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Original Article

Assessing lower extremity muscle pennation angles and physical performance in female athletes

TAMRYN B. SOLOMONS[1], AMINA HAJAT[2], ANDREW GREEN[3]
[1,3]Department of Sport and Movement Studies, Faculty of Health Science, University of Johannesburg, SOUTH AFRICA.
[2]Medical Imaging & Radiation Sciences, Faculty of Health Science, University of Johannesburg, SOUTH AFRICA.

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Abstract

Problem statement: Currently, there is a lack of research exploring the relationship between lower-limb muscle pennation angles and physical performance. In this study, we aimed to investigate the morphological and physiological adaptations in muscle architecture among athletes, potentially influencing performance outcomes. Specifically, there is a need for further investigation into muscle pennation angles (PA) and performance parameters in female athletes. Addressing these gaps is crucial for implementing effective performance enhancement strategies and sport-specific training programmes to optimize sport performance in the female athlete population. **Approach:** A quantitative study was performed to examine relationships between muscle pennation angles and physical performance. Muscle pennation angles were assessed using ultrasonography in both extended and flexed states. Physical performance data were collected from 22 female athletes participating netball and football. Various performance tests including vertical jump, 40m sprints, Change of Direction (COD) tests and one Repetition Maximum (1RM) tests were conducted. A Shapiro-Wilk test evaluated data distributions. A correlation analyses assessed the strength of linear relationships between PAs and performance parameters, with a significance level of $p<0.05$. **Purpose:** While existing literature extensively explores the impact of muscle fascicle length changes during exercise and training protocols in various sports, there is a noticeable lack of attention given to the significance of muscle pennation angles in force production and muscle velocities. This study aims to address this gap by evaluating the relationships between pennation angles and physical performance among netball and football athletes. Additionally, it recognises the interdependence of fascicle length and pennation angles, highlighting their architectural responses to training and sport demands.

Results: Correlations presented ($p>0.05$) small to moderate relationships amongst PAs and performance parameters. Specifically, significant correlations between the left *tibialis anterior* PA, COD ability *t*-test ($p = 0.006$), 1RM strength ($p = 0.010$) and relative strength ($p = 0.009$) in the extended state. Correlations were also present between the right *tibialis anterior* PA, 40m sprint ($p = 0.001$) and COD ability *t*-test ($p = 0.000$) in the extended state. There were significant correlations between right *tibialis anterior* PA, 10m sprint ($p = 0.011$), 40m sprint ($p = 0.008$) and COD ability t-test ($p = 0.002$) in the flexed state. **Conclusion:** These findings highlight the significance of muscle architecture adaptations, particularly pennation angles, influencing force production and shortening velocities during athletic activities such as jumping, sprinting and COD actions. This study provides valuable insight into the relationship between muscle architecture and physical performance in female athletes.

Key words: muscle architecture, pennation angle, force production, performance parameters, ultrasonography

Introduction

Muscle architecture is an important element for muscle function as muscles generate movement and coordination, which influence the performance of athletes in all sports (Sekir, Arslan, Ilhan & Akova, 2019). However, the importance of muscle architectural changes is not only limited to elite athletes but also to individuals who engage in recreational activities and those in rehabilitation. Enhanced muscle architecture can lead to improved physical capabilities and overall health, demonstrating its importance across populations and fitness levels. Muscle architecture comprises of three prominent components, namely: muscle pennation angle (PA), fascicle length (FL) and muscle thickness (MT) (Hamza, Elbadry, Saad, Larion & Alexe, 2019). More specifically, the PA has been reported to have an influence on force production and fascicle length change has been associated to the velocity of contraction. It has also been widely reported that muscle thickness and an increased muscle cross-sectional area (CSA) are related to the increase in force production and overall muscle strength, ultimately translating into enhanced athletic performance. Consequently, the anatomical properties of an athlete's muscle influence the functional properties of the skeletal muscle, impacting various aspects of

Corresponding Author: TAMRYN B. SOLOMONS, E-mail: tamrynsolomons11@gmail.com

performance such as power, speed, change of direction and agility (Aagaard, Anderson & Simonsen, 2001; Cuthbert, Ripley, McMahon, Evans, Haff & Comfort, 2020).

