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Fascicle Arrangement in College-Aged Athletes

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Fascicle Arrangement in College-Aged Athletes

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Doctor of Philosophy in Sport Physiology and Performance

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by

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ABSTRACT

Fascicle Arrangement in College-Aged Athletes

by

Jacob R. Goodin

Purpose: To compare muscle architecture variables between sport and sex in competitive athletes, and to compare muscle architecture with performance variables in strong versus weak athletes, and good versus poor jumpers. ***Methods:*** The vastus lateralis (VL) and lateral gastrocnemius (LG) muscles of 139 collegiate athletes were collected using ultrasonography to determine muscle thickness (MT), pennation angle (PA), fascicle length (FL), and relative fascicle length (FL_{rel}). Absolute and relative peak power, absolute and relative isometric peak force, and jump height were measured in a subset of baseball and soccer athletes. A 5x2 factorial analysis of variance (ANOVA) was used to investigate differences in group means between sex and sport for muscle architecture variables in the larger cohort. A 2x2 factorial ANOVA was used in the in the smaller cohort to investigate differences between strong and weak athletes, and good and poor jumpers. ***Results:*** Significant main effects were observed for sex in VL muscle thickness (MT), VL pennation angle (PA), LG MT, and LG fascicle length (FL). Significant main effects were observed for sport in VL MT, VL FL, VL relative fascicle length (FL_{rel}) and LG MT. Significant interaction effects were observed for LG PA and LG FL_{rel}. Muscle architecture profiles were significantly different between strong and weak, and good and poor jumpers in baseball, but not soccer athletes. Soccer athletes had greater PA but smaller FL than baseball athletes. ***Conclusions:*** Muscle architecture may play a role in sport selection, undergoes directed adaptation to sport specific training demands, and may differentiate between high and low performers in more anaerobic athletes. Males had greater muscle thickness than females.

Patterns of PA and FL values between sport and sex differed between VL and LG. More aerobic athletes such as soccer athletes may have greater VL PA and smaller VL FL than more anaerobic athletes such as baseball athletes.

DEDICATION

I dedicate this dissertation first to God, within whom I live and move and have my being. Secondly, I dedicate this to my wife Lisa, who has toiled faithfully beside me for 5 years through graduate school, and who probably deserves a PhD more than I do.

ACKNOWLEDGEMENTS

I would also like to thank my committee members, who each played a role in leading me down the path to completion. To Dr. Mizuguchi, who has been understanding, gracious, and most of all a wealth of information and critical insight. To Dr. Bazyler, my friend and mentor not only in research but in personal and ethical conduct. To Dr. Gentles for always leaving your door open and explaining things so clearly. And of course, to Dr. Stone, without whom this program wouldn't exist—thank you for being a living legend and for elevating sport science to the level it is today.

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CHAPTER 1

INTRODUCTION

Statement of Problem

In vertebrates, the production of power is achieved via skeletal muscle contraction. Although muscle fiber morphology helps determine individual fiber contractile properties, whole muscles derive their force production characteristics from the overall composition and arrangement of muscle fibers—bundled into “fascicles”—relative to the line of force generation (Lieber and Friden, 2000). The architectural arrangement of fascicles within different muscles varies greatly and can be described using four primary aspects: muscle thickness (MT), fascicle length (FL), pennation angle (PA), and cross-sectional area (Ward, Eng, Smallwood, and Lieber, 2009). Together with muscle fiber type, these properties help determine a muscle’s contraction velocity and force production capacity. Given this architectural basis for power generation, and the fact that different sports possess distinct mechanical and metabolic demands, observation and understanding of muscle architecture characteristics could be used as a tool for both talent identification and athlete monitoring purposes.

Examinations of muscle architecture have been made in both male and female athletes from several sports. Abe, Kumagai, and Brechue (2000) observed greater FL and smaller PA in the vastus lateralis (VL) and lateral gastrocnemius (LG) of male sprinters compared to distance runners or age-matched controls, and the same findings were later observed in a group of female sprinters when compared with age-matched controls (Abe, Fukashiro, Harada, and Kawamoto, 2001). Kearns, Abe, and Brechue (2000) have compared sumo wrestlers to controls and found greater MT, PA, and FL in select muscles in the sumo group. Research by Kanehisa, Muraoka, Kawakami, and Fukunaga (2003) reported greater MT and FL in male soccer players and swimmers than females, and that soccer players possessed shorter fascicles and greater PA, while swimmers had greater MT and longer fascicles.

Despite these findings those of several other cross-sectional studies (Abe, Brown, and Brechue, 1999; Abe et al., 2001; Alegre, Lara, Elvira, and Aguado, 2009; Brechue and Abe, 2002; Jajtner et al., 2013; Kumagai et al., 2000), little is known about sex-related differences in muscle architecture or whether previously observed differences extend into other sports. Furthermore, normative and comparative muscle architecture data in athletes is scarce. In order to function as an observational tool for talent identification and athlete monitoring, inherent differences in fascicle arrangement between competitive athletes of different sports and sexes should be clarified to establish a set of architectural goalposts for coaches and sport scientists.

Current evidence supports a large to very large relationship between CSA and peak force in different athletes using various peak force measurements. However, an interesting feature of the literature is that, to date, this research has been conducted using relatively small and homogenous samples of athletes, thereby limiting the inferential power of these findings and potentially misestimating the true size of the relationship. Furthermore, methodological discrepancies between these studies—such as different modes of peak force measurement—complicate direct comparisons between athlete samples.

Therefore, the purposes of this dissertation are three-fold. To examine MT, PA, FL, and relative fascicle length (FL_{rel}) for two lower body muscles in a large cohort of competitive, college-aged male and female athletes in order to better understand differences and similarities between them, to investigate strength- and jumping ability-based differences in absolute and relative isometric peak force (IPF and IPFa), peak power (PP and PPa), jump height (JH), and muscle architecture profiles in male baseball and soccer athletes, and to gain insight into the usefulness of muscle architecture variables as athlete monitoring and talent identification variables.

Definitions

1. Aponeurosis: a fibrous sheet-like extension or expanded tendon that can also act as fascia. Provides a contrasting border to define the superficial and deep surfaces during ultrasonography.
2. Athlete Monitoring and Testing: A process of measuring and observation that gathers relevant biometric, physical, physiological, psychological, and/or performance data at regular intervals during the training process to provide actionable data for the sport performance staff and guide the training process.
3. Cross-Sectional Area (CSA): The area of the cross section of a muscle perpendicular to its line of pull.
4. Fascicle Length (FL): The length of a muscle fascicle measured from the deep to superficial aponeurosis.
5. Relative Fascicle Length (FL_{re}): The length of a muscle fascicle relative to limb or segment length.
6. Isometric Peak Force (IPF): The highest force value recorded on a force-time trace generated by isometric muscle actions.
7. Muscle Architecture: the physical arrangement of muscle fascicles, particularly their length and angle in relation to the aponeurosis, and the muscle's thickness and cross-sectional area.
8. Muscle Thickness (MT): The linear distance between the superficial and deep aponeurosis, perpendicular to the deep aponeurosis.

9. Pennation Angle (PA): The angle of muscle fascicles relative to the deep aponeurosis.

10. Physiological Cross-Sectional Area: The area of the cross section of a muscle perpendicular to the angle of its fascicles.

11. Ultrasonography: the use of ultrasound pulses to produce echoes that delineate areas of contrasting density in the body.

Significance of Dissertation

The findings of this dissertation will expound upon and enhance the literature surrounding muscle architecture in athletes. This will lead to more robust normative data that can be used for research, talent identification, and athlete monitoring purposes. Researchers focused on understanding the stratification of architectural parameters across human populations will gain several new data points to draw upon. Those investigating the mechanisms that drive changes in architecture can draw inferences from the demands of these sports and the resultant architecture displayed in these samples, and further comparisons between athlete types can be made. Sport coaches and performance staff will benefit from a more precise understanding of the fascicle arrangements across sex and sports and variation within groups, establishing normative ranges and adaptive targets for talent identification and long-term training techniques. Understanding the relationships between architecture and performance will aid coaches making programming decisions, allowing them to direct adaptation toward desirable characteristics that will maximize performance outcomes, thereby potentially enhancing sport performance.

Grand Purpose

The grand purpose of this dissertation is to better guide athlete talent identification and allocation, athlete monitoring, and long-term resistance training programming and periodization decisions by expanding our knowledge of muscle architecture and its contribution to performance measures in athletes. Knowledge of which morphological variables are most associated with sport performance factors, as well as how these variables are stratified across demographic factors and strength levels will aid in the coach's and sport scientist's decision making and increase the likelihood of favorable training outcomes for athletes. This grand purpose can be broken into three objectives.

The first objective is to examine how fundamental demographic factors such as sport type and sex are related to muscle structure. Specifically, are there significant differences in MT, PA, or FL area among athletes of different sports and sexes? A more nuanced understanding of how architectural factors vary between and within these groupings will guide researchers as they make comparative observations and investigate longitudinal changes in muscle structure. It will also aid coaches in evaluating and identifying athletes and potential recruits, and may be expanded upon to establish normative data for various sports.

The second objective is to examine whether there are differences in muscle architecture profiles between strong and weak athletes and between good and poor jumpers in two metabolically different sports. It is known that muscle CSA creates a basis for force production via increases in parallel contractile fibers, and that stronger athletes are more powerful, but direct comparisons in CSA and PP in strong versus weak athletes of different sports have yet to be made. It may be that athletes in sports with different metabolic and kinetic parameters rely to different degrees on strength for power and jumping performances. This knowledge will aid coaches in prioritizing morphological versus neurological adaptations for power performance, and will increase our understanding of differences between strong and weak athletes. This objective will also further our understanding of the relationship between muscle architecture profiles with application to talent identification and athlete monitoring

Delimitations

This dissertation is primarily concerned with investigating muscle architecture in athletes, and will only reference literature regarding special and general populations when inferences can be generalized to an athletic population as well. Furthermore, an ethical treatment of the athletes who have volunteered for this research is paramount, and this extends beyond their wellbeing to their preparedness for competition and training. To this end, data collection was limited by available contact hours, student-athlete schedules, and the unique needs of each team that participated in the athlete monitoring program. Although additional measurements—such as examining upper body musculature and performance tests or using electromyography to differentiate between neural and muscular components of strength—would have enhanced our analysis, the additional impact to the athletes was unjustified.

Muscle architecture data was collected on a total sample of 189 athletes. However, a smaller subset of this sample was chosen for each of the two studies. For the first study comparing group differences, only teams representing both sexes were included to enable a factorial ANOVA analysis that could detect sport by gender interactions. For the second study, only athletes who completed an isometric mid-thigh pull (IMTP) were included, as the dependent variable IPF was collected during IMTP testing.

Limitations

Although ultrasonography has been shown to be valid and reliable for measuring muscle architecture (Kwah, Pinto, Diong, and Herbert, 2013), recent data published out of our laboratory has provided novel insight into current measurement methodologies (Wagle et al., 2017), suggesting that standing ultrasound measurements may provide greater ecological validity if the goal is to examine relationships to performance. However, data for this study had been collected prior to the publication of these findings

Ideally, a robust evaluation of muscle architecture measurements for efficacy as diagnostic and monitoring tools would include time series data to compare percent change between the measured and dependent variables. This is of course not possible in observational cross-sectional research. On these topics, the current investigation can infer differences between these variables, but can still suggest causation, albeit only as hypotheses and in the context of the surrounding literature.

Finally, what may be the largest limitation is the difference in level of competition even between college-aged athletes in the current sample. Teams from the National Association of Intercollegiate Athletics (NAIA), National Collegiate Athletics Association (NCAA), and several athletes from an Olympic Training Site were combined in a single analysis. Therefore, results should be interpreted with this factor in mind.

CHAPTER 2

REVIEW OF THE LITERATURE

Introduction

Among all tissues of the human body, muscle is unique in its capacity for force production. Force is produced at the level of the sarcomere and transmitted to the tendon via continuous sheets of connective tissue travelling the full length of the muscle (Jeffreys and Moody, 2016). Although fiber biochemistry primarily determines individual fiber contractile properties, whole muscles derive their contractile characteristics from the overall composition and arrangement of muscle fibers—bundled into "fascicles"—relative to the line of force generation (Bodine et al., 1982; Lieber, 1992; Lieber and Friden, 2000; Lieber and Fridén, 2001). The architectural arrangement of fascicles within different muscles varies greatly (Lieber and Friden, 2000; Lieber and Fridén, 2001) and can be described using three primary aspects: fascicle length, pennation angle, cross-sectional area (Gans, 1982; Ward et al., 2009). Together, these properties largely determine a muscle's contraction velocity and force production capacity (Blazevich, Cannavan, Coleman, and Horne, 2007; Kawakami et al., 2000; Lieber and Blevins, 1989; Sacks and Roy, 1982). For instance, muscles with large pennation angles and short fascicles are optimal for force production, while small pennation angles and long fascicles predispose a muscle to large excursions and high velocities (Jeffreys and Moody, 2016). Furthermore, the large inter-individual variation in the architecture of specific muscles due to the confluence of genetics and training has been found to correlate with various measures of athleticism (Abe et al., 2001; Abe et al., 2000; Brechue and Abe, 2002; Fukutani and Kurihara, 2015; Ikegawa et al., 2008; Jeffreys and Moody, 2016; Lee and Piazza, 2009; Mangine, et al., 2014; Stenroth et al., 2016). For instance, vastus lateralis muscle thickness has been found to correlate with 1RM power clean performance (Mcmahon, Turner, and Comfort, 2015b); isometric mid-thigh pull peak force (Mcmahon, Stapley, Suchomel, and Comfort, 2015a); peak velocity, peak power, and jump height during countermovement and static jumps (Secomb et al., 2015); and powerlifting performance (Brechue and Abe, 2002). This makes investigations into architectural properties particularly relevant to those interested in improving athletic performance.

The immense range and complexity of human movement necessitates variation between architectural properties of different muscles, and to date not all muscles or regions have been studied extensively (Luu, Zhang, Pelland, and Blemker, 2015). Those muscles most commonly studied in relation to sport and athletic performance are the knee and ankle extensors, particularly the vastus lateralis (Abe et al., 2001; Abe et al., 2000; Alegre et al., 2009; Brechue and Abe, 2002; Earp et al., 2010; Fukutani and Kurihara, 2015; Jajtner et al., 2013; Kanehisa et al., 2003; Kearns et al., 2000; Kumagai et al., 2000; Mangine et al., 2014; Mangine et al., 2014; Mcmahon et al., 2015a; Mcmahon et al., 2015b; Nimphius, Mcguigan, and Newton, 2012; Secomb et al., 2015; Zaras et al., 2014; Zaras et al., 2016) and lateral gastrocnemius (Abe et al., 2001; Abe et al., 2000; Alegre et al., 2009; Brechue and Abe, 2002; Earp et al., 2010; Fukutani and Kurihara, 2015; Kanehisa et al., 2003; Kearns et al., 2000; Kumagai et al., 2000; Lee and Piazza, 2009; Mcmahon et al., 2015a; Mcmahon et al., 2015b; Secomb et al., 2015). Most authors have focused on relationships between architecture in these muscles and various aspects of sport performance (Abe et al., 2001; Alegre et al., 2009; Brechue and Abe, 2002; Earp et al., 2010; Kumagai et al., 2000; Mangine et al., 2014; Mcmahon et al., 2015a; Mcmahon et al., 2015b; Secomb et al., 2015; Zaras et al., 2016), changes in architecture through a training period (Kearns et al., 2000; Nimphius et al., 2012; Zaras et al., 2014), or on comparing architecture differences between two distinct groups of athletes or between athletes and healthy controls (Abe et al., 2000; Alegre et al., 2009; Fukutani and Kurihara, 2015; Jajtner et al., 2013; Kanehisa et al., 2003; Kearns et al., 2000; Mangine et al., 2014). Although findings have confirmed strong relationships between muscle architecture and athletic qualities, it is presently unclear whether and to what extent they differ across sex or sport metabolic and mechanical demands.

