Plantarflexor Torque and Work is Positively Correlated with Medial Gastrocnemius Fascicle Length in Healthy Young Adults

John F Drazan[1], Todd J Hullfish[1], Josh R Baxter[1]

[1]Department of Orthopedic Surgery, University of Pennsylvania, Philadelphia, Pennsylvania, United States

Corresponding Author:
Josh R Baxter[1]
Human Motion Lab, 3737 Market Street, Philadelphia, Pennsylvania, 19104, United States
Email address: josh.baxter@uphs.upenn.edu

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ABSTRACT

Ankle kinetics are critical for ambulatory function in elite athletes, the elderly, and many patient populations. Despite the robust findings linking plantarflexor muscle structure to gross function with these populations, the link between plantarflexor fascicle length and ankle kinetics has not been established in the literature. In this study, we determined the relationship between muscle structure and peak torque and total work produced by the plantarflexors during maximal effort contractions. We measured resting fascicle length and pennation angle of the medial gastrocnemius using ultrasound in healthy adult subjects (n=12). Subjects performed contractions on a dynamometer during isokinetic and isometric conditions. Longer fascicles were positively correlated with higher peak torque and total work ($R^2 > 0.41$, $p < 0.013$) across all isokinetic velocities. Higher pennation angles were negatively correlated with peak torque and total work ($R^2 > 0.296$, $p < 0.067$). None of these correlations were significant in isometric conditions. This provides experimental evidence demonstrating the link between plantarflexor muscle structure and ankle kinetics in healthy young adults which has hitherto not been experimentally demonstrated in existing literature.

INTRODUCTION

Torque generation about the ankle plays a crucial role human locomotion and is largely determined by the structure of the plantarflexor muscles. Small variations in plantarflexor structure explain functional differences in athletes (Abe et al., 2000; Kearns et al., 2000), the elderly (Thom et al., 2007), and patients with Achilles tendon injuries (Hullfish et al., 2018). Sprinters benefit from reduced mechanical advantage and longer muscle fascicle to accelerate at the start of a sprint race (Abe et al., 2000; Lee and Piazza, 2009). Even amongst highly trained sprinters, faster athletes have longer plantarflexor fascicles than their slower counter parts (Abe et al., 2001; Kumagai et al., 2000). Conversely, elderly adults with limited mobility benefit from increased plantarflexor leverage to generate the torques required to walk quickly (Lee and Piazza, 2012). Achilles tendon ruptures stimulate rapid remodeling of the plantarflexor muscles (Hullfish et al., 2018) that permanently reduce muscle shortening capacity and heel raise function (Baxter et al., 2018).

Plantarflexor function is governed by active muscle shortening that acts about the ankle joint to extend the foot. Plantarflexion power is better explained by joint leverage than muscle mass, which suggests that muscle shortening demands are stronger determinants of plantarflexor power than isometric muscle force (Nagano et al., 2007). Several critical musculoskeletal parameters have been linked to plantarflexor torque and work capacity. Plantarflexor muscle volume and moment arm are both correlates of peak isometric torque (Baxter and Piazza, 2014). The effects of fascicle length on isokinetic muscle function have been demonstrated in isolated muscle preparations (Lieber, 1997) and expanded to plantarflexor function using computational musculoskeletal models (Baxter et al., 2019). The force-velocity properties of skeletal muscle were first described by A.V. Hill in his seminal work on muscle function (Hill, 1938). However, these foundational properties of skeletal muscle mechanics relating fascicle length to force-velocity have not yet been demonstrated in the physiologic context of the human plantarflexors (Ema et al., 2016).

The purpose of this study was to determine the relationship between muscle structural parameters, which govern fascicle shortening speed, and plantarflexor function in healthy young

adults. Given that longer and less pennate fascicles increase the potential for total muscle shortening velocity, we hypothesized longer fascicles be correlated with increased plantarflexor torque and work and that increased pennation would be correlated with decreased plantarflexor torque and work during isokinetic contractions. To test this hypothesis, we quantified the fascicle length and pennation angle in the medial gastrocnemius using ultrasound imaging and measured plantarflexion torque and work in maximal isometric and isokinetic conditions at three rates of ankle rotation on an isokinetic dynamometer. Based on our previous computational modeling (Baxter et al., 2019) , we hypothesized that fascicle length would be the strongest correlate with plantarflexor kinetics, while pennation angle would be less strongly correlated.