The PA located between the fascicles, is the structural property of the whole muscle that directs muscle function of an individual. Additionally, muscle adaptations and changes in muscle architecture occur as a result of the training regiments and the mechanical demands of a sport code. In pennate muscles, the muscle fibres are positioned at an oblique angle to the muscle's line of action which can result in mechanical advantages, as the positioning increases force production capabilities and transmission (Roberts, Eng, Sieboda, Holt, Brainerd, Stover, Marsh & Azizi, 2019). The influences on architectural change, muscle contraction, and force production are also attributed to the CSA. Physiological cross-sectional area (PCSA) is associated with the potential for force production muscles. A larger PCSA indicates a greater number of muscle fibres that can contract simultaneously, leading to enhanced muscle force generation and higher force per unit of muscle mass (Roberts et al., 2019).

The size of PAs can also be modified through specific training protocols and interventions, as well as isometric and isotonic concentric and eccentric contractions (Timmins, Ruddy, Presland, Maniar, Shield, Williams & Opar, 2016). Changes in PA influences the architectural gear ratio (AGR), which refers to the ratio between muscle velocity and muscle fibre velocity. Shortening velocities of muscle influences the velocity of muscle fibre during muscle contraction which affects the angular velocities, suggesting either a higher or lower force generation potential (Azizi & Roberts, 2014). The fibre rotations during contraction decreases the force output in muscle but would increase in velocity output during higher gear ratios. Conversely, the increase in force output in muscle and a decrease in velocity during lower gear ratios (Azizi, Brainerd & Roberts, 2008). The involvement of contractile properties in the rate of force development implies that muscle AGR could influence the rate of force generation (Werkhausen, Gløersen, Nordez, Paulsen, Bojsen-Møller & Seynnes, 2022). In addition, the variations of the PA sizes, fascicle length and muscle fibre arrangements are because of different exercise interventions, indicating that these components are not independent and change in response to training and sports demands. Accurate measurement of these components using techniques such as ultrasound imaging ensures replicable data, essential for analyzing muscle architecture. Brightness-mode (B-mode) ultrasonography has become a common method to evaluate muscle architecture and muscle anatomy (Simoneau-Buessinger, Leteneur, Bisman, Gabrielli and Jakobi, 2017; Van Hooren, Teratsias & Hodson-Tole, 2020). Specifically, PAs, muscle fascicles and muscle thickness can be easily determined through ultrasound examinations. Therefore, ultrasound imaging can be incorporated into screenings to evaluate muscle architecture during rest and movements (Van Hooren *et al*., 2020). Understanding the change in muscle architecture is important for developing effective, sport-specific training programmes that enhance performance and reduce injury risk.

Existing literature has placed much emphasis on the importance of muscle fascicle length changes during exercise in light of training protocols and sporting codes. However, less attention has been given to the significance of muscle PAs and their function regarding force production and velocities within the overall structure of muscle architecture. Therefore, the primary aim of this research study is to assess the relationships between lower extremity muscle PA and physical performance of netball and football female athletes. Limited research has been conducted on the relationship between lower-limb muscle PAs and physical performance, particularly in female athletes, highlighting the need for further investigation (Emmonds, Heyward & Jones, 2019). This study will explore the morphological and physiological adaptations in muscle architecture that influence performance outcomes, providing valuable insights into female athletes' specific demands in netball and football.

Materials and Methods

This study used a cross-sectional design method to assess the relationship between PAs and physical performance tests of the muscles of the lower extremity and the sports performance of female athletes. The study participants (n = 22; age: 21.1 ± 2.1 years) included 11 netball (age: 20.5 ± 1.4 years) and 11 female football (age: 21.8 ± 2.6 years) athletes. The study yielded significant relationships between PAs and physical performance, which indicates that the sample size of 22 participants was sufficient to detect substantial associations within the study population. The recruitment process involved collaboration with the Sport Bureau, head of sport science, sport scientists and coaches at the University of Johannesburg in order for the athletes to participate in the study. All participants were selected on the basis that they met the inclusion criteria. The inclusion criteria required participants to be fit to play athletes at the University of Johannesburg. Participants who consented to participate in the study were required to be 18 years or older. Athletes would have also needed to be injury-free when physical performance tests and ultrasound tests were conducted. Athletes who were unable to complete the physical performance tests were not eligible to participate in the study. The exclusion criteria included athletes with incomplete data sets to ensure that only participants with complete and reliable data were included in the data analysis. Athletes were invited to participate in the study, and those who volunteered to partake were provided with a consent form which was to be signed before athletes could partake in the study. Participants were provided with full aims and objectives as well as the potential risks of the study. The potential risks included shortness of breath and muscle soreness when participating in performance tests.