Therefore, the purpose of this review is to survey the literature surrounding muscle architecture measurements in athletes and well-trained individuals with the goal of illustrating the present understanding of morphological differences across sex and metabolic demands of the sport. Secondly, studies investigating relationships between muscle architecture and measures of performance will be reviewed to enhance understanding about the potential for architectural measurements to be used in conjunction with or separate from performance measures that may influence training decisions.

Measures of Muscle Architecture in Athletes and Correlations to Performance

Ultrasound has been identified as a valid and reliable tool for measuring muscle fascicle properties (Ando et al., 2014). Research investigating muscle architecture in athletes has focused primarily on lower body musculature, likely because most sports depend primarily on power output generated by the lower body musculature, even in throwing sports where this may be counterintuitive (Suchomel, Nimphius, and Stone, 2016). Muscle power depends on several factors, including muscle mass, muscle fiber-type composition, and neural activation (Cormie and Mcguigan, 2011), with muscle architecture perhaps playing a role (Kawakami et al., 2000). Several attempts have been made to classify lower body muscle architecture characteristics in athletes of various sports and in trained individuals, most commonly in the vastus lateralis, lateral gastrocnemius, and medial gastrocnemius muscles. It is difficult to draw a precise understanding of architectural differences from the research, however, due to methodological shortcomings or differences from study to study. The following section will attempt to summarize what is known about muscle architecture measurements of the vastus lateralis, lateral gastrocnemius, and medial gastrocnemius in athletic and well-trained populations, and to identify gaps in understanding as potential future research opportunities. Each architectural characteristic—muscle size, pennation angle, and fascicle length, will be examined separately.

Muscle Size

Measures of muscle size can correlate strongly with muscle strength (Bamman, Newcomer, Larson-Meyer, Weinsier, and Hunter, 2000), and because of the relationship between measures of muscle thickness, anatomical cross-sectional area, and muscle volume (Albracht, Arampatzis, and Baltzopoulos, 2008; Miyatani, Kanehisa, Ito, Kawakami, and Fukunaga, 2004), all three variables can be used as estimates of muscle size. Several studies used muscle thickness as an index of anatomical cross-sectional area due to their strong correlation ($r = 0.91$, $P < 0.001$), and therefore literature using both cross-sectional area and muscle thickness will be examined simultaneously. Muscle thickness is measured as the distance from the superficial to deep aponeurosis perpendicular to the muscle's longitudinal axis, while cross-sectional area takes into account the total area of a cross-section of muscle perpendicular to the longitudinal axis, and therefore more appropriately reflects sarcomeres in parallel in fusiform muscles when compared to muscle thickness. Physiological cross-sectional area is the area of the cross-section perpendicular to the muscle's angle of pennation and is thus a better measure of sarcomeres in parallel in pennate muscles. These measures of sarcomeres in parallel have been shown to correlate positively with strength and power sports such as powerlifting (Brechue and Abe, 2002) and shotput (Methenitis et al., 2016; Zaras et al., 2013), as well as activities such as sprinting

(Mangine et al., 2014; Methenitis et al., 2016) and jumping (Alegre et al., 2009; Methenitis et al., 2016) (Figure 2.1).

Sprint Ability

Muscle size may be an important factor in sprint performance. Abe et al. (2000) examined well-trained male sprinters and distance runners, and found muscle thickness of the vastus lateralis, medial gastrocnemius, and lateral gastrocnemius to be statistically higher in the

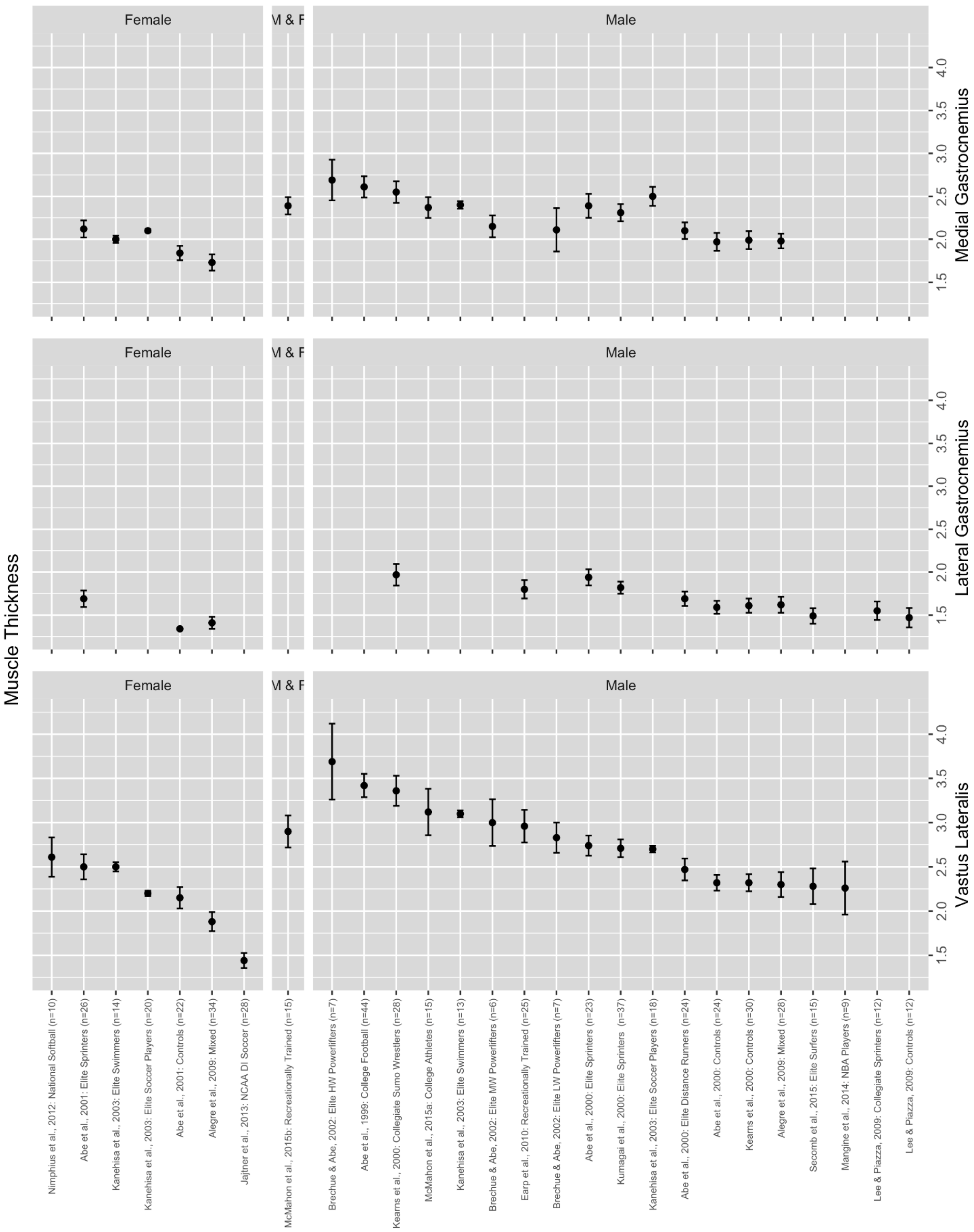

Figure 2.1. Muscle thickness (cm) for lower body musculature (mean ± SD).

sprinters (2.74 ± 0.28 cm, 2.39 ± 0.34 cm, 1.94 ± 0.23 cm) compared to distance runners (2.47 ± 0.31 cm, 2.10 ± 0.24 cm, 1.69 ± 0.21 cm) or controls (2.32 ± 0.22 cm, 1.97 ± 0.26 cm, 1.59 ± 0.19 cm). Two follow-up studies from the same laboratory examined relationships between muscle architecture and 100-m performance in both elite male (Kumagai et al., 2000) and elite female (Abe et al., 2001) sprinters. Kumagai et al. (2000) divided 37 elite male sprinters into a "fast" (100-m best: 10.0 – 10.9s) group and a "slow" (100-m best: 11.00 – 11.70s) group. Although both groups had similar muscle thickness in the vastus lateralis (2.75 ± 0.30 cm vs 2.67 ± 0.32 cm for the fast and slow groups, respectively) and medial gastrocnemius (2.37 ± 0.37 cm vs 2.25 ± 0.19), the fast group had significantly greater lateral gastrocnemius muscle thickness (1.93 ± 0.23 cm vs 1.71 ± 0.20 cm). Absolute and relative muscle thickness of the lateral gastrocnemius, but not medial gastrocnemius or vastus lateralis, showed significant negative correlations with 100-m sprint time (r = –0.36 and r = –0.42, respectively), as did absolute and relative anterior thigh musculature thickness at 30% of femur length (r = 0.38 and r = 0.39, respectively) and posterior thigh musculature thickness at 50% of femur length (r = 0.45 and r = 0.41, respectively). Furthermore, the fast group had greater thickness of the anterior and posterior thigh musculature at 30% and 50% of femur length, confirming an altered "muscle shape" that the authors speculated could be due to either genetic or training differences (see Table 2.1 for comparisons). This finding confirmed previous data showing the same trend between sprinters and distance runners (Abe et al., 2000), and between black and white American football players (Abe et al., 1999). In all three cases the group with faster sprint times had greater muscle thickness in the anterior and posterior proximal thigh musculature (Kumagai et al., 2000). The second follow-up study by Abe et al. (2001) compared a group of elite female 100-m sprinters to similar-aged controls. The sprint group had greater absolute muscle thickness of the vastus lateralis (2.50 ± 0.37 cm vs 2.15 ± 0.29 cm), medial gastrocnemius (2.12 ± 026 cm vs 1.84 ± 0.20 cm), and lateral gastrocnemius (1.69 ± 0.25 cm vs 1.34 ± 0.27 cm). Anterior and posterior thigh musculature at 30%, 50%, and 70% of femur length were also significantly greater in the sprint group, however the authors did not report correlations between any measures of thickness and sprint performance. Based on this data it appears that in elite sprinters, muscle thickness of the vastus lateralis, lateral gastrocnemius, and medial gastrocnemius is greater in males than females, in sprint athletes than non-sprint athletes, and in faster sprinters than slower sprinters. Furthermore, greater thickness of the proximal portion of the anterior and posterior thigh musculature may be advantageous to sprint performance and separate faster sprinters from their slower counterparts.

Jumping Ability

Secomb et al. (2015) tested 15 elite male surfers and found positive correlations between absolute thickness (measured at 50% of the femur length) of the left and right vastus lateralis and squat jump height (r = 0.72 and r = 0.70 for left and right, respectively) and countermovement jump height (r = 0.63 and r = 0.80 for left and right, respectively). Data from Alegre et al. (2009) that includes both male and female athletes and non-athletes also showed a significant positive correlation between vastus lateralis thickness and countermovement jump height (r = 0.49) and countermovement jump peak power (r = 0.47). In contrast, a study by Earp et al. (2010) found no significant correlations between vastus lateralis thickness and countermovement, squat, or depth jump performance in resistance-trained males.

Strength

Muscle thickness is correlated with both body size and force production ability. A study by Kearns et al. (2000) found that college sumo wrestlers had greater absolute muscle thickness than an age-matched control group in the vastus lateralis (2.63 ± 0.35 cm vs 1.71 ± 0.22 cm), medial gastrocnemius (2.55 ± 0.34 cm vs 1.99 ± 0.29 cm), and lateral gastrocnemius (1.97 ± 0.34 cm vs 1.61 ± 0.23 cm). Brechue and Abe (2002) examined vastus lateralis and lateral gastrocnemius muscle thicknesses in 20 drug-free national powerlifting competitors. After grouping subjects into light-weight (*n* = 7; 63.9 ± 5.6 kg), middle-weight (*n* = 7, 78.4 ± 6.7 kg), and heavy-weight (*n* = 6, 135.1 ± 26.5 kg) groups, the authors found that the heavy-weight group had significantly greater muscle thickness of the vastus lateralis and lateral gastrocnemius (3.69 ± 5.8 cm and 26.9 ± 3.2 cm, respectively) than the middle-weight (30.0 ± 3.3 cm and 21.5 ± 1.6 cm, respectively) and light-weight (28.3 ± 2.3 cm and 21.1 ± 3.4 cm, respectively) groups. General muscle thickness of the hamstrings and quadriceps groups correlated strongly with performance in the back squat (r = 0.83 and r = 0.82, respectively), bench press (r = 0.69 and r = 0.67, respectively), and deadlift (r = 0.77 and r = 0.79, respectively). The authors speculated that strong correlations between lower leg musculature thickness and the bench press were due to the general muscular development associated with the training of elite powerlifters. Compared with the aforementioned sprinters (Abe et al., 2001; Abe et al., 2000; Kumagai et al., 2000), the sumo wrestlers had greater lower body muscle thicknesses (measured at 30, 50, and 70% of the anterior and posterior thigh), and the powerlifters had greater lower body muscle thicknesses than both groups. This is likely due to the unique requirements of each sport, because as the required force output increases and velocity decreases, muscle size increases.

Moderate to strong statistical correlations have been found between absolute vastus lateralis thickness and isometric mid-thigh pull peak force in elite male surfers (Secomb et al., 2015) (*r* = 0.53 and *r* = 0.60 for the left and right legs, respectively) and in a heterogeneous group of male collegiate athletes (Mcmahon et al., 2015a) (*r* = 0.62). A second heterogeneous group of collegiate athletes, this time male and female, were examined by Mcmahon et al. (2015b), who found a significant moderate relationship between vastus lateralis muscle thickness and relative 1-RM power clean ($r = 0.506$, p = 0.027) and between medial gastrocnemius muscle thickness and absolute 1-RM power clean ($r = 0.476$, $p = 0.036$).

Sex Differences

Kanehisa et al. (2003) found that both absolute and relative vastus lateralis and medial gastrocnemius muscle thickness was greater in elite male than elite female soccer players and swimmers, and that swimmers had greater absolute and relative muscle thickness of the vastus lateralis than soccer players (see Figure 2.1). Using a heterogenous sample of club volleyball players, physical education students, and sedentary individuals, Alegre et al. (2009) compared jumping performance and muscle architecture between sexes and found significant differences between men and women in absolute muscle thickness of the vastus lateralis (2.3 ± 0.38 cm vs 1.88 ± 0.32 cm, respectively), lateral gastrocnemius (1.98 ± 0.23 cm vs 1.73 ± 0.28 cm, respectively), and medial gastrocnemius (1.62 ± 0.25 cm vs 1.41 ± 0.21 cm, respectively). It remains unclear whether the observed muscle thickness differences between males and females are due to sex differences, as so far the three studies comparing males to females have shown a mix of outcomes. It is clear, however, that absolute measures of muscle thickness tend to be larger in males than in females, and that relative measures (taking either body size or muscle size into account) either minimize or remove these differences. Sex-related differences in muscle size may be muscle-dependent, as Alegre et al. (2009) found trends between sexes to be different between the vastus lateralis and gastrocnemii muscles.