METHODS

Plantarflexor muscle structure and function was quantified in 12 healthy young adults (6 male, age: 25 ± 4.54, BMI: 23.1 ± 4.48) who provided written informed consent in this IRB approved by the University of Pennsylvania IRB (828374). Subjects were recreationally active and had no reported history of Achilles tendon injury in either leg. We acquired measurements of plantarflexor structure and function of the right leg with subjects positioned prone on an isokinetic dynamometer (System 4, Biodex, Shirley, NY). Each subject was positioned on a treatment table that was rigidly secured to the dynamometer while wearing standardized lab shoes. After their foot was secured to the foot plate with the medial malleolus aligned with the spindle of the dynamometer, each subject selected their ankle range of motion by fully dorsiflexing and plantarflexing their ankle. Once the subject specific range of motion was set, the investigator set the ankle neutral position, which was recorded for post-processing. To ensure consistency between subjects, all experimental procedures were performed by a single investigator.

To quantify medial gastrocnemius structure, we acquired ultrasound images of the medial gastrocnemius throughout the entire passive range of motion of each subject. We positioned the 7.5 MHz, 6 cm probe (LV7.5/60/128Z-2, SmartUs, TELEMED) over the mid-substance of the muscle belly and secured it to the leg using a custom-made cast and strap system. Ultrasound images were acquired between 30 and 60 Hz while each subject's ankle was moved through its passive range of motion moving from plantarflexion to dorsiflexion at a rate of 10 degrees/s. We quantified resting fascicle length, pennation angle, and muscle thickness with the ankle at the resting angle. This resting angle was set to 16 degrees based on values of average resting ankle position across 42 patients reported in the literature (Zellers et al., 2018). We manually identified the superficial and deep aponeuroses and a muscle fascicle by selecting two points on each structure to form a line (Fig. 1). This manual approach of fascicle measurement has been demonstrated to be repeatable within the same observer (Drazan et al., 2019). We calculated fascicle length as the distance between the superficial and deep attachments of the fascicle and pennation angle as the angle between the fascicle and the deep aponeurosis. We averaged each of these measurements of structure across three passive range of motion trials to determine the measures of resting muscle structure we used in our analyses.

To determine plantarflexor work and peak torque, subjects performed maximal voluntary plantarflexor contractions on an isokinetic dynamometer in maximal isometric contractions at neutral ankle angle and isokinetic contractions at three rotational speeds. The subject's right foot was secured to a foot plate with the medial malleolus of the ankle aligned with the dynamometer's spindle. First, we measured peak isometric plantarflexor torque with the ankle at

neutral with subjects in prone position. Next, peak isokinetic plantarflexion contractions were performed throughout the entire range of motion at three speeds: slow (30 degrees per second), medium (120 degrees per second), and fast (210 degrees per second). At the start of each of these trials, we confirmed that the subject positioned their ankle in their peak dorsi-flexion angle. We provided verbal encouragement (McNair et al., 1996) as well as visual feedback to ensure that subjects maximally contract their plantarflexors during each condition. Subjects continued to perform maximal plantarflexion contractions for each test condition until the peak torque was consistent for two consecutive trials. We calculated peak torque for all of the contraction conditions and total work for each of the three isokinetic conditions and selected peak torque and maximal work values at each condition to test our research question.

To test our hypothesis that fascicle length would be positively and strongly correlated with plantarflexor kinetics and that pennation angle would be negatively and moderately correlated with plantarflexor kinetics, we performed univariate linear regression to determine the relationship between measures of medial gastrocnemius structure with plantarflexor torque and work at each contraction condition. We calculated the effect size of these regression analyses using the coefficient of determination (R^2), which is an index of the correlation strength ranging between 0 and 1 where values between 0 and 0.04 indicate negligible correlation, 0.04 and 0.25 indicate weak correlation, 0.25 and 0.64 indicate moderate correlation, and 0.64 and 1 indicate strong correlation (Morton et al., 2005). We set an *a priori* alpha level of 0.05 and performed all statistical analysis using scientific computing software (MATLAB, MathWorks, Natick, MA).

Because muscle structure and anthropometry varied in our subjects, we quantified muscle thickness and lower-leg length to determine if these factors accounted for some of the variability in plantarflexor kinetics. We calculated muscle thickness as the product of the resting fascicle length and the sine of the pennation angle. We quantified lower-leg length by measuring the distance between reflective markers placed on the lateral malleolus and the proximal head of the fibula that was measured using a 12 camera motion capture system (Raptor Series, Motion Analysis Corporation, Rohnert Park, CA). To evaluate the effect of patient stature on resting muscle structure, we linearly regressed fascicle length, pennation angle, and muscle thickness against body mass and leg length. Additionally, muscle thickness was linearly regressed against fascicle length and pennation angle.

