) and slightly, although non-significantly ( $p > .05$ ), an increase in the pennation angle of the vastus lateralis muscle and 2) both programs potentially induced positive physiological adaptation as showed by a significant increase in 1RM strength ( $p < .05$ ).

The vastus lateralis is used to evaluate muscle strength due to its anatomical importance as the largest and most powerful component of the quadriceps, contributing significantly to knee extension strength, accessibility for various measurement techniques – including ultrasound due to its superficial position, and strong correlation with functional performance<sup>37,38</sup>.

The findings of this study align with previous studies which have demonstrated that strength training resulted in significantly increased fascicle length of trained muscles in humans<sup>22-24</sup>. For instance, Walker and colleagues demonstrated that even in already-trained men, a significant 13.7% increase in fascicle length of the vastus lateralis muscle was observed following eccentric strength training, where the muscle was stretched eccentrically to its full range of motion under heavy external load<sup>24</sup>. Additionally, Franchi and teams compared eccentric-only with concentric-only resistance training of the quadriceps muscle, reporting a significant 19%

increase in fascicle length in the eccentric group<sup>22</sup>, suggesting the importance of eccentric loading in inducing fascicle length changes when the muscle was stretched.

In our current study, both the HI and MIX groups exhibited significant increases in fascicle length, with increments of 16.85% ( $p = .01$ ,  $d = 1.28$ ) and 15.97% ( $p = .013$ ,  $d = 1.32$ ), respectively. These findings contributed to the literature by indicating that training programs that involved a combination of concentric and dynamic contractions with a full range of motion could effectively elicit fascicle length adaptations. Therefore, using a MIX program instead of the conventional HI program might lower muscle stress with comparable strength gain.

However, it's worth noting that not all studies align with our findings. For instance, a recent study demonstrated that after a 7-week training program, there was no statistically significant change in the fascicle length of the vastus lateralis muscle among participants (87.9 vs 87.1 mm,  $p = 0.77$ ) from pre to post-test, respectively<sup>25</sup>. Potential reasons were possibly due to the conventional protocol that did not emphasize eccentric training on the vastus lateralis, a limited number of participants ( $n = 13$ ), and individual variability among the participants – four participants showed increases above the calculated coefficient of variation (CV), while five showed decreases below the CV.

Additionally, the adaptation of fascicle length following strength training was

observed across various muscles in both the upper and lower extremities. The previous study also reported a significant increase of approximately 9% in fascicle length of the triceps belly after 6 weeks of triceps cable pushdown training<sup>26</sup>, suggesting that all pennate muscles might have the potential to increase fascicle length following a period of strength training. Furthermore, the insights about the relationship between fascicle length and muscle hypertrophy were questioned by leading researchers: Fukutani and Kurihara. They conducted a comparison between two groups of participants, one trained and one untrained, using ultrasound imaging to assess muscle size and fascicle length. Surprisingly, despite the greater muscle thickness observed in the resistance-trained participants, both groups exhibited similar fascicle lengths<sup>27</sup>. This indicates that fascicle length might not always accurately reflect muscle size or hypertrophy; nevertheless, this hypothesis was challenged by some previous studies<sup>10,28</sup>. However, our current study did not include data collection on muscle thickness, limiting the exploration of this hypothesis. Yet, fascicle length remains an important consideration in understanding muscular adaptations to training. Further investigation is warranted to fully understand the relationship between fascicle length and muscle size in the context of resistance training adaptations.

Mechanistically, the increase in fascicle length could be attributed to sarcomerogenesis, the process of adding sarcomeres in series

within muscle fibers<sup>29</sup>. In the context of our study, where training involved a full range of motion, it was plausible that the muscles were stretched under load to their maximum length, potentially stimulating the generation of sarcomeres in series<sup>30</sup>. This notion was supported by the study by Noorkoiv and groups, which demonstrated that the sum increase in fascicle length of the vastus lateralis and rectus femoris muscles was greater when knee extensors were trained at long muscle lengths, involving full muscle stretching, compared to training at short muscle lengths, with increases of about 13.1% versus 8.7%, respectively<sup>23</sup>. Similarly, McMahon and teams had observed that loading the quadriceps in a lengthened position in untrained participants resulted in a significant increase in fascicle length, approximately 29.4%, compared to only 14% when the quadriceps were loaded in a shortened position<sup>31</sup>. This collective data suggests that training programs emphasizing loading muscles when stretching at longer lengths may be more effective in inducing fascicle length adaptations.