Pennation Angle

Pennation angle is the angle of the fascicle with respect to the muscle's line of force generation, and is closely correlated with changes in physiological cross-sectional area following resistance training (Farup et al., 2012) as part of the hypertrophic process of adding sarcomeres in parallel (Figure 2.2).

Sprint Ability

Research by Abe et al. (2001; 2000) and Kumagai et al. (2000) demonstrates that the angle of pennation in lower body locomotive musculature is similar between males and females but distinct for muscles with different force production demands. It was found that elite male sprinters possess smaller angles of pennation (18.5 ± 13.1, 21.5 ± 3.0, 14.1 ± 1.5 in the vastus lateralis, medial gastrocnemius, and lateral gastrocnemius, respectively) than elite distance runners (23.7 ± 2.1, 23.3 ± 1.8, 16.1 ± 2.6) but similar angles to controls (7.13 ± 1.18, 5.69 ± 0.75, 7.16 ± 1.44) (see Figure 2.1). Similarly, Kamagai's group (2000) found that faster sprinters had lesser pennation angles than slower sprinters in vastus lateralis (19.0 ± 3.2 vs 21.1 ± 2.1, respectively), medial gastrocnemius (21.4 ± 2.9 vs 23.5 ± 2.6, respectively), and lateral gastrocnemius (14.0 ± 1.4 vs 15.2 ± 2.1, respectively). In this study pennation angle also had a significant positive moderate correlation with 100-m sprint time in all three muscles (vastus lateralis: $r = 0.34$, medial gastrocnemius: $r = 0.37$, lateral gastrocnemius: $r = 0.46$). The elite female sprinters observed by Abe et al. (2001) had significantly lesser pennation angle than a control group in the vastus lateralis muscle (17.7 ± 2.8 vs 20.1 ± 3.5, respectively), but no significantly different measures in the medial or lateral gastrocnemii. Pennation angle of the vastus lateralis and lateral gastrocnemius tended to correlate positively with 100-m sprint times ($r = 0.36$ and $r = 0.34$, respectively) but not significantly. Taken together, these results indicate that in velocity-based competitions such as the 100-m sprint, lesser angles of pennation are favored, possibly due to the resultant allowance for more sarcomeres in series for a given muscle thickness. This lower pennation angle is possibly offset by greater muscle thickness or cross-sectional area in sprinters compared to distance runners.

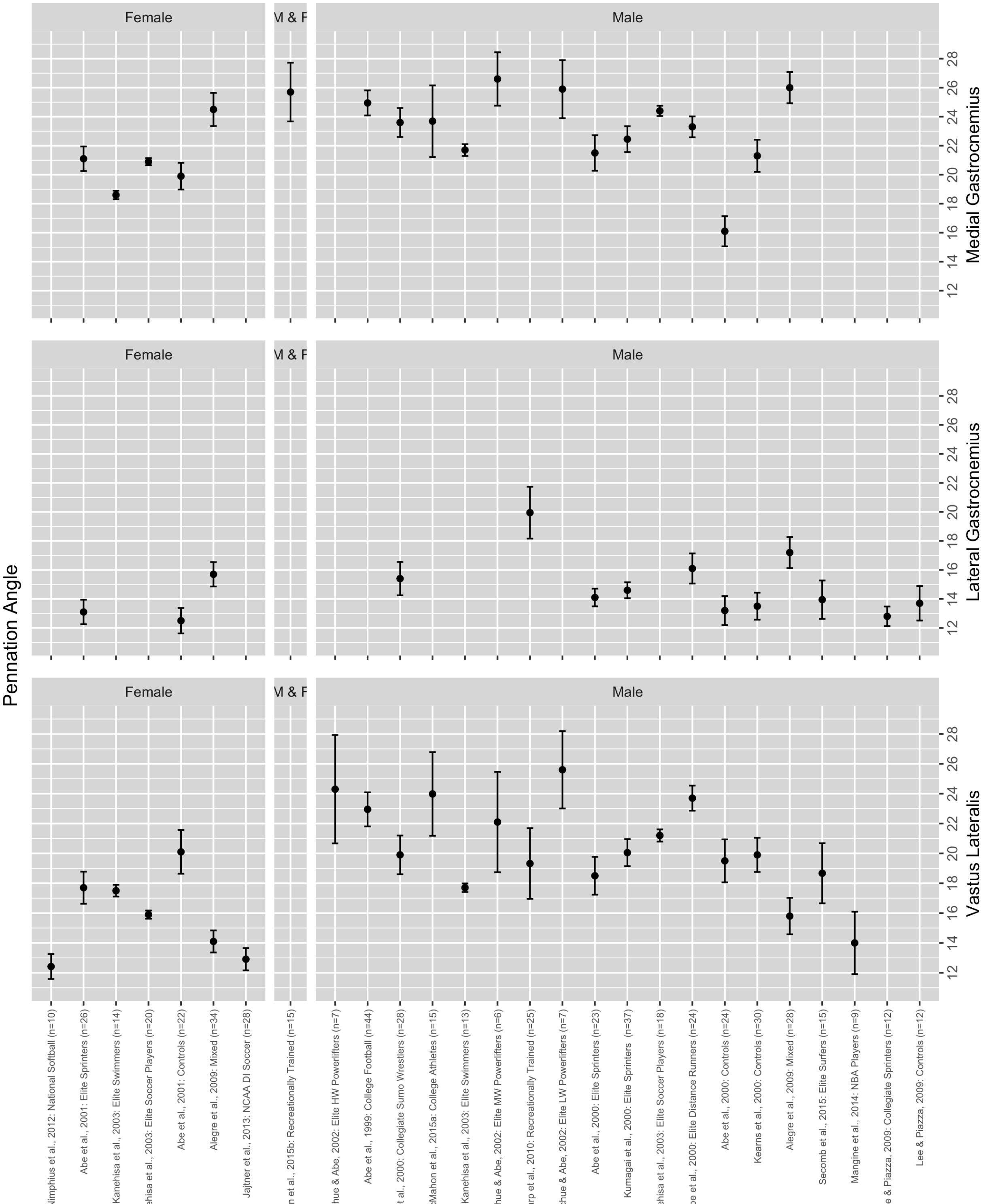

Figure 2.2. Pennation angle (degrees) for lower body musculature (mean ± SD).

Jumping Ability

Research by Earp et al. (2010) and Secomb et al. (2015) has demonstrated that pennation angle in the lateral gastrocnemius is an important factor contributing to jump performance. Earp et al. (2010) found small but significant correlations between lateral gastrocnemius pennation angle and squat jump height ($r = 0.46$), countermovement jump height ($r = 0.47$), and depth drop jump height ($r = 0.45$), but no significant correlations between vastus lateralis pennation angle and any jump measures. Secomb et al. (2015) measured pennation angle in both the right and left vastus lateralis and lateral gastrocnemius, finding significant correlations between the left lateral gastrocnemius pennation angle and countermovement jump peak velocity ($r = 0.63$) and squat jump peak force ($r = 0.53$). Earp et al. (2011) observed that strength and power-trained males with a larger lateral gastrocnemius pennation angle performed better in depth drop jumps than those with lesser angles but longer fascicles, suggesting that in pennate muscles, increased pennation angle increases an athlete's ability to resist external forces (such as in depth drop jumps or change-of-direction) due to the dissipation of forces from the tendon by a factor of cosine of the angle of pennation.

Strength

In collegiate sumo wrestlers, pennation angle of the medial (23.6 ± 2.7 vs 21.3 ± 3.1) and lateral (15.4 ± 3.1 vs 13.5 ± 2.6) gastrocnemii were statistically greater than in controls, though the vastus lateralis was similar between groups. Based on their study of muscle architecture in elite powerlifters, Brechue and Abe (2002) argue that although increased pennation angle allows for a greater packing of sarcomeres in parallel, there is a terminal point at which further increases may have a deleterious effect on force production per unit of cross-sectional area. This could be due to changes in the line of pull or the accumulation of non-contractile hypertrophy (enlarged interstitial space) in the muscle fiber. Secomb et al. (2015) observed significant correlations between left lateral gastrocnemius pennation angle and isometric mid-thigh pull peak force (r = 0.7) and relative peak force (r = 0.63). It should be noted that the left leg was the dominant leg for 13 out of 15 surf athletes in this study. In contrast, Mcmahon et al. (2015a) found no significant relationships between pennation angle of either the medial gastrocnemius or vastus lateralis to isometric mid-thigh pull performance. A second study by Mcmahon et al. (2015b) found significant correlations between pennation angle of the medial gastrocnemius and both relative (r = 0.54) and absolute (r = 0.41) 1-RM power clean in resistance trained males and females. It seems then, that pennation angle may be related to power performance and to muscle fiber hypertrophy due to training in some muscles (gastrocnemii), but not others (vastus lateralis).

Sex Differences

Kanehisa et al. (2003) observed greater pennation angles in the vastus lateralis and medial gastrocnemius of elite male soccer players than elite female soccer players and swimmers, and greater medial gastrocnemius pennation angles in elite male swimmers than elite female swimmers (see Figure 2.1). Similarly, Alegre et al. (2009) found that pennation angles were significantly larger in men than women for the vastus lateralis and lateral gastrocnemius (see Figure 2.1).

Fascicle Length

More sarcomeres in series produce greater contraction velocity while more sarcomeres in parallel produce to greater force production (at constant single fiber contraction velocity) (Mcginnis, 2013). Fascicle length is a measurement of muscle fiber length that reflects sarcomeres in series, typically measured from the superficial aponeurosis to the deep aponeurosis along the axis of the fascicle (Atsuki Fukutani and Toshiyuki Kurihara, 2015). Fascicle length strongly influences muscle shortening velocity (Bodine et al., 1982) and is positively associated with success in sports requiring high contraction velocity, such as sprinting (Abe et al., 2001; Abe et al., 2000; Kumagai et al., 2000) (Figure 2.3).

Sprint Ability

Absolute and relative fascicle length has been shown to be longer in the vastus lateralis, lateral gastrocnemius, and medial gastrocnemius of elite male sprinters than both distance runners or sedentary controls (Abe et al., 2000). The same trend was found in elite female sprinters by Abe et al. (2001) in all three muscles, however the difference between groups in relative medial gastrocnemius fascicle length was not significant. Relative fascicle length was negatively correlated to 100-m sprint performance in the vastus lateralis (r = -0.39) and lateral gastrocnemius (r = -0.40) after controlling for percent body fat. Absolute fascicle length also correlated with 100-m sprint time in the vastus lateralis (r = -0.51) and lateral gastrocnemius (r = -0.44) (Abe et al., 2001). Kumagai et al. (2000) found significant relationships between 100-m sprint time and both absolute and relative fascicle length of the vastus lateralis (r = -0.44 and r = -0.43 for absolute and relative, respectively), medial gastrocnemius (r = -0.40 and r = -0.44), and lateral gastrocnemius (r = -0.54 and r = -0.57) of elite male sprinters. Fascicle length may be either an adaptation to high velocity activity, or predispose an athlete to excel at such sports that require them.

Jumping Ability

Earp et al. (2010) have suggested that increased pennation angles and shorter fascicles in the vastus lateralis and lateral gastrocnemius contribute to jump performance as pre-stretch loads increase. In a follow-up study Earp et al. (2011) showed that lateral gastrocnemius fascicle

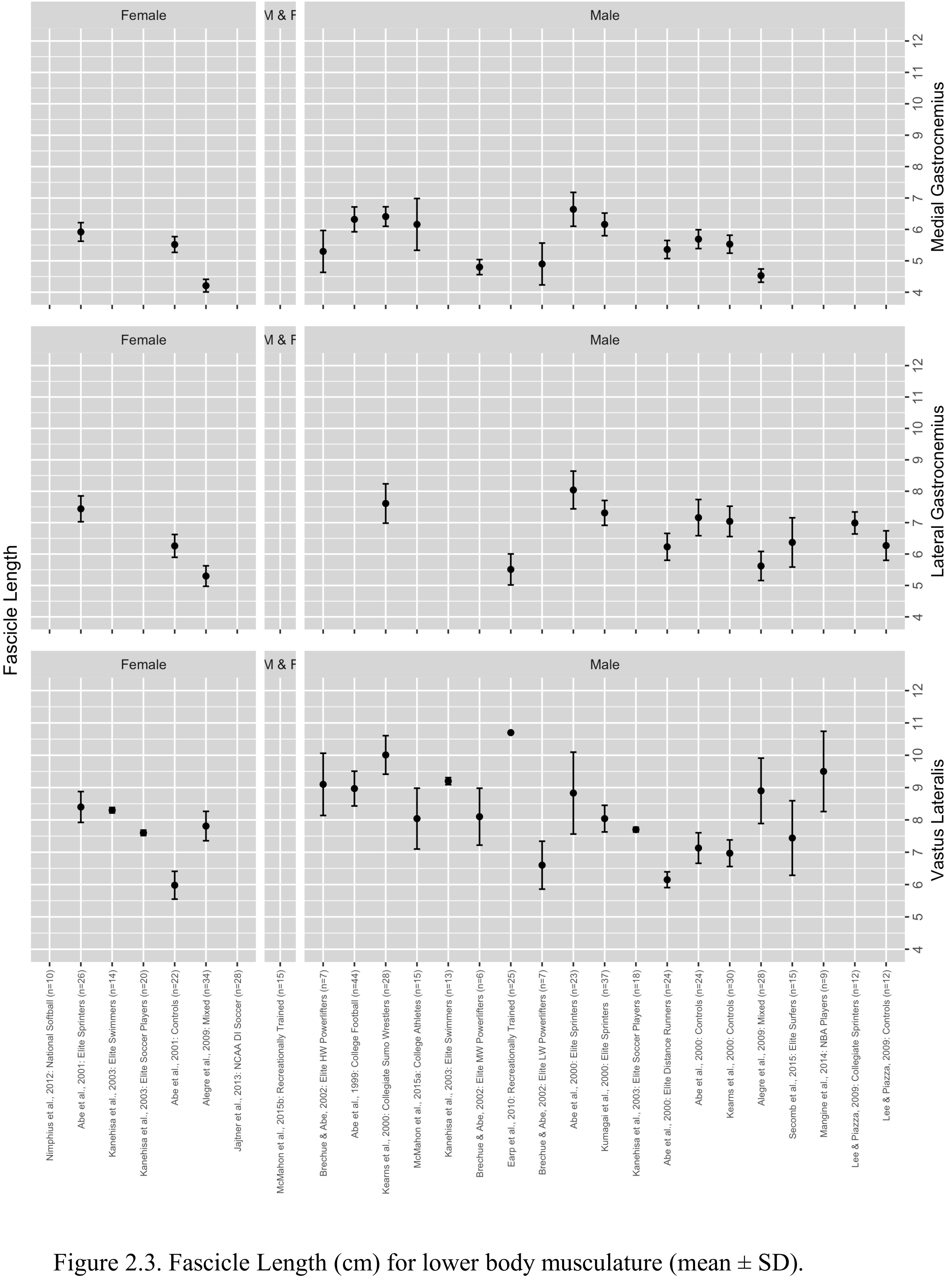

Figure 2.3. Fascicle Length (cm) for lower body musculature (mean ± SD).

length was positively correlated with early rate of force development in countermovement jumps (*r* = 0.461), but inversely correlated with early rate of force development in depth drop jumps (*r* = -0.485). Secomb et al. (2015) indirectly confirmed these findings by showing positive relationships between greater pennation angle (and therefore shorter fascicles) and muscle-tendon complex stiffness in the vastus lateralis and lateral gastrocnemius.