RESULTS

Fascicle length was positively and moderately correlated with plantarflexor work (Fig. 2A) and peak torque (Fig. 3A) during isokinetic plantarflexion contractions. More than half of the variability in plantarflexor work ($R^2 = 0.599$, $p = 0.003$) and peak torque ($R^2 = 0.521$, $p = 0.008$) during 30°/s isokinetic contractions was explained by resting fascicle length. However, the correlation between resting fascicle length and plantarflexor work and peak torque decreased during faster isokinetic contractions at 120°/s ($0.413 > R^2 > 0.415$, $p < 0.024$) and 210°/s ($0.477 > R^2 > 0.4494$, $p < 0.013$). Fascicle length had the weakest correlation with peak torque during isometric conditions ($R^2 = 0.325$, $p = 0.053$). Subjects generated less torque and did less work as rotational velocity increased (Table 1).

Pennation angle was negatively and moderately correlated with plantarflexor work ($0.255 > R^2 > 0.39$, $p < 0.052$) and peak torque ($0.296 > R^2 > 0.417$, $p < 0.067$ during isokinetic plantarflexion contractions (Fig. 2B and Fig. 3B). However, these correlations had a smaller effect size than resting fascicle length for each test condition and only reached statistical

significance during 30°/s (p = 0.047) and 210 °/s (p = 0.023) conditions for measurements of peak torque. Peak isometric torque was not explained by resting pennation angle (R^2 = 0.09, p = 0.345).

Muscle thickness was moderately and significantly correlated with fascicle length (R^2 = 0.536, p < 0.001) but not correlated with pennation angle (R^2 = 0.064, p = 0.084). Despite the positive correlation between resting muscle thickness and fascicle length, resting muscle thickness was not significantly correlated with any isokinetic testing condition (Table 2). Muscle thickness was positively and weakly correlated with peak torque at isometric max (R^2 = 0.161). However, this correlation did not reach statistical significance (p = 0.197).

Muscle structure was weakly correlated with subject stature (Table 3). Fascicle length was weakly correlated with leg length (R^2 = 0.084, p = 0.046) and body mass (R^2 = 0.132, p = 0.011). Pennation angle was weakly correlated with body mass (R^2 = 0.098, p = 0.030) but not leg length. Muscle thickness was not correlated with either leg length or body mass.

DISCUSSION

In this study, we established the relationship between plantarflexor structure and function in a cohort of healthy young adults. Our findings support our hypothesis that resting fascicle length is positively correlated with plantarflexor function while pennation angle has a smaller, negative correlation with plantarflexor function. To determine if plantarflexor function was simply explained by muscle thickness, we regressed muscle thickness with plantarflexor kinetics and found no effect on plantarflexor function in any condition. Although muscle kinetics have been shown to be positively affected by increased fascicle length in isolated muscle experiments (Lieber, 1997); to our knowledge, this is the first study to link natural variation in gastrocnemius fascicle length with plantarflexor kinetics in healthy adults (Ema et al., 2016).

Our measurements of medial gastrocnemius structure and plantarflexor kinetics compare favorably with previous reports in the literature. We decided to measure resting muscle structure at 16 degrees plantarflexion to approximate muscle-tendon slack (Zellers et al., 2018). Other measurements of gastrocnemius structure were acquired with the ankle either under load or neutrally aligned which may explain slightly longer (4-9 mm) and less pennate (6-11 degrees) muscle fascicles (Baxter and Piazza, 2014; Kubo et al., 2003; Thom et al., 2007) than those we measured in this current study. Similarly, our measurements of pennation at slack are similar to earlier measurements in the medial gastrocnemius at the same position (Hoang et al., 2007). Our measurements of plantarflexion torque and work capacity compares well with the literature. Our values for torque and work done at 30 and 120 degrees per second compares well with previously reported values (Randhawa and Wakeling, 2013; Woodson et al., 1995) and our values for maximal isometric torque compares well with studies with similar subject positioning (Arampatzis et al., 2006). A previous study reported higher values for torque generation, however in this case, the subjects were all male and were seated rather than positioned in prone (Baxter and Piazza, 2014).

As hypothesized, fascicle length and pennation angle, which govern absolute muscle shortening velocity (Lieber and Ward, 2011), have greater effects on isokinetic plantarflexor function than muscle thickness. The results are intuitive within our understanding of the force-velocity properties of muscle. While fascicles of different lengths undergo the same absolute contractile velocity during a given isokinetic contraction, longer fascicles have additional sarcomeres in series which reduce relative shortening velocity. This enables longer fascicles to operate at

slower velocities on the force-velocity curve, increasing force production at all isokinetic speeds (Fig. 4A) (Lieber and Fridén, 2000). Similarly, the force-velocity effects are also affected by variation in pennation angle. Greater muscle pennation increases the fascicle shortening demands for a given muscle shortening contraction. Thus, more pennate muscles generate less force and do less work in isokinetic conditions (Fig. 4B). Our experimental findings that fascicle length explained more variation in plantarflexor kinetics than pennation angle agrees with the theoretical framework of the force-velocity properties of muscle and our recent computational model (Baxter et al., 2019).