Furthermore, emphasis was placed on participants withdrawing their participation at any point. The study was approved by the University of Johannesburg Research Ethics Committee (REC-556-2020).

Procedure

Physical Performance Parameters Height (to the nearest 0.1 cm) and weight (to the nearest 0.1 kg) were measured using a portable stadiometer (Seca 213 Portable stadiometer) and an electronic scale (Seca 813) respectively. All participants were required to do a series of physical performance tests to assess the lower extremity. Specifically, these tests assessed muscular strength and power. The performance parameters included the vertical jump, running acceleration and speed (10m & 40m), change of direction (COD) ability *t*-Test and a One Repetition Maximum (1RM) leg press. All equipment was calibrated as per the manufacturer's instructions. The vertical jump test was assessed using a Vertec (Sports Imports, Hilliard, OH, USA) and has proven to be a reliable measure to assess lower-body power (ICC range = 0.90-0.97) (Nadzalan, Mohamad, Lee & Chinnasee, 2018). Participants were instructed to stand directly under the Vertec with their arm fully extended upward, with both feet placed on the ground and the lowest vane lowered to the tip of their middle finger. Their jump height was the highest vane on the Vertec from a standing position exerting maximal power. Participants were allowed three attempts, and their highest reading was recorded. Lower body power was calculated using an equation which estimates the peak power output (Peak Anaerobic Power Output or PAPw) from the vertical jump height (Sayers, Harackiewicz, Harman, Frykman & Rosenstei, 1999). Running acceleration and speed were quantified over 10m and 40m using timing lights (Smart Speed Pro – Fusion Sport, Queensland, Australia). The 10m and 40m sprint test required participants to run from a standing start position as fast as possible in a linear direction over 40m. The average for both 10m and 40m for netball and football participants were calculated using two sprint trials. The reliability of sprints tests over 5-40m has proven to be excellent (ICC range = 0.84-0.99) (Paul & Nassis, 2015; Shalfawi, Young, Tønnessen, Haugen & Enoksen, 2013). The COD *t*-test required participants to run across a series of markers that were set up. The markers were set up in a T formation where the timing lights were the start and end points of the test. Participants started from a standing position and proceeded to sprint as fast as possible through the timing lights, forward to the centre marker. From the centre marker, participants side-shuffled to the left marker and then side-shuffled past the centre marker to the right marker. They then side-shuffled from right marker back to the centre marker and ran backwards through the timing lights. Participants were only required to perform one trial of the COD test. The COD *t*-test is a reliable measure to assess COD ability (ICC range = 0.85-0.98) (Nadzalan *et al*., 2018). Lastly, a 1RM leg press was used to assess maximum strength and test for lower extremities load. An estimated warm-up load allowed participants to complete 3-5 repetitions. Thereafter, an estimated conservative near maximal load allowed the participant to perform 2-3 repetitions. Once the participant had completed the required repetitions, there was a load increase, and the participant was instructed to perform a 1RM effort. Loads were increased and decreased accordingly until the participant was able to perform a 1RM with adequate technique (Grgic, Lazinica, Schoenfeld & Pedisic, 2020). Furthermore, the 1RM test itself is a reliable to assess maximum strength (ICC range = 0.90-0.99) (Grgic *et al*., 2020).