Strength

According to Brechue and Abe (2002) and Kearns et al. (2000), fascicle lengthening is believed to occur following strength training as a protective mechanism against future muscle damage, particularly following eccentric loading, an adaptation that may also limit changes in pennation angle. This may be beneficial to strength output by decreasing the fascicle's angle of pull in relation to the muscle's line of force generation. Sumo wrestlers possess significantly greater relative fascicle length than a sedentary control group in the vastus lateralis (0.25 ± 0.04 vs 0.20 ± 0.03), medial gastrocnemius (0.16 ± 0.03 vs 0.14 ± 0.02) and lateral gastrocnemius (0.19 ± 0.04 vs 0.18 ± 0.04). The heavy-weight and middle-weight groups of elite powerlifters measured by Brechue and Abe (2002) showed significantly greater absolute vastus lateralis fascicle lengths than the light-weight group, and the heavy-weight group showed significantly greater relative vastus lateralis fascicle length than the light-weight group. No differences were found in either relative or absolute fascicle length of the lateral gastrocnemius between any of the groups, nor did measures of fascicle length in this muscle show correlations to powerlifting performance. Relative fascicle length of the vastus lateralis, however, showed significant correlations with performance in the back squat (*r* = 0.50), bench press (*r* = 0.56), and deadlift (*r* = 0.54). A factor possibly contributing to these differences is the fact that sumo wrestlers were taller than the control group, and the powerlifters in the heavier weight classes were taller than those in the lower weight classes.

Sex Differences

The relative fascicle lengths of the vastus lateralis, medial gastrocnemius, and lateral gastrocnemius found by Abe et al. (2001) for elite female sprinters are similar to those from elite male sprinters observed previously (Abe et al., 2000; Kumagai et al., 2000). The authors also noted that the untrained male and female control subjects from the three studies also had similar fascicle lengths, though less than those of the sprinters. In elite swimmers and soccer players, Kanehisa et al. (2003) found that females had significantly greater relative fascicle lengths than men for the medial gastrocnemius, but reported similar values for the vastus lateralis.

Conclusions

Although recent investigations have begun to shed light on differences and similarities in muscle architecture between males and females in different sports, the picture is far from clear. To date, 13 distinct samples of male athletes have been observed, and only five samples of female athletes. Furthermore, to the author’s knowledge, just two studies have examined male and female athletes concurrently (Abe, Brechue, Fujita, and Brown, 1998; Kanehisa et al., 2003), and furthermore the data from Abe et al. (1998) did not distinguish between athletes of different sports.

Based on clear differences between sports and sexes and the presence of an interaction effect between sport and sex found by Kanehisa et al. (2003), it seems possible that further meaningful differences exist in male and female athletes in other sports. Future research should aim to expand our present understanding through observational investigations in well-trained samples of male and female athletes from diverse sports. Furthermore, possible relationships between muscle architecture and various aspects of sport performance or performance testing should be investigated to better understand the importance of differences in muscle morphology. Finally, longitudinal training studies observing fascicle arrangements throughout a training cycle would begin to illuminate the question of whether morphological differences are innate or adapted.

CHAPTER 3

FASCICLE ARRANGEMENTS IN COLLEGE-AGED ATHLETES: DEMOGRAPHIC ANALYSIS

Original Investigation

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ABSTRACT

Fascicle arrangements contribute to a muscle's contractile characteristics and can adapt to favor either velocity of shortening or force generation. A nuanced understanding of associations between demographic factors and muscle architecture in athletes would be valuable for talent allocation, athlete monitoring feedback, and both short- and long-term training decisions. ***Purpose:*** To observe and compare muscle architecture variables between competitive athletes of different sports and sexes. Specifically, does muscle thickness (MT), pennation angle (PA), or fascicle length (FL) differ significantly between athletes of different sexes or sports? ***Methods:*** The vastus lateralis (VL) and lateral gastrocnemius (LG) muscles of 139 collegiate athletes were assessed for MT, PA, FL, and relative fascicle length (FL_{rel}) via ultrasonography. A 2x5 (sex by sport) ANOVA was used to investigate differences in group means for each variable. ***Results:*** Significant main effects were observed for sex in VL MT, VL PA, LG MT, and LG FL ($p < .001$ to .035). Significant main effects were observed for sport in VL MT, VL FL, VL FL_{rel} and LG MT ($p < .001$ to .007). Significant interaction effects were observed for LG PA and LG FL_{rel} ($p < .037$ and $p < .035$). ***Conclusions:*** These results indicate that muscle architecture may play a role in sport selection for athletes and undergoes directed adaptation to unique sport specific training demands. Males in all sports observed had greater muscle thickness than female counterparts, although patterns of PA and FL values differed between VL and LG. Vastus lateralis muscle thickness of 2.19 cm to 2.27 cm for females and 2.61 cm to 2.77 cm for males may represent minimum values of muscularity for success in collegiate high intensity interval type team sports.

Key words: muscle architecture, ultrasound, pennation angle, sex differences, sport characteristics

INTRODUCTION

It has been demonstrated that mechanical power output is a primary outcome determinant in a variety of sports[1]. In mechanical terms, power is the product of force and velocity. In biological organisms, power production is achieved via skeletal muscle contraction. Although muscle fiber morphology is related to individual fiber contractile properties, whole muscles derive their contractile characteristics from the overall composition and arrangement of muscle fibers—bundled into "fascicles"—relative to the line of force generation[2]. The architectural arrangement of fascicles within different muscles varies greatly and can be described using four measures: muscle thickness (MT), fascicle length (FL), pennation angle (PA), cross-sectional area[3]. Together, these measures help determine a muscle's contraction velocity and force production capacity. Given this architectural basis for power generation, and the fact that different sports possess distinct kinetic, kinematic, and metabolic demands, muscle architecture characteristics could be used as a tool for both talent identification and athlete monitoring purposes.

Several modes of observing muscle architecture properties exist, including magnetic resonance imaging, computed tomography scans, and the criterion standard of direct cadaveric measurement. Recently, β-mode ultrasonography has emerged as a valid and reliable technique for studying muscle architecture[4]. This technique is optimal for use in athlete monitoring scenarios due its relative ease of implementation and non-invasive procedure.

Examinations of muscle architecture have been made in both male and female athletes from several sports with this technique. Abe*, et al.*[5] observed greater FL and smaller PA in the vastus lateralis (VL) and lateral gastrocnemius (LG) of male sprinters compared to distance runners or age-matched controls, and the same findings were later observed in a group of female sprinters when compared with age-matched controls[6]. Kearns*, et al.*[7] have compared sumo wrestlers to controls and found greater MT, PA, and FL in select muscles in the sumo group. Research by Kanehisa*, et al.*[8] reported greater MT and FL in male soccer players and swimmers than females, and that soccer players possessed shorter fascicles and greater PA, while swimmers had greater MT and longer fascicles.

Despite these findings and several other cross-sectional comparative studies[9-13], little is known about sex-related differences in muscle architecture. Furthermore, normative and comparative data in athletes is scarce. In order to function as a tool for talent identification and athlete monitoring, differences in fascicle arrangement between competitive athletes of different sports and sexes should be clarified to establish a set of architectural goalposts for coaches and sport scientists. Therefore, the primary purpose of this study was to observe and compare muscle architecture variables (MT, PA, FL, and FL_{rel} of the VL and LG muscle) between competitive athletes of different sports and sexes for use as monitoring and talent identification variables. Secondarily, we sought to draw exploratory inferences about relationships between muscle architecture and known metabolic, kinetic, and kinematic aspects of each sport.

METHODS

Subject Characteristics

A group of 139 male (n = 78) and female (n = 61) athletes from the National Association of Intercollegiate Athletics (NAIA), National Collegiate Athletics Association Division I (NCAA D1), and US Olympic Training Site (OTS) participated in this study as part of an ongoing athlete monitoring program. Athletes were recruited from collegiate men's and women's NAIA basketball (n = 15, 16), men's and women's NCAA D1 soccer (n = 29, 20), men's and women's NCAA D1 tennis (n = 6, 8), men's and women's OTS weightlifting (n = 14, 7), and men's and women's NAIA cross-country (n = 12, 10) (Table 3.1). Urine-specific gravity was determined using a refractometer (Atago, Tokyo, Japan), and athletes with urine samples reading > 1.020 urinary specific gravity were asked to drink water and retest to ensure hydration-status would not affect the ultrasound measurements[14]. Testing was conducted during a period of reduced training during the onset of the fall semester training period for all athletes. To be eligible for the study athletes must have been at least 18 years of age. All participants voluntarily read and signed written informed consent documents pertaining to the long-term athlete-monitoring program and all testing procedures in accordance with the guidelines of East Tennessee State University's Institutional Review Board.

Table 3.1. Subject characteristics when divided into groups. Values are displayed as means ± SD.

	Basketball		Cross-Country		Soccer		Tennis		Weightlifting	
	Male (*n* = 15)	Female (*n* = 16)	Male (*n* = 12)	Female (*n* = 10)	Male (*n* = 29)	Female (*n* = 10)	Male (*n* = 8)	Female (*n* = 8)	Male (*n* = 14)	Female (*n* = 7)
Age (years)	20.7 ± 2.5	19.7 ± 1.5	19.7 ± 0.9	19.6 ± 0.8	20.8 ± 1.3	19.6 ± 1.2	21.4 ± 1.9	19.7 ± 0.6	28.2 ± 6.1	20.1 ± 2.1
Height (cm)	190.1 ± 9.5	169.8 ± 5.8	172.7 ± 6.6	164.7 ± 9.6	177.8 ± 5.6	164.6 ± 4.6	178.1 ± 9	169.7 ± 9.6	176.9 ± 4.3	156.9 ± 7.3
Body mass (kg)	86.5 ± 8.7	68.6 ± 10.6	65.3 ± 7.5	58.6 ± 4.9	74.8 ± 7	60.6 ± 6.4	76.9 ± 11.8	72.4 ± 7.9	88 ± 11.1	72.4 ± 17.8
Bodyfat (%)	9.7 ± 3.6	23.8 ± 4.6	10.3 ± 2	15 ± 3.3	8.5 ± 2.4	15.1 ± 3.5	10.8 ± 4	20.4 ± 4.3	14.2 ± 5.7	21.1 ± 7.2
Femur length (cm)	46 ± 3	43.7 ± 2.2	42 ± 2.5	40.7 ± 1.6	42.8 ± 2	40.2 ± 1.8	43.1 ± 2.3	42.1 ± 3.1	42.8 ± 2	39 ± 2.8
Shank length (cm)	47.5 ± 3.3	41.4 ± 2.1	43.5 ± 2.6	40.9 ± 1.7	43.3 ± 1.9	39.4 ± 1.5	43.4 ± 2.5	40.9 ± 3.3	43.4 ± 1.8	37.6 ± 3.2

Biometric Data

Standing height was measured to the nearest 0.01 meters using a stadiometer (Cardinal Scale Manufacturing Co., Webb City, MO), and body mass was measured using a digital scale (Tanita B.F. 350, Tanita Corp. of America, Inc., Arlington Heights, IL). Percent body fat was assessed via skinfold estimation using Lange calipers (Cambridge Scientific Industries, Cambridge, MD) and a 7-site protocol[15].

Ultrasound Measures

The VL and LG muscles were chosen due to their prevalence in the literature and so that results could be interpreted in light of previous findings showing relationships between muscle architecture and measures of performance in various athletic populations[6,9-13,16,17]. A 7.5 MHz ultrasound probe was used to measure CSA, MT, PA, and FL of the VL and LG of the right leg (General Electric Healthcare, Wauwatosa, WI).

For VL measurements, the athlete laid on their left side with hips perpendicular to the examination table in the frontal plane and a knee angle of 125 ± 5° as measured by a handheld goniometer[18]. This positioning was selected to improve image clarity during cross-sectional scans and promoted relaxation of the knee extensors. The sampling location for the VL was determined by the point of intersection between the VL and 5cm medial to 50% of the femur length, which was defined as the distance between the greater trochanter and the lateral epicondyle of the femur[18].

For LG measurements, the athlete laid prone with hips and knees fully extended. Images were sampled at 30% of the lower leg length, defined as the distance between the popliteal crease and the lateral malleolus[19].

Both the VL and LG locations were marked with permanent marker and the ultrasonography probe oriented longitudinally in the sagittal plane, parallel to the length of the muscle for each sample. The probe was covered with water-soluble transmission gel to aid acoustic coupling and avoid depression of the skin, which may cause changes in the measured parameters[20]. Cross-sectional area was measured by placing the probe perpendicular to the length of the muscle and moving it in the transverse plane along the skin to collect a cross-sectional image. Muscle thickness and PA were quantified in still images captured longitudinally in the sagittal plane using the measuring features of the ultrasound machine.

Muscle thickness was determined as the distance between the subcutaneous adipose tissue–muscle interface and inter-muscular interface. Pennation angle was determined as the angles between the echoes of the deep aponeurosis of the muscle and the echoes from interspaces among the fascicles[18]. Cross-sectional area was measured by tracing the inter-muscular interface in the cross-sectional images[21]. Fascicle length was calculated from MT and PA using the following equation[18,22]:

$$Fascicle\ length = MT \cdot SIN\ (PA)^{-1}$$

The ultrasound examiner collected 3 longitudinal images from each sonogram. The means of MT, PA, and FL measurements were assessed from the images and used for further analysis[23]. Relative fascicle length (FL_{rel}) was calculated as the product of LG FL and the inverse of shank length, and the product of VL LG and the inverse of femur length, as measured during ultrasonography.

Statistical Analyses

Repeated measures were assessed for both absolute and relative reliability using two-way mixed effects, single measurement intraclass correlation coefficients (ICC [3,1]) with absolute agreement[24,25] and coefficient of variation, respectively[26]. Eight 2x5 (sex by sport) omnibus ANOVAs were computed to detect differences in the mean values of MT, PA, FL, and FL_{rel} for both VL and LG. Statistically significant interaction effects were followed by post-hoc interaction contrasts and simple comparisons, and statistically significant main effects without a statistically significant interaction were followed by post-hoc pairwise comparisons. A Scheffe adjustment to the critical F value was used to control the family-wise error rate within main effects for interaction contrasts and simple effects, while a Tukey-Kramer adjustment was used for pairwise comparisons of marginal means. Cohen's *d* effect sizes were calculated using pooled standard deviations for cell means and marginal means to determine practically significant differences[27]. Effect size values of *d* were interpreted as 0.2 to 0.49 = "small", 0.5 to 0.79 = "medium", 0.8 to 1.29 = "large", 1.3 to 1.99 = "very large", and 2.0 and above = "extremely large". Critical alpha was set to $p < 0.05$. Statistical analyses were performed using SPSS software version 22 (IBM Co., New York, NY, USA) and Microsoft Excel 2010 version 14 (Microsoft Corporation, Redmond, WA, USA). Figures were generated using R Studio[28,29] and two custom data visualization packages[30,31].