Our results are notable because while the force-velocity properties of skeletal muscle have been well defined in isolated muscle preparations in animal models, the effects of natural variability in muscle fascicle lengths on kinetic function have not been reported in humans. Force-length characteristics have been demonstrated in humans in vivo (Maganaris, 2001). Despite evidence of variations in muscle structure between different populations of human subjects (Abe et al., 2000; Hullfish et al., 2018; Kearns et al., 2000; Kubo et al., 2003; Lee and Piazza, 2009), a recent review of the literature on muscle structure and function concluded that there were no studies reporting the relationship between fascicle length and muscle shortening velocity in humans (Ema et al., 2016). Another study found that elbow extensor velocity under no load was positively correlated with muscle volume and pennation angle but not muscle length (Wakahara et al., 2013). However, this previous study on elbow extensor kinetics did not correlate muscle structure with maximal isokinetic contractions under load and also did not directly measurement fascicle length.

This study was affected by several limitations. Despite having a small sample size, our study results are in strong agreement with both basic principles of skeletal muscle mechanics (Lieber and Fridén, 2000) and computational simulations (Baxter et al., 2019). We did not confirm maximal effort during contraction using electromyography. Instead, we provided subjects verbal encouragement and real-time visual feedback and had each subject repeat each contraction condition until their peak torques were consistent between consecutive trials. We used ultrasound to measure fascicle length and pennation angle but did not quantify muscle volume or moment arm. Our recent work found that moment arm measured with ultrasound imaging is not a good surrogate measure of geometric moment arm (Baxter and Piazza, 2018). We used muscle thickness as a proxy for muscle volume, however this yielded weak and insignificant correlations. Additionally, we did not quantify the lateral gastrocnemius or soleus muscle. While the lateral gastrocnemius functions similarly to the medial muscle belly (Héroux et al., 2016), the soleus muscle is a uniarticulate muscle with different mechanics during plantarflexor contractions (Bojsen-Møller et al., 2004). However, our findings appear to be robust given that more than 40% of plantarflexor kinetics during plantarflexion rotations were explained by variation in fascicle lengths of the medial gastrocnemius muscle.

In conclusion, our study demonstrates the link between resting structure of the medial gastrocnemius with isokinetic plantarflexion function. These findings may have important implications on plantarflexor function following muscle remodeling elicited either through injury or training. However, isokinetic plantarflexor function has limited translation to activities of daily living, and future work should directly test the link between muscle structure and movement biomechanics.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

FIGURE CAPTIONS

Figure 1 (1 column). Resting muscle architecture was measured from an ultrasound frame captured when each subject's ankle was in 16° plantarflexion. An examiner identified the two aponeuroses as well as a fascicle within the frame, each of which was approximated as a straight line. Pennation angle was calculated as the angle between the fascicle and the deep aponeurosis and muscle thickness was calculated as the sine of the pennation angle times the length of the fascicle.

Figure 2 (1 column). Plantarflexor work produced at three isokinetic speeds (30°/s – *top row*, 120°/s – *middle row*, and 210°/s – *bottom row*) is positively correlated with (*A*) fascicle length and negatively correlated with (*B*) pennation angle. Fascicle lengths explained more variation in plantarflexor work than pennation angle.

Figure 3 (1 column). Peak plantarflexor torque produced at three isokinetic speeds (30°/s – *second row*, 120°/s – *third row*, and 210°/s – *bottom row*) is positively correlated with (*A*) fascicle length and negatively correlated with (*B*) pennation angle. Conversely, fascicle length explains less variation in peak isometric torque (*top row*) and pennation angle is not correlated with isometric torque. Fascicle lengths explained more variation in plantarflexor work than pennation angle.

Figure 4 (1 column). (*A*) Longer and (*B*) less pennate fascicles decrease relative shortening velocity during a given joint rotation, which results in increased fascicle force. The force-velocity properties of skeletal muscle are more sensitive to changes in fascicle length than pennation angle, which agrees with our experimental findings that ankle torque is more strongly correlated with fascicle length than pennation angle.

Table 1. Descriptive data on subjects, muscle structure, and plantarflexion function.