Ultrasound Imaging Ultrasound testing sessions were completed on a separate occasion to performance tests. The ultrasound tests took place at the university's clinic. A high frequency linear array transducer on a Mindray, M5, (Mindray Medical International Co., Ltd. Shenzhen, China) was used. Stickers were used as markers and were placed on the mid-section of each muscle group, on both limbs prior to conducting ultrasound tests. Ultrasound gel was placed on the skin of the participant where the sonographer obtained images of the PA and arrangement of muscle fibres for each muscle group. The PA was measured bilaterally, in the: *biceps femoris*; *gastrocnemius*; *rectus femoris; tibialis anterior* and *vastus lateralis* muscles at the mid-point of each muscle belly. Ultrasounds of the thigh muscles were further repeated with the knee in passive flexion at 90°. Similarly, ultrasound of the shank muscle were repeated with the foot in plantar (medial head of *gastrocnemius*) and dorsiflexion (*tibialis anterior*). The athletes' legs (knee and ankle) were passively flexed and fully extended in order to get an accurate result of the PA in the muscle. The flexed and extended states were in passive joint manipulation positions; therefore, no active muscle contractions were done by the participants. All measurements were recorded. Moreover, it is important that a trained imaging personnel should obtain ultrasound images for accurate evaluation. To determine the muscle PA, an on-screen protractor was used to measure and determine the angle between the aponeurosis and muscle fascicle. Specifically, the aponeurosis was used as a point of origin and two push-points on the edge of the protractor were placed on the aponeurosis and muscle fascicle. The PA measured were triplicated by three independent assessors and the average of these three measurements were recorded. The inter-rater reliability (IRR) was within acceptable range. (*Bicep Femoris* = 0.996, *Gastrocnemius* = 0.978, *Rectus Femoris* = 0.989, *Tibialis Anterior* = 0.995, *Vastus Lateralis* = 0.988).

Data Analysis

Statistical Analyses Descriptive statistics data were presented as mean and standard deviation for anthropometrics, physical performance parameters and muscle PAs. Inferential statistics were performed using Statistical Program for Social Sciences (SPSS) IBM version 27. A Shapiro-Wilk test was used to evaluate the data distributions. Correlation coefficients (Pearson's and Spearman's) were used to assess the strength of linear relationships between PAs and physical performance parameters, where a significance level of $p<0.05$ was enforced.

Results

Summary statistics of anthropometrics and physical performances test are presented in table 1. Pennation angles in flexed and extended states are reported in table 2.

Table 1. A comparison of anthropometrics and physical performance parameters between netball and football athletes

Stature (cm)	165.3 ± 7.9
Body mass (kg)	59.6 ± 8.0
Vertical Jump (cm)	37.2 ± 6.9
Peak Anaerobic Power Output (W)	2904.7 ± 410.0
Sprint 10m (s)	2.1 ± 0.3
Sprint 40m (s)	5.5 ± 1.3
COD t-test (s)	12.3 ± 1.3
Strength 1RM (kg)	169.3 ± 42.0
Relative Strength	2.9 ± 0.8

Table 2. Muscle pennation angles in the left and right lower extremity in extended and flexed states

Muscle Group	Total n = 22
Bicep Femoris	
Left Extended (°)	14.2 ± 3.4
Left Flexed (°)	16.6 ± 2.9
Right Extended (°)	15.4 ± 4.3
Right Flexed (°)	16.9 ± 3.8
Gastrocnemius	
Left Extended (°)	18.6 ± 3.9
Left Flexed (°)	17.7 ± 4.4
Right Extended (°)	16.7 ± 2.7
Right Flexed (°)	17.3 ± 3.2
Rectus Femoris	
Left Extended (°)	15.0 ± 2.8
Left Flexed (°)	13.0 ± 2.4
Right Extended (°)	14.9 ± 2.5
Right Flexed (°)	12.8 ± 1.9
Tibialis Anterior	
Left Extended (°)	15.1 ± 4.1
Left Flexed (°)	14.4 ± 4.1
Right Extended (°)	15.6 ± 4.9
Right Flexed (°)	16.7 ± 5.4
Vastus Lateralis	
Left Extended (°)	16.1 ± 2.3
Left Flexed (°)	13.4 ± 2.0
Right Extended (°)	15.0 ± 2.7
Right Flexed (°)	12.3 ± 1.4

Correlations between muscle PAs and physical performance parameters are presented in Table 3 (extended state) and Table 4 (flexed state).