RESULTS

Intraclass correlation coefficients for muscle architecture measurements revealed near-perfect relationships between ultrasound images, with ICCs ranging from 0.986 to 0.999 ($p <$ 0.001) and CVs ranging from 0.54% to 2.92%.

Residual Analysis

Data points 1.5 times the interquartile outside of the median quartiles were flagged as potential outliers. A second dataset was created to exclude the potential outliers and a sensitivity analysis was performed to compare analysis of variance (ANOVA) results between each dataset. Results were similar between the two datasets and it was determined that none of the potential outliers were due to clerical or instrumental error. Therefore, the decision was made to keep the outlying observations in the dataset to avoid introducing statistical bias (via winsorizing) or producing poor estimates of the true parameter (via trimming)[32]. Normality was assessed via Shapiro-Wilks normality test and visual inspection of the Q-Q plots of residuals and found to be sufficient. The assumption of equality of variances was met based on deviations from group medians[33] (p = 0.085 to 0.741).

Table 3.2a. ANOVA Between Sex and Sport for Vastus Lateralis Muscle Architecture

Muscle thickness	*df*	MS	*F*	*p*	*effect size*
Sex	1	3.635	33.283	0.000	0.205
Sport	4	0.959	8.784	0.000	0.214
Sex × Sport	4	0.118	1.083	0.368	0.032
Error	129	0.109	-	-	-

Pennation Angle	*df*	MS	*F*	*p*	*effect size*
Sex	1	81.721	11.017	0.001	0.079
Sport	4	9.928	1.338	0.259	0.040
Sex × Sport	4	9.919	1.337	0.260	0.040
Error	129	7.418	-	-	-

Fascicle Length	*df*	MS	*F*	*p*	*effect size*
Sex	1	1.792	0.564	0.454	0.004
Sport	4	13.253	4.172	0.003	0.115
Sex × Sport	4	1.406	0.443	0.778	0.014
Error	129	3.177	-	-	-

Rel. Fascicle Length	*df*	MS	*F*	*p*	*effect size*
Sex	1	0.001	0.552	0.459	0.004
Sport	4	0.006	3.731	0.007	0.104
Sex × Sport	4	0.001	0.568	0.686	0.017
Error	129	0.002	-	-	-

Note.—MS = Mean squares, effect size = partial η^2.

Table 3.2b. ANOVA Between Sex and Sport for Lateral Gastrocnemius Muscle Architecture

Muscle thickness	*df*	MS	*F*	*p*	*effect size*
Sex	1	1.645	20.480	0.000	0.137
Sport	4	0.326	4.056	0.004	0.112
Sex × Sport	4	0.095	1.188	0.319	0.036
Error	129	0.080	-	-	-

Pennation Angle	*df*	MS	*F*	*p*	*effect size*
Sex	1	12.595	0.809	0.370	0.006
Sport	4	14.297	0.918	0.456	0.028
Sex × Sport	4	41.101	2.638	0.037	0.076
Error	129	15.578	-	-	-

Fascicle Length	*df*	MS	*F*	*p*	*effect size*
Sex	1	18.337	11.833	0.001	0.084
Sport	4	1.188	0.766	0.549	0.023
Sex × Sport	4	3.443	2.222	0.070	0.064
Error	129	1.550	-	-	-

Rel. Fascicle Length	*df*	MS	*F*	*p*	*effect size*
Sex	1	0.001	1.693	0.196	0.013
Sport	4	0.000	0.441	0.779	0.013
Sex × Sport	4	0.002	2.679	0.035	0.077
Error	129	0.001	-	-	-

Note.—MS = Mean squares, effect size = partial η^2.

Table 3.3a. Cell and marginal mean ± standard deviation for VLMT

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex*
Female	2.27 ± 0.39	2.15 ± 0.31	2.4 ± 0.3	2.19 ± 0.36	2.6 ± 0.37	2.32 ± 0.36*
Male	2.77 ± 0.41	2.28 ± 0.27	2.73 ± 0.29	2.61 ± 0.26	3 ± 0.35	2.7 ± 0.38*
Sport*	2.51 ± 0.47 *c w*	2.51 ± 0.47 *b s w*	2.6 ± 0.33 *c w*	2.4 ± 0.37 *w*	2.86 ± 0.42 *b s c t*	

Table 3.3b. Cell and marginal mean ± standard deviation for VLPA

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex*
Female	12.32 ± 1.9	14.74 ± 2.62	13.43 ± 2.19	12.83 ± 3.91	14.63 ± 2.4	13.42 ± 2.58*
Male	15.02 ± 2.99	14.19 ± 2.23	15.59 ± 2.68	15.28 ± 3.37	16.27 ± 3.37	15.36 ± 2.88*
Sport	13.63 ± 2.8	13.63 ± 2.8	14.71 ± 2.69	14.06 ± 3.75	15.73 ± 2.91	

Table 3.3c. Cell and marginal mean ± standard deviation for VLFL

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex
Female	10.83 ± 1.98	8.51 ± 0.59	10.52 ± 1.51	10.39 ± 2.3	10.54 ± 2.24	10.25 ± 1.87
Male	10.9 ± 1.58	9.47 ± 1.61	10.4 ± 1.78	10.19 ± 1.74	11.07 ± 2.22	10.45 ± 1.83
Sport*	10.86 ± 1.77 *c*	10.86 ± 1.77 *b s w*	10.45 ± 1.66 *c*	10.29 ± 1.97	10.89 ± 1.84 *c*	

Table 3.3d. Cell and marginal mean ± standard deviation for $VLFL_{rel}$

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex
Female	0.247 ± 0.044	0.21 ± 0.016	0.259 ± 0.039	0.248 ± 0.044	0.263 ± 0.051	0.247 ± 0.043
Male	0.236 ± 0.038	0.224 ± 0.033	0.243 ± 0.043	0.236 ± 0.031	0.261 ± 0.052	0.241 ± 0.042
Sport*	0.242 ± 0.041	0.242 ± 0.041 *s w*	0.249 ± 0.042 *c*	0.242 ± 0.037	0.262 ± 0.042 *c*	

Table 3.3e. Cell and marginal mean ± standard deviation for LGMT

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex*
Female	1.91 ± 0.25	1.8 ± 0.27	1.58 ± 0.32	1.65 ± 0.23	1.61 ± 0.19	1.72 ± 0.
Male	2.05 ± 0.36	1.86 ± 0.32	1.86 ± 0.18	2 ± 0.42	1.97 ± 0.3	1.93 ± 0.
Sport*	1.98 ± 0.31 *s*	1.98 ± 0.31	1.74 ± 0.28 *b*	1.83 ± 0.38	1.85 ± 0.31	

Table 3.3f. Cell and marginal mean ± standard deviation for LGPA

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex
Female	21.4 ± 6.01	21.79 ± 3.73	18.21 ± 3.8	21.19 ± 3.95	20.91 ± 5.19	20.34 ± 4
Male	21.09 ± 3.71	20.01 ± 2.73	21.23 ± 3.66	19.34 ± 3.54	18.56 ± 2.14	20.34 ± 3
Sport	21.25 ± 4.95	21.25 ± 4.95	20 ± 3.97	20.26 ± 3.75	19.34 ± 4.02	Interacti

Table 3.3g. Cell and marginal mean ± standard deviation for LGFL

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex*
Female	5.54 ± 1.35	4.96 ± 1.36	5.25 ± 1.45	4.61 ± 0.45	4.75 ± 1.43	5.14 ± 1.
Male	5.83 ± 1.42	5.45 ± 0.86	5.23 ± 0.83	6.3 ± 2.2	6.25 ± 0.98	5.68 ± 1.
Sport	5.68 ± 1.37	5.68 ± 1.37	5.24 ± 1.11	5.45 ± 1.77	5.75 ± 1.29	

Table 3.3h. Cell and marginal mean ± standard deviation for $LGFL_{rel}$

	Basketball	Cross-country	Soccer	Tennis	Weightlifting	Sex
Female	0.13 ± 0.03	0.12 ± 0.03	0.13 ± 0.04	0.11 ± 0.02	0.12 ± 0.03	0.13 ± 0
Male	0.12 ± 0.03	0.12 ± 0.02	0.12 ± 0.02	0.15 ± 0.05	0.15 ± 0.02	0.13 ± 0
Sport	0.13 ± 0.03	0.13 ± 0.03	0.13 ± 0.03	0.13 ± 0.04	0.14 ± 0.03	Interacti

Note: Tukey-Kramer adjusted statistically significant comparisons of marginal means denoted by the following symbols: * = difference between sexes, *b* = different to basketball, *c* = different to cross-country, *s* = different t
weightlifting. Statistically significant F effects of Sport and Sex are denoted by *

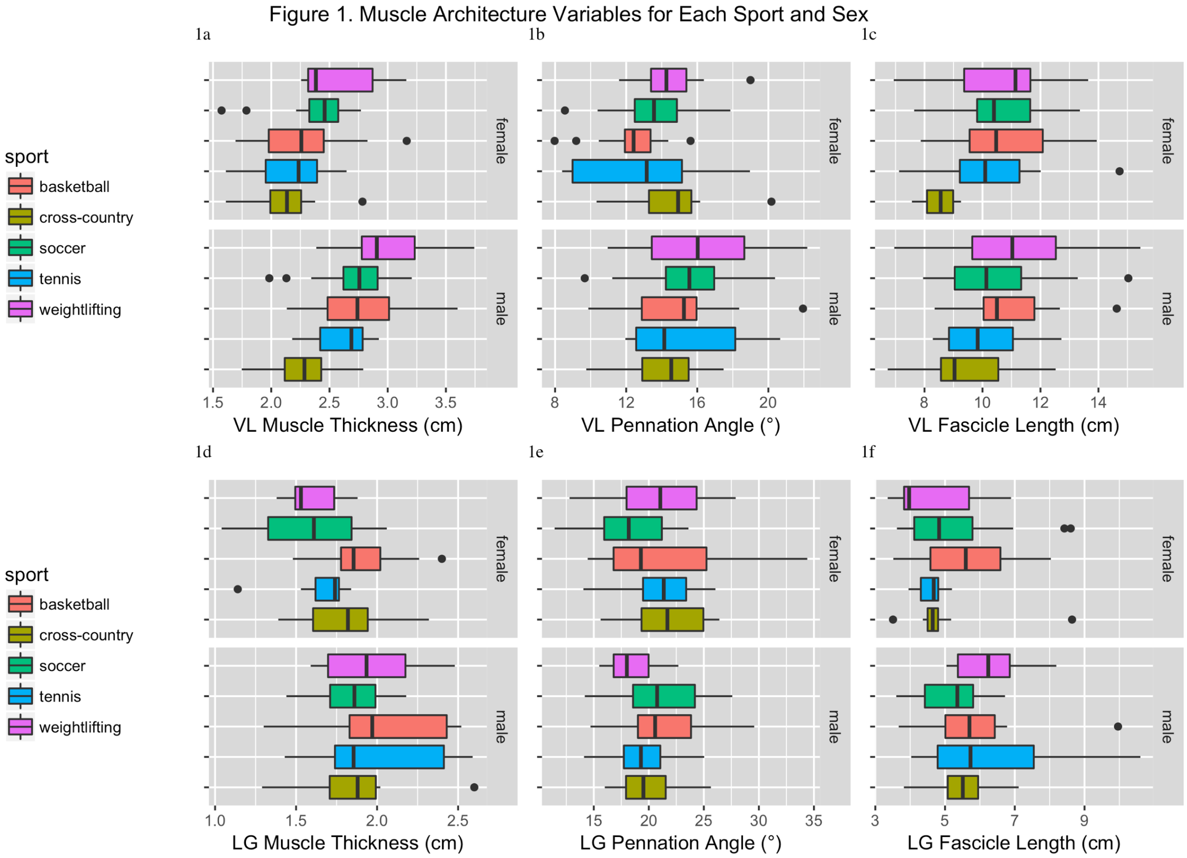

Figure 3.1. Muscle architecture of vastus lateralis and lateral gastrocnemius across sport and sex. Muscle thickness (1a, 1d), PA (1b, 1e), and FL (1c, 1f) are displayed as boxplots showing mean, SD, and 3•SD for each sport and sex.

Interaction Effects

For both LG PA and FL_{rel}, there was a statistically significant interaction effect, wherein the effect of sex to depends on sport (Tables 2a and 2b). Post-hoc interaction contrasts for LG PA compared males to females between soccer and each of cross-country, basketball, tennis, and weightlifting, while for LG $FL_{rel,}$ males and females were compared between soccer and each of cross-country, tennis, and weightlifting; and basketball to each of weightlifting and cross-country. None were statistically significant after Scheffe adjustment (adjusted critical F = 9.768). Thus, additional interaction contrasts were examined by combining certain sports based on observed patterns of the cell means of LG PA and LG FL_{rel}. For LG PA, soccer athletes were compared to the combined means of the other sports between the sexes because soccer athletes' means appeared to have a different pattern than the other sports. On the other hand, for LG FL_{rel}, the first contrast compared the combined means of cross-country, tennis, and weightlifting to those of the other sports between the sexes and the second compared the combined means of tennis and weightlifting to those of basketball and soccer between the sexes, omitting cross-country in the second contrast because cross-country appeared to have similar means between the sexes. The contrast for LG PA statistically showed that female soccer athletes possess smaller PA than their male counter-parts while in the other sports, male athletes possess smaller PA than their female counter-parts ($F_{(1, 129)} = 10.161$). The second contrast for LG FL_{rel} statistically indicated that female tennis and weightlifting athletes possess smaller FL_{rel} than their male counter-parts while female basketball and soccer athletes possess larger FL_{rel} than their male counter-parts (F(1,129) = 10.355). The first contrast for LG FL_{rel}, namely the second contrast with cross-country included with tennis and weightlifting athletes, failed to show statistical significance ($F_{(1, 129)} = 8.767$). The contrasts were followed up with Cohen's *d* effect sizes in order to understand the magnitude of a possible difference in practical settings. It is important to note that the lack of statistical significance for some contrasts suggests that any of the difference magnitudes discussed below for the interaction contrasts do not have a probability high enough to be observed frequently and/or can be due to type I error while the lack of statistical significance does not necessarily mean that an observation made in this study never happens in practical settings. Nonetheless, based on Cohen's *d* for the interaction contrasts using the cell means, females had similar PA to males for basketball ($d = 0.06$) and larger PA than males for cross-country ($d = 0.55$), tennis ($d = 0.49$), and weightlifting ($d = 0.59$). Based on

Cohen's *d* for the complex interaction contrast using combined unweighted means, male weightlifting, tennis, cross-country, and basketball athletes had smaller LG PA than their female counterparts (*d* = 0.40), while male soccer athletes had larger LG PA than female soccer athletes (*d* = 0.81). Based on cell means, male tennis players and weightlifters had greater LG FL_{rel} than females (*d* = 0.83 and 0.81, respectively). Conversely, male basketball and soccer athletes had smaller LG FL_{rel} than females (*d* = 0.35 and 0.40, respectively). Based on Cohen's *d* for complex interaction contrasts using combined unweighted means, male tennis and weightlifting athletes combined had greater LG FL_{rel} than female tennis and weightlifting athletes (*d* = 0.78), as did male tennis, weightlifting, and cross-country athletes combined (*d* = 0.61). Conversely, male soccer and basketball athletes combined had smaller LG FL_{rel} than female soccer and basketball athletes (*d* = 0.38), while cross-country athletes showed trivial differences in LG FL_{rel} between males and females (*d* = 0.13).