	Mean ± Standard Deviation
Plantarflexor Kinetics	
Peak Isometric Torque (N*m)	116.82 ± 39.13
Peak Isokinetic Torque 30°/s (N*m)	95.12 ± 31.33
Peak Isokinetic Torque 120°/s (N*m)	50.09 ± 23.96
Peak Isokinetic Torque 210°/s (N*m)	35.87 ± 16.95
Total Work 30°/s (J)	53.7 ± 20.01
Total Work 120°/s (J)	33.75 ± 17.31
Total Work 210°/s (J)	26.64 ± 12.94
Musculoskeletal Parameters	
Range of Motion (degrees)	53.70 ± 4.17
Fascicle Length (mm)	48.00 ± 10.02
Pennation Angle (degrees)	29.52 ± 4.06
Muscle Thickness (mm)	23.15 ± 4.15
Leg Length (mm)	362.2 ± 36.88
Mass (kg)	67.26 ± 19.25

Table 2. Correlations between muscle thickness and plantarflexion kinetics

	Peak Torque	Total Work
Isometric Max	0.153 (0.209)	-
Isokinetic 30 °/s	0.124 (0.262)	0.172 (0.181)
Isokinetic 120 °/s	0.104 (0.307)	0.117 (0.276)
Isokinetic 210 °/s	0.076 (0.387)	0.089 (0.347)

Correlations of determination (R^2) and regression *p*-values are reported as R^2 (*p*-value)

Table 3. Correlations between muscle structure and subject stature.

	Leg Length	Mass	Muscle Thickness
Fascicle Length	0.084 (0.046)	0.132 (0.011)	0.53 (<0.0001)
Pennation Angle	0.013 (0.445)	0.098 (0.030)	0.063 (0.083)
Muscle Thickness	0.070 (0.069)	0.037 (0.193)	-

Correlations of determination (R^2) and regression *p*-values are reported as R^2 (*p*-value)