Table 3. Correlation coefficients (r) between muscle pennation angles and performance parameters in extended states

Muscle Group	Stature (cm)	Body Mass (kg)	Vertical Jump (cm)	PAPw (Watts)	Sprint 10m (s)	Sprint 40m (s)	COD Ability T-Test (s)	Strength 1RM (kg)	Relative Strength
Bicep Femoris									
Left Extended †	-0.227	-0.374	0.057	-0.240	-0.203	-0.424*	-0.099	-0.456*	-0.209
Right Extended	0.278	0.080	-0.035	0.039	0.129	0.083	0.087	-0.497*	-0.454*
Gastrocnemius									
Left Extended	-0.407	-0.155	0.067	-0.089	-0.007	-0.120	-0.083	0.045	0.104
Right Extended	0.128	0.198	0.189	0.356	-0.289	0.061	-0.059	0.411	0.237
Rectus Femoris									
Left Extended	-0.107	0.060	0.037	0.090	-0.171	0.018	0.276	0.174	0.139
Right Extended †	-0.100	0.110	0.075	0.190	-0.085	0.130	0.077	0.327	0.207
Tibialis Anterior									
Left Extended †	-0.240	-0.190	0.369	0.287	-0.272	-0.451*	-0.564**	0.540**	0.542**
Right Extended	-0.309	-0.314	0.333	0.066	-0.483*	-0.669**	-0.829**	0.192	0.295
Vastus Lateralis									
Left Extended	-0.191	-0.210	0.157	-0.043	0.116	-0.265	0.013	-0.083	0.011
Right Extended	0.470*	0.371	0.150	0.476*	0.068	0.277	0.166	0.280	0.110

** indicates $p < 0.05$; ** indicates $p < 0.01$; † indicates Spearman's correlation*

Table 4. Correlation coefficients (r) between muscle pennation angles and performance parameters in flexed states

Muscle Group	Stature (cm)	Body Mass (kg)	Vertical Jump (cm)	PAPw (Watts)	Sprint 10m (s)	Sprint 40m (s)	COD Ability T-Test (s)	Strength 1RM (kg)	Relative Strength
Bicep Femoris									
Left Flexed	-0.151	-0.253	0.272	0.059	0.398	-0.071	-0.051	-0.208	-0.056
Right Flexed	0.053	-0.029	-0.096	-0.113	-0.372	0.123	0.000	-0.260	-0.235
Gastrocnemius									
Left Flexed	0.409	-0.287	0.327	0.065	0.246	-0.056	0.282	0.099	0.218
Right Flexed	-0.089	-0.111	-0.051	-0.156	-0.054	0.259	0.266	0.047	0.077
Rectus Femoris									
Left Flexed †	-0.082	0.133	-0.038	0.234	0.094	-0.053	0.229	0.158	-0.053
Right Flexed †	0.063	-0.006	0.085	0.245	0.153	-0.093	0.145	-0.281	-0.289
Tibialis Anterior									
Left Flexed	-0.032	-0.043	0.155	0.118	-0.285	-0.331	-0.296	0.271	0.259
Right Flexed †	-0.168	-0.345	0.261	0.106	-0.531*	-0.549**	0.627**	0.061	0.206
Vastus Lateralis									
Left Flexed †	-0.160	-0.151	0.239	-0.002	-0.40	-0.413	-0.377	-0.068	0.086
Right Flexed	-0.017	-0.029	0.358	0.332	0.216	0.113	0.079	0.341	0.302

** indicates $p < 0.05$; ** indicates $p < 0.01$; † indicates Spearman's correlation*

Correlation coefficients for extended states

There were moderate correlations in the extended state between the left *bicep femoris* and 40m sprint (r = -0.424; *p* = 0.049) and 1RM strength (r = -0.456; *p* = 0.029). In the extended state moderate significant correlations can be observed between the right *bicep femoris*, 1RM strength (r = -0.497; *p* = 0.019) and relative strength (r = -0.454; *p* = 0.034). Apart from significant correlations there were no other significant correlations between PAs and performance parameters in extended states of the left or right *bicep femoris*, *gastrocnemius*, *rectus femoris* and *vastus lateralis* (Table 3).