Sex Related Differences

Males had statistically greater VL MT and PA than females (Table 3.2a), and greater LG MT and FL than females. (Table 3.2b).

Sport Related Differences

The main effect of sport was statistically significant for VL MT, FL and FL_{rel} (Table 3.2a), and for LG MT (Table 3.2b). According to statistically significant pairwise comparisons, weightlifters had the largest VL MT, basketball and soccer athletes had smaller VL MT than weightlifters but greater VL MT than cross-country athletes, and cross-country and tennis athletes had the smallest VL MT ($p < .001$ to .020) (Table 3.2a). Basketball, soccer, and weightlifting athletes had greater VL FL than cross-country athletes ($p = .003$ to .020) (Table 3.2c). Soccer athletes and weightlifters had greater VL FL_{rel} than cross-country athletes ($p = .021$

and .005, respectively) (Table 3.2d). Weightlifters had greater LG MT than tennis (p = .004) (Table 3.2e).

DISCUSSION

The primary purpose of this study was to observe and compare muscle architecture variables (MT, PA, FL, and FL_{rel} of the VL and LG muscle) between competitive athletes of different sports and sexes to investigate the usefulness of muscle architecture as an athlete monitoring tool. Secondarily, we sought to draw exploratory inferences about muscle architecture based on known metabolic, kinetic, and kinematic aspects of each sport. The findings from this investigation can be used to further elucidate phenotypic differences between sexes and athletes based on muscle architecture, and provide insight for collegiate athlete-monitoring and talent identification programs. Male and female cross-country, basketball, soccer, tennis, and weightlifting athletes were chosen to represent a diversity of sport-specific physiological demands so that inherent differences could be observed. To the authors' knowledge, this is the first single study to compare muscle architecture across more than two sports with both sexes, and to do so in a context of an ongoing testing and monitoring service.

Interaction Effects

Previous attempts to determine muscle architecture differences between sport and sex found interaction effects in fascicle arrangement[8], and our data support these findings. The presence of statistically significant interaction effects for LG PA and FL_{rel} in the current sample of collegiate athletes has implications for athlete-monitoring paradigms, namely that these measures must be interpreted in the context of the sex and sport of the athlete. Based on the interaction contrasts, female soccer athletes appear to have smaller LG PA than their male counterparts while all the other sports, when pooled together, appear to have the opposite trend (i.e. male athletes having smaller LG PA than female athletes) (Table 3.2f). This finding is peculiar because weightlifting, tennis, cross-country, and basketball vary widely in metabolic, kinetic, and kinematic demands, while soccer has aspects that are similar to cross-country (a large aerobic component) and both tennis and basketball (repeated high intensity work intervals and rapid changes of direction). Previous work on sprinters[5,6], soccer players, and swimmers[8] reported that males had greater PA than females in the VL, LG, and medial gastrocnemius, a trend that the soccer players from this study conform to. If these data are to be believed, then sex differences in LG PA may depend on the sport in question. Moreover, there is no discernable pattern of commonality between sports in which males have larger PA (sprinting, soccer, swimming) or in which females have larger PA (tennis, weightlifting and cross-country).

For LG FL_{rel}, male tennis and weightlifting athletes pooled together appear to have greater $FL_{rel,}$ than their female counterparts while basketball and soccer athletes appear to show the opposite trend with cross-country having a trivial effect size (Table 3.2h). Relative fascicle length calculations attempt to scale for anthropometric differences between samples by accounting for segment length. With anthropometric discrepancies accounted for, FL_{rel} should better reflect true differences between individuals, groups, or time-points. The statistical interaction effect in FL_{rel} but not FL suggests that FL_{rel} may be a more informative monitoring variable and that fascicle differences between samples exist independent of anthropometric differences. The specific pattern in our data may be dependent on LG MT values. Although a sex by sport interaction was not statistically significant for LG MT, the difference between males and females based on effect size was larger for weightlifters, tennis, and soccer athletes than for cross-country and basketball athletes. In soccer athletes, males' larger LG MT is likely due to the aforementioned difference in LG PA.

Based on effect sizes, it appears that male soccer athletes have greater LG MT than females, due primarily to larger PA, while male tennis and weightlifting athletes have greater LG MT than females due primarily to greater FL_{rel}. Sex differences in basketball and cross-country athletes appear to be marginal based on effect size. This data suggests that males and females may adapt to sport-specific demands differently, or that the sex differences in successful sport strategy at the collegiate level is large enough to drive different fascicular adaptations. It is possible in soccer that males must rely on greater force production of the plantar flexors to accomplish change-of-direction and acceleration tasks, while females—perhaps due in part to lighter body mass—have less forceful plantar flexors but are capable of similar contractile velocities as males. Whether this is an adaptation or merely a deficiency cannot be determined from this cross-sectional analysis without accompanying performance data. There is a possibility that the caliber of athletes examined in this study are not representative of high-performing athletes in their sport and sex. Moreover, considering the number of comparisons in the present paper, the possibility of both type I and type II error must be acknowledged. Therefore, it is possible that these findings are unique to this sample of athletes only. Nevertheless, the interaction effects in this data illustrate the need for sport scientists to utilize monitoring programs that assess underlying morphological changes to quantify the adaptive responses of individuals and groups to training, with the knowledge that these responses may be different across sport and sex. Specifically, male tennis, weightlifting, basketball, and cross-country athletes had smaller LG PA than females, the opposite of what has been found in the general population[34]. This indicates that in these sports, the greater LG MT found in males can be attributed to longer FL_{rel}. Male soccer athletes may depend more heavily on force production and lower leg stiffness during acceleration and change-of-direction tasks, which is made possible through greater sarcomere packing afforded by large PA values in the LG. Female soccer athletes on the other hand may rely on velocity of fiber shortening to accomplish these tasks due to having smaller LG PA than male soccer athletes and other female athletes, but greater LG FL_{rel}. This finding supports investigations that have found statistically greater stiffness in the lower legs of males than females during hopping and jumping tasks, and may have implications for sex-bias in risk of non-contact soft tissue injuries[35].

Because of the relationship between PA, FL and force production characteristics of a whole muscle, monitoring changes in both PA and FL in conjunction with strength and power measures may contribute to sport scientists' understanding of the complex relationships between training stimuli and adaptations in the athletes they are working with, and how these differ across both sport and sex. It should be noted that the caliber of the athletes in each sample likely effects a team's homogeneity in regard to these variables, such that sample variance decreases as competition level increases. Caution should be taken when attempting to use LG PA or FL_{rel} to identify sport-specific performance potential, as these relationships may not become clear until high levels of competitiveness are reached, or may not exist at all.

Sex Differences

It is known that sex differences in hypertrophic response to training is largely due to hormonal factors[36], and that on average men have greater muscle mass than women[37,38]. Our data is in line with this sentiment, and shows that in collegiate athletes, males have larger VL and LG MT than females, agreeing with similar findings from previous examinations of these muscles between sexes[8,12]. In sport, increased muscle size is beneficial in situations when an athlete would benefit from either increased force production, increased physical size, or both. It is important then, to recognize that female athletes may be biologically limited in this regard.

Indeed, the collegiate female soccer athletes in the present study have already obtained larger VL MT values (Table 3.2a) than previous investigations of female soccer athletes at the collegiate[13] and elite levels[8], suggesting that increased soccer performance for females may not be dependent upon increasing VL MT to that of males. Moreover, despite the ability of females to gain MT at similar rates to males[39], a study of 693 elite (international caliber) athletes found that females had lower lean body mass than males both relatively and absolutely, such that on average an elite female athlete carried 85% of the lean body mass of her male counterpart. Based on MT monitoring data, training history, and specific sport needs, it may be determined that females should spend more time in strength-endurance—hypertrophy—phases of training to account for their lower starting point. Conversely, it may be more appropriate to focus on other parameters of muscle architecture such as PA or FL, or on neural factors of performance, considering that females may have limited hypertrophic potential. The current data set supports that the biological limit to attainable muscle thickness is lower in female athletes than in male athletes[40]. However, psychosocial factors such as body image concerns, as well as environmental factors such as lack of access to or instruction in weight training may also contribute to the lower observed muscle sizes in females. A collateral benefit of an athlete monitoring service should be to educate female athletes and their coaches about the many potential benefits that increased muscle mass can have on sport performance and injury prevention.

Given the muscle architecture model proposed by Maxwell*, et al.*[41], a salient question is whether PA or FL drives the difference in MT between sexes. This model posits an increase in PA to either accommodate or cause increases in MT and cross-sectional area when fiber number and FL are held constant[41]. The shift in PA allows for increased sarcomere packing and drives increases in MT relative to the sine of PA. In our data, larger VL MT in males is accompanied by larger PA, while larger LG MT is accompanied by longer FL, suggesting that MT differences between males and females are muscle-dependent. Both PA and FL are inherited but trainable morphological qualities, so the observed values may be a result of different training histories, different adaptive responses to current training, or of underlying heritable traits that have been selected for differently between male and female athletes. The present study design does not reveal where the difference lies, but rather that differences should be expected when assessing male and female athletes.

Sport Differences

Each sport can be placed on a qualitative scale of mostly aerobic to mostly anaerobic by total competition time and work to rest ratios. According to this continuum, cross-country is an aerobic sport, tennis, soccer, and basketball are mixed aerobic/anaerobic sports, and weightlifting is an anaerobic sport. Furthermore, the sports follow the same rank order for overall kinetic output due to the inverse relationship between duration of exertion and intensity of exertion[42]. The observed pattern in VL MT—endurance athletes with the lowest values and strength athletes with the highest—is unsurprising, given that longer durations of activity and greater volumes of training within a single session tend to lead to muscle fiber type conversion to slower, smaller myosin isoform fibers[43]. The intensity of work is also decreased during prolonged activity, so potential sport-specific drivers of muscular hypertrophy (such as peak mechanical tension) may be lessened. Indeed, basketball athletes have the shortest competition duration (with the exception of cross-country, whose training consist of all low force endurance training) of the mixed aerobic/anaerobic sports. Weightlifters had the largest PA and FL_{rel}, and the second-largest FL, which makes sense given their large VL MT values.

Keeping in mind that a goal of any monitoring program is to evaluate training stimuli and resultant adaptive responses, sport scientists should collect longitudinal muscle architecture data and, when possible, compare them to measures of internal and external training load, as well as changes in performance. Examples of longitudinal muscle architecture monitoring in the literature has revealed differences between sports. Nimphius*, et al.*[17] observed increased VL MT and FL, but decreased VL PA in highly trained female softball players over the course of a competitive season, finding very strong correlations between percent change in VL FL and two-base sprint times. Jajtner*, et al.*[13] compared NCAA Division I female soccer starters to non-starters using magnitude-based inferential analysis and noted possible effects of playing time on the observed decreases in VL and rectus femoris MT and PA over the course of the competitive season. Bazyler*, et al.*[44] determined that stronger NCAA Division I female volleyball athletes maintained jumping ability and VL MT better than weaker athletes, despite dramatic reductions in resistance training volume during a taper. These and the present data point to sport-dependent differences in muscle architecture, both in pre-season values and changes in those values over the course of a competitive season.

Sport scientists should consider that cross-sectional measures of muscle architecture—as in this study—may not accurately reflect an athletes' sport-specific potential, but rather their current training status. Despite the aforementioned trends based on metabolic demands, considerable inter-individual variation exists among athletes of the same sport, making measures of muscle architecture ambiguous variables for talent identification. The presence of multiple outlying data points suggests that a wide range of muscle architecture parameters are capable of meeting sport-specific demands, and that trends deduced based on comparisons of group means may not be reducible to the individual athlete. Measures of muscle size discriminate most clearly between athletes of different sport types, and thus may represent meaningful variables for comparison to other athletes or groups. On average, athletes in sports with large aerobic emphasis, low force contractions, and high training volume loads will have lower MT than athletes in sports with high anaerobic emphasis, high force demands, and lower training volume loads. Individual measures of fascicle angle and length may be best suited to measuring adaptation of by monitoring changes in architecture that favor either force production capacity or fiber contraction velocity in conjunction with hypertrophic changes. The literature is unclear as to whether increase or decreases in PA or FL irrespective of MT are more or less beneficial. However, it seems that increases in MT occurring as a result of increased PA may have deleterious effects on the muscle force-to-volume ratio due to suboptimal force vectors of individual muscle fibers[11]. Strength and power athletes who may benefit from large VL MT are encouraged to seek training methods shown in the literature to selectively increase FL over PA.

CONCLUSIONS

Muscle architecture characteristics between male and female athletes of different sports may be associated with unique metabolic, kinetic, or kinematic demands of that sport. Although in resistant trained collegiate athletes it is unclear whether these differences are due to variance in phenotypic expression or in sport-specific training parameters, differences between males and females in this regard may depend on sport. Finally, due to these differences in muscle architecture and possible associations with sport-specific characteristics, muscle architecture may be a meaningful monitoring tool alongside traditional performance testing. However, caution should be taken when talent identification is the goal, as there is high inter-individual variation within sports, a problem that is likely inflated in less competitive athletes. Muscle architecture may hold the most promise as an indicator of the direction of morphological adaptation to prescribed training, allowing sport scientists to adjust training content and quantity based on resultant architectural changes and desirable physical characteristics for each sport. Future research should focus on the time course of change in muscle architecture during normal sport and resistance training to determine relationships to training parameters and whether those parameters differ between sports or sexes.

PRACTICAL APPLICATIONS

These findings demonstrate that muscle architecture characteristics are different between sports and between males and females, and that between sport differences may be influenced by the metabolic profile of the sport. Good collegiate female soccer players may have low LG PA with high LG FL_{rel} among females, while good collegiate male soccer players may have high LG PA with low LG FL_{rel} among males. Collegiate male weightlifting and tennis athletes may possess greater LG FL_{rel} compared to other male athletes. Vastus lateralis MT values for average collegiate athletes in high intensity interval type sports range from 2.19 cm to 2.27 cm for females and from 2.61 cm to 2.77 cm for males. Coaches should identify these ranges as markers of minimal muscularity in the VL to successfully compete at the collegiate level. These minima can further be used in talent identification or long-term athlete development settings, whereby, athletes training for high intensity interval type sports should be within this range, and primarily anaerobic athletes should be above this range. Coaches who incorporate muscle architecture variables into their monitoring program should do so in conjunction with measures of training volume load and performance in order to create an empirical source of training feedback to adjust future training content. Measures of muscle size such as MT can be compared to sport and resistance training volume load, while PA, FL, and FL_{rel} should be used to in conjunction with these and other performance measures to indicate whether MT changes are due to serial or parallel sarcomere additions.

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CHAPTER 4

DIFFERENCES IN MUSCLE ARCHITECTURE, PEAK POWER, PEAK FORCE, AND PHYSICAL CHARACTERISTICS BETWEEN ATHLETES OF DIFFERENT STRENGTH LEVELS, JUMPING ABILITY, AND SPORT.