Additionally, the slight, albeit non-significant ( $p = 0.05$ ), increase in pennation angle observed in our study (1.7degree and 2.9degree in HI and MIX, respectively) was consistent with findings from previous research, indicating that resistance training typically resulted in increases in the pennation angle due to muscle hypertrophy<sup>9</sup>. For instance, the effects of strength training in healthy male participants undergoing a 14-week training

program with intensities ranging from 4 to 12 RM, had showed a significant increase in the pennation angle of the vastus lateralis muscle from 8 degrees to 10.7 degrees, corresponding to a relative change of approximately 35.5%<sup>8</sup>. Furthermore, this was supported by another previous study showing that a resistance training program focusing on moderate to heavy loads (4-10RM) led to a 23% increase in pennation angle, from approximately 10.4 degrees to 12.9 degrees, after 10 weeks of training, whereas this adaptation was not observed after endurance training<sup>32</sup>.

Interestingly, Ema and colleagues employed training programs very similar to our current study, by utilizing a knee extension machine with intensity at 80% 1RM and repetition tempo of 2 seconds for both eccentric and concentric – as did our current study<sup>33</sup>. They reported that after 12 weeks of knee extensor training, the increase in muscle thickness (1.7 mm and 2 mm at proximal and distal regions, respectively) co-occurred with the increase in pennation angle (1.2 degrees and 1.9 degrees at the proximal and distal regions, respectively) in the vastus lateralis muscle<sup>33</sup>. These findings suggested that resistance training, particularly when performed with moderate to heavy loads and controlled repetition tempi, could effectively promote increases in the pennation angle as well as muscle hypertrophic adaptations.

In the present study, while statistical significance was not observed, it is worth noting that our training duration was only 6 weeks.

Additionally, considering that the p-value was 0.05, which approached the threshold of statistical significance, it was plausible that a slightly longer training period could yield significant differences.

In terms of physiological adaptations, our current study demonstrated a significant increase in 1RM strength in both training groups (19.47% and 26.61% in HI and MIX, respectively). This outcome aligned with prior studies, indicating that after a period of strength training, muscle strength gains were commonly observed, regardless of whether the training intensity was high or low, with or without blood flow restriction<sup>34-35</sup>.

For example, a recent meta-analysis indicated that both high-load training (>60% 1RM) and low-load training (<60% 1RM) could effectively induce increases in one repetition maximum strength. However, the statistical analysis revealed a significant favoring of high load (effect size = 1.69 vs 1.32,  $p = 0.00$ , equivalent percentage gain to 35.3% vs 28%)<sup>34</sup>. This was in accordance with a recent meta-analysis, focusing on older individuals, conducted by Centner and groups. They found that muscle hypertrophy was similar between high-intensity and low-intensity blood flow restriction, yet strength gain was favored by high-intensity training<sup>36</sup>.

Nonetheless, the findings of our current study were contrasting, though interesting. The current findings showed that when half of the volume of high-intensity program sets was replaced by low-intensity blood flow

restriction sets, the increase in maximum strength was not affected. The MIX group could still increase 1RM strength to a similar degree as the HI group (26.61% vs 19.47%, respectively). Our current finding was in line with the previous mentioned study by Ema and teams, which found a similar extent of increase in 1RM knee extension strength (26.4%) after periods of 12 weeks of knee extensor training at 80% 1RM<sup>33</sup>, yet our study lasted for only 6 weeks. Therefore, we put forwards the practical implication that training programs might not necessarily need to be composed exclusively of high-intensity sets in order to maximize increases in maximum strength. Lastly, it should be noted that all our participants were sport-science students, whose baseline strengths might differ from the general population. Further study in other populations might yield interesting issues.

### Conclusion

In summary, both knee extensor training programs resulted in significant increases in fascicle length, yet no significant difference was observed in the pennation angle. It was plausible that longer training periods (exceeding 6 weeks) may be necessary to achieve statistical significance. Besides, the findings indicated that both training programs effectively induced positive physiological adaptations, as proven by the increase in maximum strength.

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