The left *tibialis anterior* PA in the extended state displayed significant correlations in the 40m sprint (r = -0.451; *p* = 0.035), COD ability *t*-test (r = -0.564; *p* = 0.006), 1RM strength (r = 0.540; *p* = 0.010) and relative strength (r = 0.542; *p* = 0.009). There was a moderate correlation between the left *tibialis anterior* PA and 40m sprint. However, significant relationships can be observed between the left *tibialis anterior* PA, COD ability *t*-test, 1RM strength and relative strength. The right *tibialis anterior* PAs of the in the extended state also displayed moderate to significant correlations in the 10m sprint (r = -0.483; *p* = 0.023), 40m sprint (r = -0.669; *p* = 0.001) and COD ability *t*-test (r = -0.829; *p* = 0.000). There was a moderate correlation between the right *tibialis anterior* PA and 10m sprint. However, there was a significant correlation between the right *tibialis anterior* PA and 40m sprint and a significant correlation between the right *tibialis anterior* PA and COD ability *t*-test. Lastly the *vastus lateralis* PA of the right leg in an extended state only displayed moderate correlations in stature (r = 0.470; *p* = 0.027) and PAPw (r = 0.476; *p* = 0.025) (Table 3).

Correlation coefficients for flexed states There was no significant correlations between PAs and performance parameters for the flexed states of the *bicep femoris*, *gastrocnemius*, *rectus femoris* and *vastus lateralis* for either side (Table 4). The only significant correlations were presented in the right *tibialis anterior* PAs in the 10m sprint (r = -0.531; *p* = 0.011), 40m sprint (r = -0.549; *p* = 0.008) and COD ability t-test (r = -0.627; *p* = 0.002) (Table 4). Significant correlations were observed between the right *tibialis anterior* PA and 10m sprint, 40m sprint and COD ability t-test (Table 4).

Discussion

The current study investigated correlations between PAs in extended and flexed states and athletic physical performance. Notably, significant relationships exist between the *tibialis anterior* PAs and 10m and 40m sprint times, COD ability and strength performances, as well as the *bicep femoris* PAs and strength performances. Different sporting codes may elicit specific muscle adaptations, potentially influencing muscle architecture. This concept is supported by Monte and Zamparo (2019), who highlighted the influence of varying demands across sports. Athletes sampled from netball and football, two sport codes with distinct playing surfaces, dimensions and physical demands were expected to display differences in muscle architecture (Brancaccio, Somma, Provenzano & Rastrelli, 2013).. Consequently, the observed differences in muscle architecture between netball and football athletes may impact force, velocity and power development during physical performances (Ema, Wakahra, Mogi, Miyamoto, Komatsu, Kanehisa & Kawakami, 2013).

The correlation between stature and the right *vastus lateralis* PA implies dynamic structural changes and contractions within the *vastus lateralis* muscle during muscle activity and motion (Chleboun, Harrigal, Odenthal, Shula-Blanchard & Steed, 2008). These structural changes are influenced by types of contractions and shortening velocities of muscle fibres, potentially affecting mechanisms related to locomotion. Moreover, the study findings suggest that muscle architecture is more closely associated with contractile functioning than body dimensions rather than anthropometric dimensions (Lieber & Ward, 2011).

The correlation between PAPw and the right *vastus lateralis* PA may be attributed to fascicle shortening and the stretch shortening cycle (SSC) during the propulsion phase (Nikolaidou, Marzilger, Bohm, Mersmann & Arampatzis, 2017). Moreover, muscles with greater fascicle lengths are able to generate increased force capabilities at higher shortening velocities at a slower rate because of more sarcomere in series (Secomb, Nimphius, Farley, Lundgren, Tran, & Sheppard, 2015). However, additional research studies that evaluate more sensitive power metrics should be performed to further clarify and enhance understanding the relationships between muscle architecture and jump performance.