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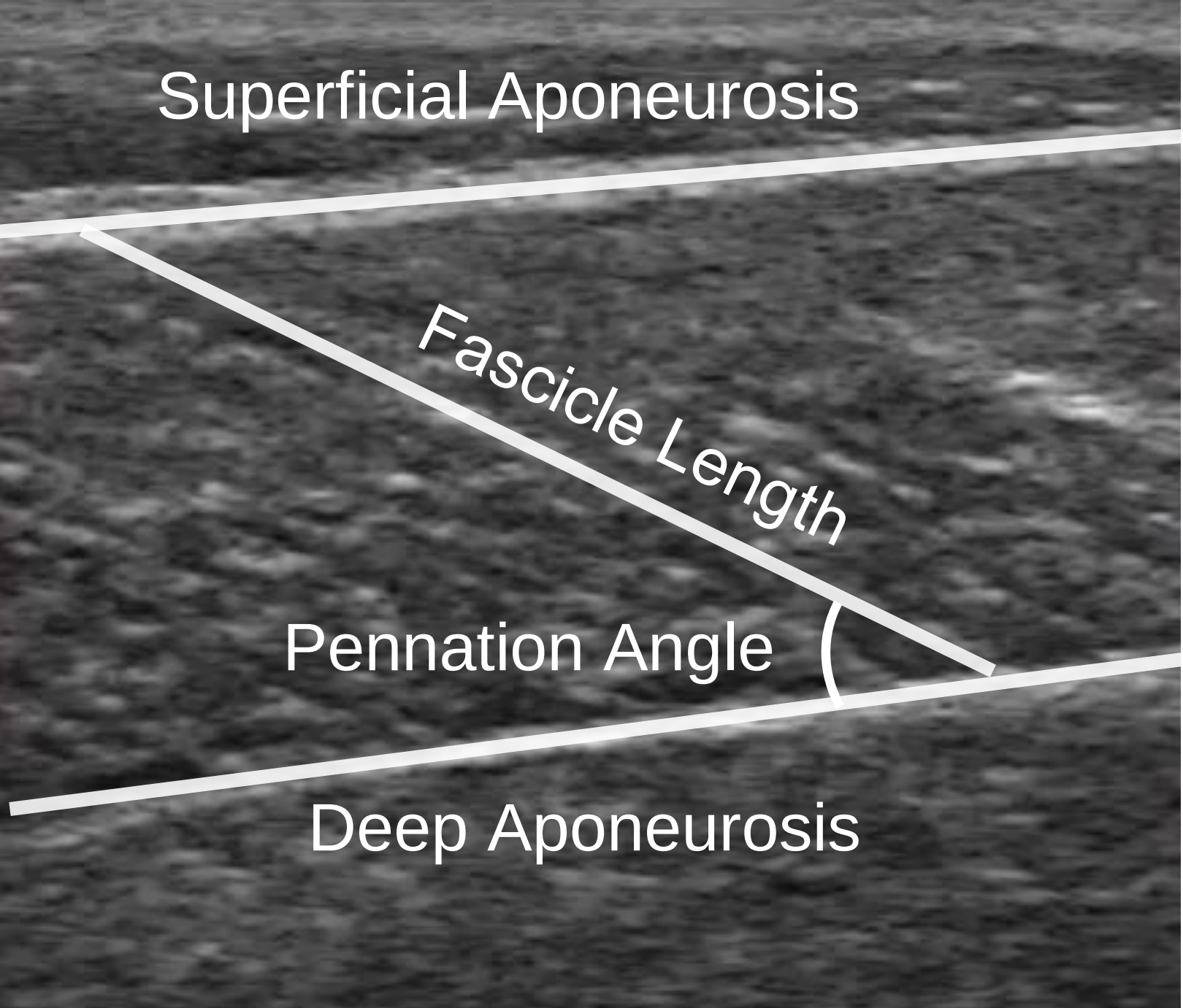
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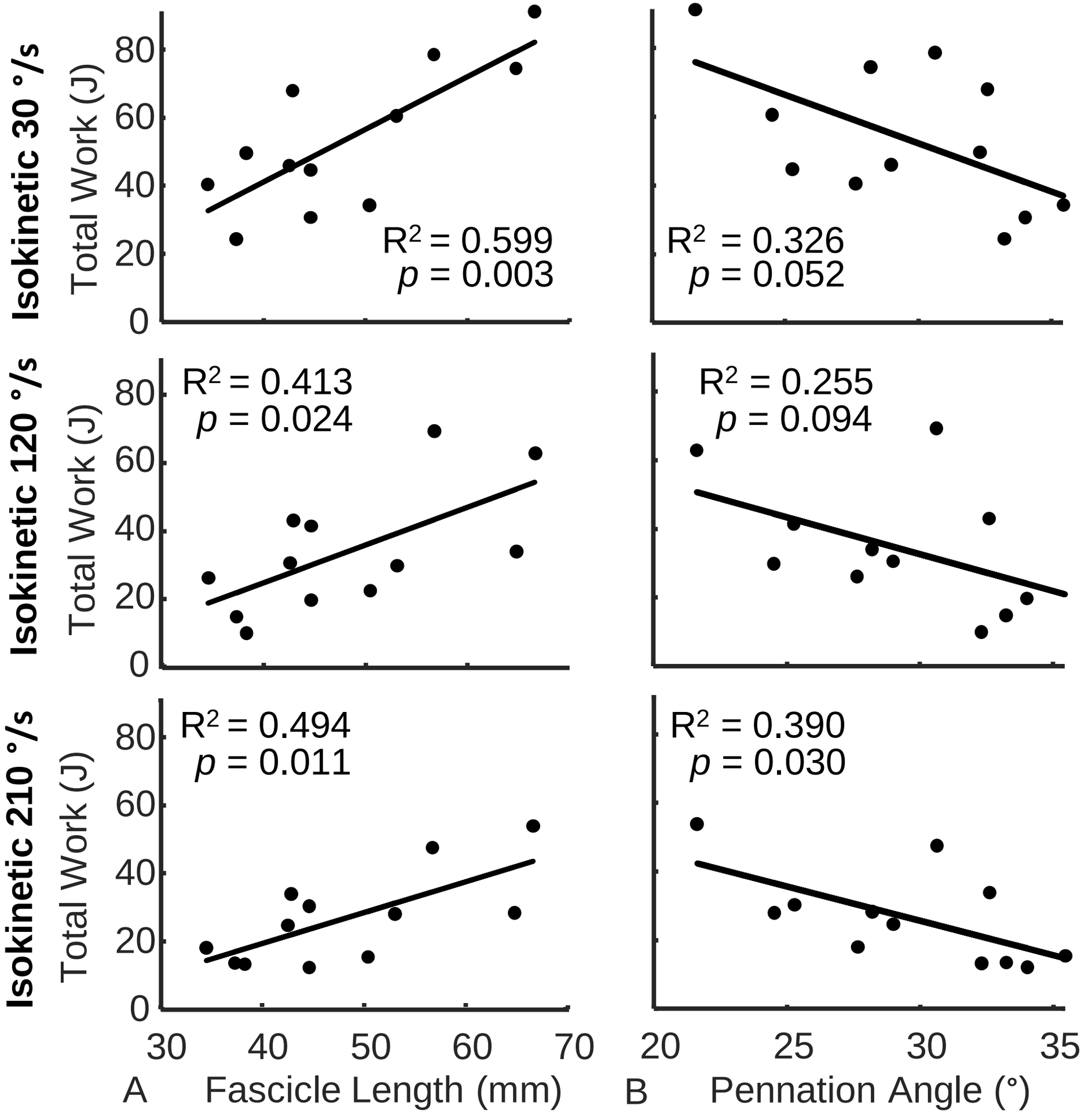
Deep Aponeurosis