Original Investigation

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ABSTRACT

Optimal muscle function is dependent on neuromuscular and morphological factors. Improved knowledge of architectural monitoring variables associated with relative strength and jumping ability would improve athlete monitoring and testing efforts. ***Purpose:*** To investigate sport-related differences between strong and weak athletes in jumping ability, power production, and muscle architecture, and to draw conclusions for athlete monitoring and resistance training programming. ***Methods:*** Using ultrasonography we measured vastus lateralis cross-sectional area, muscle thickness, pennation angle, and fascicle length in 56 male collegiate baseball and soccer athletes. Relative isometric peak force, relative peak power, and countermovement jump height were measured on force plates. A 2x2 ANOVA was used to investigate sport by strength and sport by jump height interactions for all performance and architectural variables. T-tests were conducted comparing the 5 best and worst jumpers from each sport. ***Results:*** Weak baseball athletes were heavier, had greater % body fat, and lower jump height than all other groups. Higher jumping baseball athletes were stronger, more powerful, and had greater muscle size and mass than low jumpers, while higher jumping soccer athletes were weaker, more powerful, and had lower muscle size and mass than low jumpers. Baseball athletes had longer fascicles but smaller pennation angles than soccer athletes. ***Conclusions:*** Relative strength and power discriminate between high and low jumpers for baseball, but not soccer athletes. Muscle cross-sectional area may be a more sensitive and meaningful measure of muscle size than thickness. Soccer specific endurance training may interfere with muscle strength and size but not jump height compared to baseball athletes. However, this soccer sample may have been too homogenous to detect differences between strength and jump levels. Muscle architecture measures are recommended in conjunction with performance measures to enhance athlete explanatory power of monitoring efforts.

Key words: muscle architecture, pennation angle, cross-sectional area, isometric force, jump height

INTRODUCTION

Power is a scalar quantity equivalent to the product of force and velocity. Muscular peak power (PP) represents the greatest power achieved during a specific task, and has been associated with enhanced sport performance[1,2]. Peak concentric power is developed in order to produce maximal velocity of a mass—either an athlete's body or an external object—as observed during maximal effort sprinting, jumping, throwing, and change of direction tasks[3]. The relationship between contractile force and velocity is constrained by a muscle's ability to generate force in a given amount of time and the number of force-producing actin-myosin cross-bridges. Given constant muscle activation and a constant rate of actin-myosin cross-bridging per fiber, contraction force and velocity are inversely related—as the velocity of contraction increases, the amount of force produced will decrease. At load-limited lower velocities—and more time to develop and cycle cross-bridges—greater forces can be produced. Peak power is then achieved at some combination of submaximal force and velocity, and can be modelled using an inverse parabola[4]. In maximal and neaer-maximal efforts, this relationship holds true across multiple levels of organization, including whole muscle multi-joint movements[5].

Muscle architecture properties such as cross-sectional area (CSA), muscle thickness (MT), pennation angle (PA), and fascicle length (FL) interact to contribute to the resultant force and power production properties in whole muscle[6]. A study comparing resistance trained to sedentary men found that peak force may be proportional to CSA regardless of fiber type[7]. In this study, vastus lateralis muscle fibers from resistance-trained men had significantly greater CSA, peak force, and peak power than sedentary men, although after normalizing for fiber CSA there was no difference between groups. The authors attributed the variance in force and power between groups to differences in single fiber CSA. Similarly, a pair of recent investigations found statistically significant relationships between VL CSA and isometric peak force (IPF)[8] and 1RM power clean[9]. The velocity of muscle contraction is associated with its number of serial sarcomeres, with more sarcomeres allowing for greater velocities due to simultaneous sarcomere contraction along the length of a myofibril. For this reason, a pair of recent investigations have examined muscle architecture variables in the context of in-season athlete-monitoring in collegiate soccer players[10] and well-trained softball players[11]. Together, these findings hint at the utility of muscle architecture measurements for athlete monitoring purposes.

To date, only two investigations have directly compared muscle architecture between athletes in sports with differing metabolic demands. It has been shown that sprinters exhibit greater VL MT and FL than distance runners[12], and that elite swimmers have greater VL and LG MT and FL than elite soccer players[13]. It remains to be seen whether these findings—namely that more anaerobic athletes and aquatic athletes have greater FL than more aerobic athletes and terrestrial athletes, respectively—are true of athletes in other sports. Greater knowledge of sport-specific architectural profiles could benefit talent identification efforts and enhance early identification of sport-specific potential in developing athletes.

Investigations comparing strong to weak athletes have found that strong athletes jump higher[14], have less bilateral asymmetry[15], and adapt with greater magnitude to power training[16] and combined strength and ballistic training[17] than weak athletes. While it is clear that the physiological underpinnings of muscular force and power are multifactorial and dependent upon both neural and morphological mechanisms[18], what remains unclear is the degree to which CSA and related architectural parameters mediate differences in strength between athletes of different sports. Given the aforementioned differences in architectural profile between sprinters and distance runners, and between swimmers and soccer athletes, it is likely that relationships between muscle architecture and performance are sport specific. To the authors' knowledge, muscle architecture, force, and power, as well as measurable performance outcomes such as vertical jump height, have yet to be directly compared across strength levels in sports with different metabolic and kinetic demands. Moreover, comparisons of these variables between good and poor jumpers would further benefit practitioners seeking to adopt these measures as into an athlete monitoring program.

Therefore, the purpose of this paper is to examine differences in anthropometric, performance, and muscle architecture measurements between strength and jumping ability in two sports with differing metabolic demands, with the goal of improving the understanding of these measures for use in athlete monitoring and talent identification programs.

METHODS

Subject Characteristics

A group of 56 male collegiate baseball (BSB) (n = 28) and soccer (SOC) (n = 28) athletes participated in this study as part of an ongoing athlete monitoring program (Table 4.1). These two sports were chosen based on their differing metabolic and kinetic demands. Baseball is a power sport with external object acceleration priorities—such as throwing, hitting, and catching—that requires intermittent linear sprinting, curvilinear sprinting, and backpedaling at intervals that allow for complete rest between tasks[19]. Soccer is a semi-continuous speed-endurance sport with BM acceleration priorities involving intermittent bouts of sprinting, kicking, and dribbling separated by incomplete rest periods (with the exception of the goalie) of walking or jogging[20]. Therefore, these sports were selected as a basis for examining whether IPFa is expressed and used differently between athletes with different training and competition goals. All participants were 18 years of age and voluntarily read and signed written informed consent documents pertaining to the long-term athlete-monitoring program and all testing procedures in accordance with the guidelines of East Tennessee State University's Institutional Review Board.

Table 4.1. Participant descriptive characteristics

	age (years)	height (cm)	weight (kg)	BF%	FFM (kg)
Baseball	20.3 ± 1.2	181.2 ± 5.6	84.3 ± 13.1	10.9 ± 4.2	74.7 ± 9
Soccer	20.7 ± 1.2	178.8 ± 6.5	75.2 ± 7.6	8.2 ± 2.4	68.9 ± 6.3

Values are displayed as mean ± standard deviation

Biometric Data

Standing height was measured to the nearest 0.01 meters using a stadiometer (Cardinal Scale Manufacturing Co., Webb City, MO), and body mass (BM) was measured using a digital scale (Tanita B.F. 350, Tanita Corp. of America, Inc., Arlington Heights, IL). Percent body fat was assessed via skinfold estimation using Lange calipers (Cambridge Scientific Industries, Cambridge, MD) and a 7-site protocol[21].

Hydration

Urine-specific gravity was determined using a refractometer (Atago, Tokyo, Japan), and athletes with urine samples reading > 1.020 urinary specific gravity were asked to drink water and retest to ensure hydration-status would not affect the ultrasound measurements[22].

Ultrasound Measures

A 7.5 MHz ultrasound probe was used to measure CSA, MT, PA, and FL of the VL and LG of the right leg (General Electric Healthcare, Wauwatosa, WI). For VL measurements, the athlete laid on their left side with hips perpendicular to the examination table in the frontal plane and a knee angle of 125 ± 5º as measured by a handheld goniometer[23] to improve image clarity during cross-sectional scans and promoted relaxation of the knee extensors. The point 5 cm medial to 50% of the femur length—defined as the distance between the greater trochanter and the lateral epicondyle of the femur— was used as the sampling location[23].

The location was marked with an ink marker and the ultrasonography probe oriented longitudinally in the sagittal plane, parallel to the muscle for each sample. The probe was covered with water-soluble transmission gel to avoid depression of the skin, reduce measurement error, and aid acoustic coupling[24]. Cross-sectional area was measured by placing the probe perpendicular to the muscle and moving it across the skin in the transverse plane to collect a cross-sectional image. Pennation angle was quantified in still images captured longitudinally in the sagittal plane using the ultrasound machine's built-in measurement features and was determined as the angles between the echoes of the deep aponeurosis of the muscle and the echoes from interspaces among the fascicles[23]. Cross-sectional area was measured by tracing the inter-muscular interface in the cross-sectional images[25]. Fascicle length was calculated from MT and PA using the following equation[23]:

$$Fascicle\ length = MT \cdot SIN\ (PA)^{-1}$$

The ultrasound examiner took 3 longitudinal images from each sonogram. The means values of MT, PA, and FL measurements were assessed from the images and used for further analysis[26].

Performance Testing

Athletes performed a standardized warm-up procedure before the onset of performance testing consisting of 25 jumping jacks, one set of five 20kg mid-thigh pulls, and three sets of five 60kg mid-thigh pulls[27]. Peak power was recorded during countermovement jumps (CMJ) using a 0kg PVC pipe placed across the shoulders in the traditional high bar back squat position. Athletes were instructed to jump as high as possible at the command of "3, 2, 1, jump!" using a self-selected countermovement depth. Each jump test series began with a warm-up jump at 50% and 75% effort before a minimum of 2 maximal effort jumps. Additional jumps were performed if the athlete failed to adhere to the aforementioned instructions or if the jump height (JH) difference between trials was >2 cm. Peak power and JH (based on flight time) were measured using dual uniplanar force plates with a sampling frequency of 1,000 Hz (0.91 m x 0.91 m; Rice Lake Weighing Systems, Rice Lake, WI, USA). This value was scaled allometrically for body mass (PPa) using the following equation: $PPa = PP \cdot BM^{-2/3}$.

Isometric mid-thigh pull testing took place following vertical jump testing in a custom-designed rack (Sorinex Inc., Irmo, SC) mounted over dual uniplanar force plates sampling at 1,000 Hz (0.91 m x 0.91 m; Rice Lake Weighing Systems, Rice Lake, WI, USA). A fixed, adjustable-height barbell mounted to the rack was raised to a height corresponding with each athlete's bar height in the mid-thigh clean pull "power position" as measured during the warm-up or previous testing session. The athlete's hands were fixed to the bar using lifting straps and athletic tape and spaced to a distance corresponding to their mid-thigh clean pull grip width, with knees flexed to 125-135 degrees and hips flexed to 170-175 degrees. Each athlete performed a warm-up pull at 50% and 75% effort, separated by 45 seconds rest. During warm-up the athletes were instructed to assume the "power position" and apply tension to the bar prior to pulling. Following the warm-up they were told to pull "as fast and as hard as possible". Following a command of "3, 2, 1, pull!" the athletes gave a maximal effort pull lasting between 4-8 seconds as the group of testers continued shouting "pull!" in sustained unison as encouragement. The primary tester visually monitored the force-time curve during each pull and stopped each trial as soon as peak force began to drop. Following 1-2 minutes of rest a second trial was completed. If there was greater than a 250-N difference between pulls or if the athlete or tester felt a trial was less than maximal, a third and possibly fourth trial was performed. The highest point on the force-time trace was considered IPF, and this value was scaled allometrically for body mass (IPFa) using the equation: $\text{IPFa} = \text{IPF} \cdot \text{BM}^{-2/3}$.

Statistical Analyses

The starting *n* of 28 in each sport were divided into equal strong (STR) and weak (WEA) groups based on IPFa ranking, with the goal of maximizing an equal *n* and creating a group mean difference effect size of at least "large" based on Cohen's *d* effect size. This process was repeated using JH to divide each sample into high jumping (HIGH) and low jumping (LOW) groups. Effect size values of *d* were interpreted as 0.2 to 0.49 = "small", 0.5 to 0.79 = "medium", 0.8 to 1.29 = "large", 1.3 to 1.99 = "very large", and 2.0 and above = "extremely large". The resultant STR vs WEA group differences were $d = 3.57$ and 2.54 for BSB and SOC, respectively. The resultant HIGH vs LOW group differences were $d = 2.84$ and $d = 2.37$ for BSB and SOC, respectively.

Repeated measures were assessed for both absolute and relative reliability using two-way mixed effects, single measurement intraclass correlation coefficients (ICC [3,1]) with absolute agreement[28] and coefficient of variation, respectively[29]. Thirteen 2x2 (strength by sport) ANOVAs were computed to detect differences in mean values of height, BM, body fat % (BF%), fat-free mass (FFM), VL CSA, VL MT, VL PA, VL FL, CMJ JH, CMJ PP, CMJ PPa, IPF, and IPFa between STR and WEA groups, and BSB and SOC groups. Cohen's *d* effect sizes were computed to evaluate practically significant differences between groups for all dependent variables. Statistical analyses were performed using SPSS software version 22 (IBM Co., New York, NY, USA) and Microsoft Excel 2010 version 14 (Microsoft Corporation, Redmond, WA, USA). Figures were generated using R Studio[30,31] and two data visualization packages[32].

RESULTS

Intraclass correlation coefficients for muscle architecture measurements revealed high agreement between ultrasound images, with ICCs ranging from 0.820 to 0.976 ($p < .001$) and CVs ranging from 1.72% to 3.22%. Intraclass correlation coefficients for performance variables revealed near perfect agreement between trials, ranging from 0.940 to 0.969 ($p < .001$).

Thirteen 2x2 (strength by sport) ANOVAs were conducted to examine the effects of strength and sport on the variables of interest (Table 4.1), and of jump height and sport on the variables of interest (Table 4.2). Data falling 1.5 times the interquartile range outside of the median quartiles were flagged as potential outliers, and 3 times the interquartile range as extreme outliers. These values were scanned for clerical or measurement errors, and when none were found they were not removed from the data[33]. Data mostly met the homogeneity of variance assumption as determined by Levene's Test. However, for STR vs WEA comparisons, a ratio of greatest to smallest cell variance for FFM and BW was calculated and found to be less than 10 because these two variables had statistically significant Levene's Test p-values. All data was sufficiently normal as assessed by the Shapiro–Wilks normality test.

In the STR versus WEA analysis (Table 4.1), there were no statistically significant main effects or interaction effects for height, VL MT, VL PA, VL FL, or CMJ PP. Baseball athletes had greater BM ($F_{(1,52)} = 10.111, p = .002$) and FFM ($F_{(1,52)} = 8.079, p = .006$) than SOC athletes. For BF%, there were statistical main effects for strength ($F_{(1,52)} = 8.116, p = .048$) and sport ($F_{(1,52)} = 4.110, p = .003$), but differences depended on a statistical interaction effect ($F_{(1,52)} = 8.116, p = .006$) showing that WEA BSB athletes had greater BF% than STR BSB athletes, but that STR and WEA SOC athletes had trivial BF% differences. Vastus lateralis CSA was greater in STR athletes than WEA athletes ($F_{(1,52)} = 5.773, p = .020$), as was IPF ($F_{(1,52)} = 100.054, p <$

.001). There was a statistical interaction for CMJ PPa ($F_{(1,52)} = 4.855$, *p* = .032) showing that STR BSB athletes had greater PPa than WEA athletes, while WEA SOC athletes had greater PPa than STR SOC athletes. For IPFa, SOC athletes were stronger than BSB athletes ($F_{(1,52)}$ = 20.310, *p* < .001), and STR athletes were stronger than WEA athletes ($F_{(1,52)}$ = 144.991, *p* < .001).