Regarding sprint performance, negative correlations with PAs indicate that decreased PAs may lead to increased sprint times, consistent with findings by (Ritsche, Bernhard, Roth, Lichtensten, Keller, Zingg, Franchi and Faude (2021). This relationship emphasizes the importance of muscle adaptations relative to specific sport codes and their demands. Additionally, it also highlights the influence of muscle architecture on velocity and force production. It has been suggested that there is a correlation between sprinting and fascicle lengths, with longer fascicle lengths being associated with sprinting activities due to increased muscle force production capability (Zaras, Stasinaki, Methenitis, Karampatsos, Fatouros, Hadjicharalambous & Terzis, 2019; Mangine, Fukud, LaMonica, Gonzalez, Wells, Townsend, Jajtner, Fragala, Stout & Hoffman, 2014).

Similarly, a decreased PA is associated with increased COD times as suggested by Nadzalan *et al* (2018), with COD ability being influenced by factors such as acceleration, deceleration and effective manipulation of centre of mass during locomotion. While negative relationships were observed between the *tibialis anterior* PAs and COD, positive relationships were noted with quadriceps and hamstring muscles, indicating potential influences on acceleration abilities. (Jones, Thomas, Dos'Santos, McMahon & Graham-Smith, 2017). However, further investigations are justified to explore the relationship between PAs and COD thoroughly.

The negative and positive relationships between PAs and strength performances emphasises the intricate relationship between muscle architecture and force production (Mpampoulis, Methenitis, Papadopoulos, Papadimas, Spiliopoulou, Stasinaki, Bogdanis, Karampatsos & Terzis, 2021). Greater muscular strength is also positively related to force-time qualities, which influence athletic performance. Notably, muscular strength is not solely the potential of an athlete to produce force but also the ability to produce high levels of RFD, velocity and power during dynamic movements – and greater RFD is the basis for generating higher power output levels (Taber, Bellon, Abbott & Bingham, 2016). An increase in muscular strength greatly contributes to sport-specific athletic performance, potentially reducing potential injury risks (Suchomel, Nimphius & Stone, 2016).

Despite these findings, it is important to acknowledge the limitations of the study, including the relatively limited sample size, although it produced significant correlations, and lack of heterogeneity as this study focused on one netball and one football team from a single institution. Additionally, ultrasound testing was only performed on passive flexed and extended joint and muscle states, potentially limiting the depth of analysis compared to testing during active contractions aligned with during dynamic movements.

Conclusion

The findings of this study highlights the significance of PAs in muscles and their relationship with key gross motor performances such as jumping, spring and COD. As discussed earlier, PAs play a crucial role in force production, with larger PAs having a greater ability to densely pack contractile within muscle volumes and therefore enhancing strength capabilities. This is attributed to the parallel arrangement of muscle fibres and greater PCSA (Lee, Lee, Takeshi, Lee & Kim, 2021). Conversely, smaller PAs are more associated with reduced force production capabilities because muscle fibres are structured more in series than in parallel. As a result, muscles with smaller PAs may generate less force per unit of muscle volume compared to muscles with greater PAs. The relationship between PA and force production can be influenced by various factors, including muscle architecture , fibre type distribution and training status (Werkhausen *et al*., 2022). It important to note that the absence of correlations between PAs and certain performance parameters could be due to the distinction between active muscle contractions and passive flexion of skeletal muscle. The dynamic nature of muscle architecture during active states suggest that changes in PA are likely associated with dynamic conditions and performance (Herbert & Gandevia, 1995).

Therefore, exploring the differences between active and passive states of skeletal muscle warrants further investigation and may present additional correlations between variables. Furthermore, future research endeavours should aim to incorporate more comparative studies muscle architecture and physical performance. These studies should include investigations into relationships, symmetries, and differences among various endurance and power-based sporting populations, particularly focusing on female athletes who are often under-represented and overlooked. Conducting more research on female populations increases the probability of understanding female athletic performances. Lastly, it is important to recognise that changes in muscle architecture, particularly muscle PAs, may be influenced by the nature and training demands of specific sports. These factors can significantly impact the force and velocity produced within muscles. Therefore, continued exploration of the relationship between muscle architecture and athletic performance across diverse sporting contexts is essential for advancing our knowledge in this field.

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Conflict of interest declaration

The authors declare no conflict of interests.

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