Isokinetic 30 °/s
Isokinetic 120 °/s
Isokinetic 210 °/s
Total Work (J)
0
20
40
60
80
R² = 0.599
p = 0.003
R² = 0.326
p = 0.052
R² = 0.413
p = 0.024
R² = 0.255
p = 0.094
R² = 0.494
p = 0.011
R² = 0.390
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30
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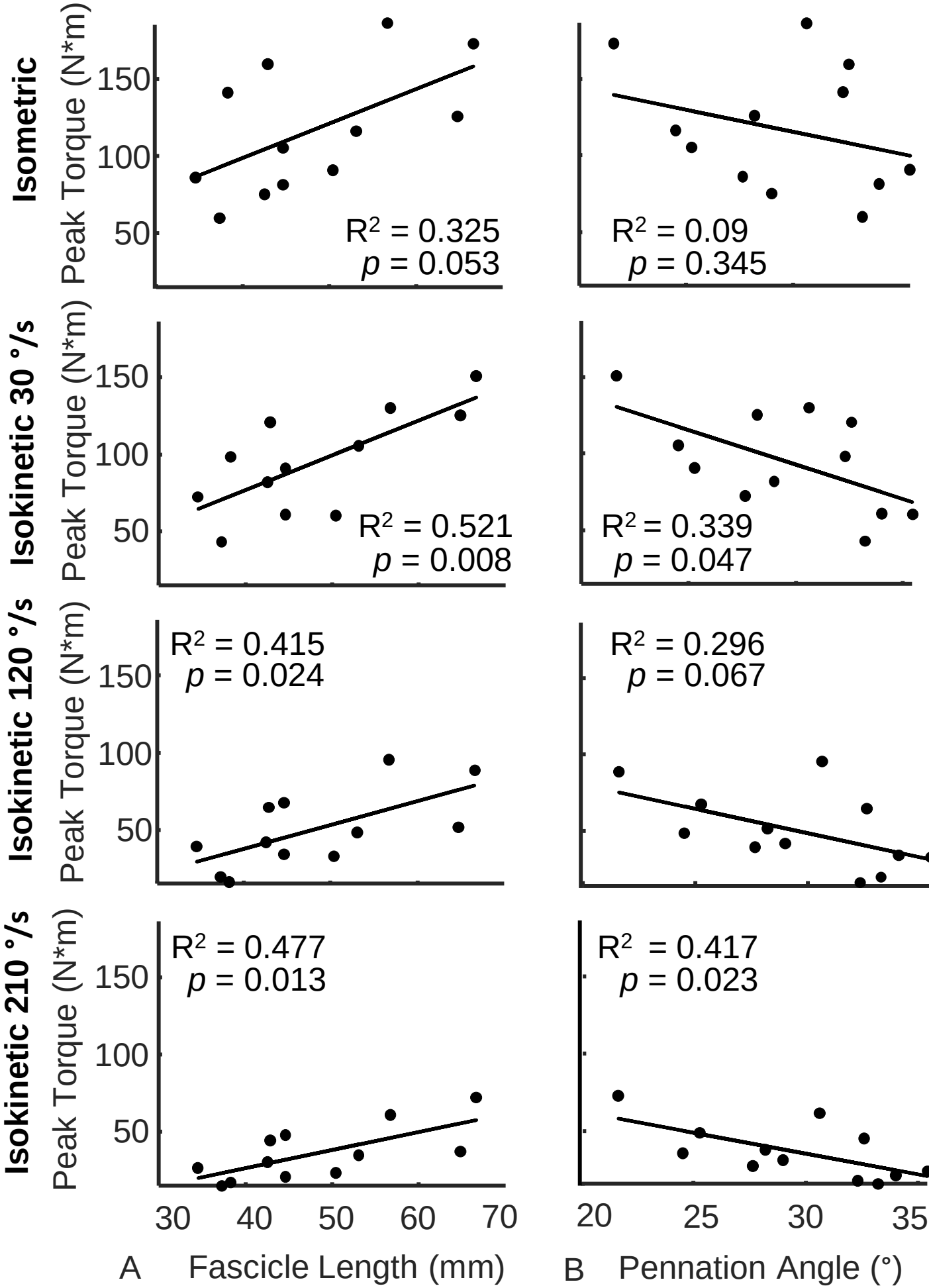
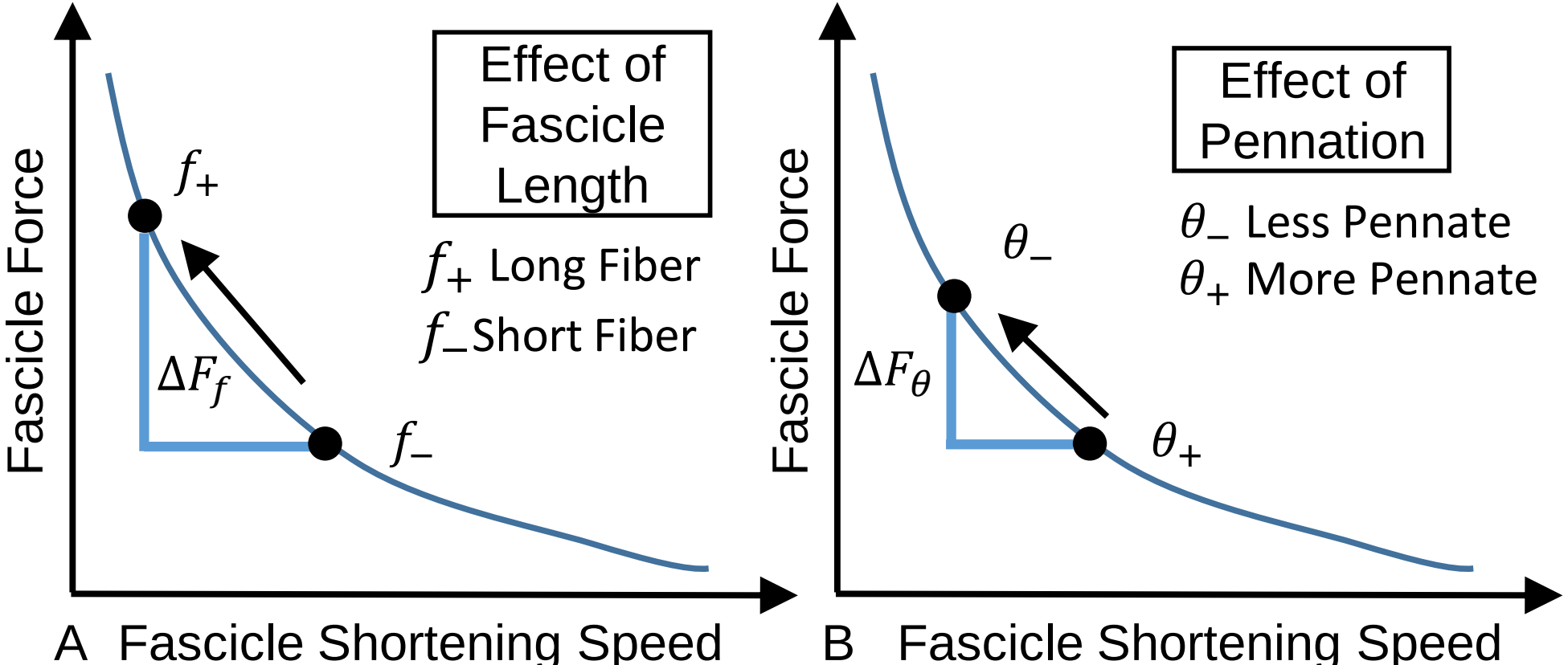
A
Fascicle Length (mm)
B
Pennation Angle (°)


Isometric
Isokinetic 30 °/s
Isokinetic 120 °/s
Isokinetic 210 °/s
Peak Torque (N*m)
150
100
50
R² = 0.325
p = 0.053
R² = 0.09
p = 0.345
R² = 0.521
p = 0.008
R² = 0.339
p = 0.047
R² = 0.415
p = 0.024
R² = 0.296
p = 0.067
R² = 0.477
p = 0.013
R² = 0.417
p = 0.023
30
40
50
60
70
20
25
30
35
A Fascicle Length (mm)
B Pennation Angle (°)


Effect of Fascicle Length
f_+ Long Fiber
f_- Short Fiber
f_+
f_-
ΔF_f
Fascicle Force
A Fascicle Shortening Speed
Effect of Pennation
θ_- Less Pennate
θ_+ More Pennate
θ_-
θ_+
ΔF_θ
Fascicle Force
B Fascicle Shortening Speed