Table 4.2. All variables presented as mean ± standard deviation for each group. Statistically significant effects and simple main effects noted, with non-significant comparisons left blank

	Baseball (BSB)		Soccer (SOC)		2x2 ANOVA and Cohen's *d* Results		
	Weak (WEA)	Strong (STR)	Weak (WEA)	Strong (STR)	Strength	Sport	Interaction, Effect Size Comparisons
height	180.8 ± 6	181.6 ± 5.5	176.9 ± 5.3	180.7 ± 7.3	STR > WEA 0.37	BSB > SOC 0.39	
BM	85 ± 16.8	83.6 ± 8.6	72 ± 7.9	78.5 ± 6.1	STR > WEA 0.21	BSB > SOC** 0.84	
BF%	12.9 ± 4.3	8.8 ± 3.1	7.9 ± 2.9	8.6 ± 1.8	WEA > STR* 0.48	BSB > SOC** 0.77	WEA BSB > STR BSB**, 1.10 STR SOC > WEA SOC, 0.29
FFM	73.5 ± 11.4	76 ± 6.1	66.2 ± 5.6	71.7 ± 5.8	STR > WEA 0.5	BSB > SOC** 0.74	
VL MT	2.59 ± 0.33	2.8 ± 0.44	2.74 ± 0.29	2.71 ± 0.3	STR > WEA 0.26		
VL PA	14 ± 2	14.4 ± 2.8	15.8 ± 3.1	15.3 ± 2.3		SOC > BSB 0.51	
VL FL	10.8 ± 1.5	11.7 ± 1.7	10.4 ± 1.8	10.5 ± 1.9	STR > WEA 0.28	BSB > SOC 0.46	
VL CSA	29 ± 5.4	34.6 ± 5.7	31.5 ± 4.5	32.2 ± 3.6	STR > WEA* 0.63		
CMJ JH	30.3 ± 4.3	34.4 ± 4.1	35.5 ± 5.7	36.2 ± 3.5	STR > WEA 0.49	SOC > BSB** 0.75	
CMJ PP	4077 ± 655	4458 ± 697	4026 ± 621	4171 ± 365	STR > WEA 0.44	BSB > SOC 0.28	
CMJ PPa	212 ± 20	233 ± 25	232 ± 27	228 ± 13	STR > WEA 0.36	SOC > BSB 0.34	STR BSB > WEA BSB*, 0.94 WEA SOC > WEA BSB* 0.86

IPF	3028 ± 308	3926 ± 347	3062 ± 386	4043 ± 360	STR > WEA*** 2.7		
IPFa	158 ± 11	206 ± 9	177 ± 18	221 ± 17	STR > WEA*** 2.78	SOC > BSB*** 0.63	

* = *p* < .05, Cohen's *d* effect sizes noted for effects considered "small" (*d* ≥ 0.2) and greater. Comparisons based on Cohen’s *d* effect sizes within the effect of sport included when interaction effect was statistically significant.

Table 4.3. HIGH vs LOW comparisons. All variables presented as mean ± standard deviation for each group. Statistically significant effects and simple main effects noted, with non-significant comparisons left blank

	Baseball (BSB)		Soccer (SOC)		2x2 ANOVA and Cohen's *d* Results		
	LOW	HIGH	LOW	HIGH	Jump	Sport	Interaction, Effect Size Comparisons
height	180.6 ± 5.6	180.3 ± 5.7	180.1 ± 5.7	177.6 ± 7.2	LOW > HIGH 0.23	BSB > SOC 0.26	
BM	85.2 ± 15.7	82 ± 9.5	77.1 ± 7.8	73.4 ± 7.2	LOW > HIGH 0.31	BSB > SOC** 0.79	
BF%	12.6 ± 4.2	8.3 ± 3.2	9.1 ± 2.5	7.3 ± 1.9	LOW > HIGH*** 0.92	BSB > SOC** 0.65	
FFM	74 ± 11	74.9 ± 6.9	69.9 ± 5.9	68 ± 6.6		BSB > SOC** 0.71	
VL MT	2.64 ± 0.42	2.74 ± 0.41	2.72 ± 0.29	2.73 ± 0.31			
VL PA	14 ± 2.7	14.9 ± 2.4	15.1 ± 3	16 ± 2.4	HIGH > LOW 0.33	SOC > BSB 0.41	
VL FL	11.1 ± 1.6	11 ± 1.9	10.8 ± 1.9	10.1 ± 1.7		BSB > SOC 0.35	
VL CSA	30.2 ± 6.2	32.8 ± 6.2	32.1 ± 4.5	31.6 ± 3.6			
CMJ JH	28.6 ± 1.4	36.2 ± 3.5	32.3 ± 2.8	39.4 ± 3.2	HIGH > LOW*** 2.23	SOC > BSB*** 0.74	
CMJ PP	4003 ± 652	4452 ± 711	4016 ± 566	4181 ± 442	HIGH > LOW 0.51	BSB > SOC 0.21	
CMJ PPa	207 ± 15	236 ± 28	221 ± 19	239 ± 20	HIGH > LOW*** 1.09	SOC > BSB 0.36	
IPF	3233 ± 502	3737 ± 494	3666 ± 629	3439 ± 610	HIGH > LOW 0.24		HIGH BSB > LOW BSB, 1.01 LOW SOC > HIGH SOC, 0.37
IPFa	168 ± 22	198 ± 18	202 ± 27	196 ± 29	HIGH > LOW	SOC > BSB*	HIGH BSB > LOW BSB, 1.48

	0.44	0.59	LOW SOC > HIGH SOC, 0.21

* = $p < .05$, ** = $p < .01$, *** = $p < .001$, Cohen's *d* effect sizes noted for effects considered "small" ($d \geq 0.2$) and greater. Comparisons based on Cohen's *d* effect sizes within the effect of sport included when interaction effect was statistically significant.

In the HIGH versus LOW analysis (Table 4.2), there were no statistically significant main effects or interaction effects for height, VL MT, VL PA, VL FL, VL CSA, or CMJ PP. Baseball athletes had greater BM ($F_{(1,52)} = 8.576$, $p = .005$) and FFM ($F_{(1,52)} = 6.811$, $p = .012$) than SOC athletes. HIGH athletes had less BF% than LOW athletes ($F_{(1,52)} = 13.472$, $p = .001$), and SOC athletes had less BF% than BSB athletes ($F_{(1,52)} = 7.326$, $p = .009$). HIGH athletes jumped higher than LOW athletes ($F_{(1,52)} = 93.553$, $p < .001$) and SOC athletes jumped higher than BSB athletes ($F_{(1,52)} = 20.550$, $p < .001$). For CMJ PPa, HIGH athletes were greater than LOW athletes ($F_{(1,52)} = 17.125$, $p < .001$). For IPF there was a statistical interaction effect ($F_{(1,52)} = 5.933$, $p = .018$) showing that HIGH BSB athletes had greater IPF than LOW BSB athletes, whereas LOW SOC athletes had greater IPF than HIGH SOC athletes. For IPFa there was a statistical main effect for sport ($F_{(1,52)} = 5.743$, $p = 020$), but differences depended on an interaction effect ($F_{(1,52)} = 7.493$, $p = .008$) showing that HIGH SOC and BSB athletes had similar IPFa, but LOW SOC athletes had greater IPFa than HIGH SOC athletes, and LOW BSB athletes had lower IPFa than HIGH BSB athletes.

DISCUSSION

The objective of this paper was to determine whether there were differences in physical characteristics, muscle architecture, jumping ability, power production, or strength production between strong and weak athletes and between high and low jumping athletes in two metabolically different sports for the purpose of drawing conclusions for athlete monitoring and resistance training programming. There were four important findings based on the results of this study. First, that BF% alone discriminates between STR and WEA and HIGH and LOW BSB athletes. Second, that relative and absolute strength measures may be good indicators of jumping ability in BSB, but not SOC athletes. Third, that measures of muscle size discriminate between both STR and WEA, and HIGH and LOW BSB athletes, but not SOC athletes. Fourth, that SOC athletes demonstrate greater VL PA but smaller FL than BSB athletes.

This study found that STR BSB athletes were leaner and more muscular than WEA athletes, while STR SOC athletes were heavier also more muscular than their WEA counterparts, but with similar BF% levels. HIGH BSB athletes were also leaner than their LOW counterparts. This would indicate that in BSB and possibly other more anaerobic team sports, coaches in talent identification situations should select players who possess low BF% and greater FFM relative to other male athletes, as these athletes are also likely to be stronger and jump higher. For SOC athletes and possibly extending to other team sports with aerobic components, competitive athletes are also likely to exhibit low BF%, but the fact that BF% was similar between STR and WEA SOC athletes but lower in HIGH than LOW SOC athletes based on effect size ($d = 0.81$) suggests that it may be correlated with jumping but not strength performance. It may be that in more aerobic sports, there is a BF% threshold, above which increasing BF% negatively affects performance, but below which any decreases in BF% do not further enhance performance. The current data suggests that this threshold may be between 7.1% and 8.6% body fat (the mean values of the STR and HIGH SOC groups, respectively) as determined by skinfold estimation.

Baseball athletes were generally heavier than SOC athletes, although the difference between sports was less between STR athletes than WEA athletes. Baseball athletes have a greater need for upper body strength and power than SOC athletes, so it may be that training priorities for these BSB athletes have focused more on increasing upper body muscle mass and quality to a greater degree than the SOC athletes, or that BSB athletes are genetically predisposed to greater BM regardless of training. Soccer, unlike BSB, does not afford players full recovery between explosive efforts, and SOC athletes may not benefit from additional FFM if it raises BM to levels that increase the metabolic cost of high intensity endurance activity. More anaerobic team sport athletes should therefore seek to prioritize FFM accumulation during their development, while more aerobic team sport athletes should be aware of diminishing returns from increases in FFM.

Based on effect size (Table 4.1), STR BSB athletes jumped higher, and had greater CMJ PP and PPa than WEA BSB athletes. In contrast, both JH and PP were similar between STR and WEA SOC athletes, and PPa was greater in the WEA SOC group. In confirmation of this trend, HIGH BSB athletes had greater IPF and IPFa than WEA BSB athletes, while the mean values for HIGH SOC IPF and IPFa were lower than those of LOW SOC. A possible explanation for the different trends between SOC and BSB athletes is the deleterious effect that concurrent training has on explosive strength qualities[34]. A collegiate SOC athlete may not be capable of producing power output in proportion to his strength level due to these effects. Therefore, relative strength level—as measured by IPFa in the current study—may be a good indicator of ability in neuromuscular performance tests such as the vertical jump for more anaerobic athletes, while coaches of more aerobic athletes may consider direct measures of vertical jump or neuromuscular performance.

Based on both effect size and statistical main effects, measures of muscle size discriminated between both strength and jumping ability for BSB athletes, but not SOC athletes. This observation is in line with the aforementioned BM and FFM differences between BSB and SOC athletes, namely that increases in muscle mass (and therefore BM) may aid more anaerobic athletes to a greater extent than more aerobic athletes, even in tests of strength and power. Previous investigations have confirmed medium to very large relationships between VL MT and power clean 1RM[9], IPF[8,35], leg press peak force[36], and aspects of vertical jumping performance[35]. The current data suggests that such relationships may not be universal, but rather depend on both sport-specific training adaptations and sport-selected heritable traits. We speculate that in homogenous groups of athletes who encounter high aerobic metabolic demands regularly in competition and training, relationships between measures of muscle size and performance outcomes will be less strong than in more anaerobic athletes. This data shows that VL CSA may be more sensitive than VL MT to differences in muscle size between sport and caliber of athlete, likely because it accounts for two dimensions instead of just one[37]. Indeed, one aspect contributing to the differences in the observed relationships between muscle size and strength and jump performance between BSB and SOC athletes could be the effect of training on regional hypertrophy. Sport-specific training content may produce varying degrees of hypertrophy along the length of the VL, as has been previously observed in sprinters when compared to distance runners[12]. For comparisons between athletes in different sports, or when assessing muscular development for the purpose of talent identification, multiple measurements (for instance at 30%, 50%, and 70% of femur length for VL[38-40]) of MT or CSA may be warranted to better understand an athlete's "muscle shape".

The fourth main finding from this data reinforces that of Abe*, et al.*[12], who observed greater VL FL but smaller PA in world-class sprinters compared to distance runners. It was found that BSB athletes have greater VL FL but smaller PA than SOC athletes, suggesting a larger trend of more anaerobic athletes having greater VL FL and smaller PA than more aerobic athletes at both the collegiate and international levels. This may be an adaptation to endurance training on the part of SOC athletes in this study. However, the data is equivocal as to differences between STR and WEA athletes. It is presently unknown whether observed differences are due to training or genetics.

It must be acknowledged that the caliber of athletes in the present study may not be indicative of the “ideal” athlete for each sport, and this is a potential limiting factor in this analysis. For example, the mean JH of the HIGH SOC and BSB groups were 36.2 cm and 39.4 cm, respectively, while the professional SOC athletes recorded by Wisløff*, et al.*[41] had a mean JH of 56.4 cm, and the mean JH of MLB athletes was found to be 71.1 cm[42] (it should be noted that these data used the best of three jumps instead of the average of two, and that the MLB athletes’ JH was measured using a Vertec). Therefore, the present findings should be interpreted with caution if application is to be made to athletes above the collegiate level of competition. Furthermore, the differences between STR and WEA and HIGH and LOW athletes may be different at truly elite levels. It has been suggested that a level of relative strength equal to a back squat 1RM of twice bodyweight is a desirable and achievable threshold for athletes to reach. It is posited that above this level, further increases in relative strength are more strongly correlated with improved performance in sport specific tasks such as jumping and sprinting[18]. Similar recommendations have been made for adolescent soccer players[43]. However, it is unlikely that the current set of athletes have reached this level of relative strength.

Conclusions

Body fat percent discriminates between STR and WEA and HIGH and LOW BSB athletes, but is homogenous for SOC athletes. BSB athletes are heavier than SOC athletes, and SOC athletes may not benefit from additional FFM due to the metabolic cost of high intensity endurance activity. STR BSB athletes are better jumpers and more powerful than WEA BSB athletes, while greater strength was not associated with better jumping or power performance for SOC athletes. Similarly, both STR and HIGH BSB athletes had greater VL CSA than WEA or LOW BSB athletes, whereas these differences were not observed for SOC. Finally, BSB athletes had greater VL FL and smaller VL PA than SOC athletes.

Applications

These findings indicate that in more anaerobic team sports, leaner, more muscular athletes are likely to be stronger and jump higher than less lean, less muscular athletes. In more aerobic sports, BF% may be homogenous and is possibly more homogenous at higher levels of competition. More anaerobic athletes should prioritize FFM accumulation during their development phases of their career and also during preparatory phases of their annual training cycle, while more aerobic athletes should seek to capitalize primarily on neuromuscular improvements in strength and power, as increases in FFM may have diminishing returns and likely do not correlate strongly with relevant performance measures. Young athletes with greater FFM, low BF%, high relative and absolute strength and power, and longer VL FL may be predisposed toward more anaerobic sports. Young athletes who are lighter, with low BF%, good jumping ability, and large VL PA may be predisposed toward more aerobic sports.

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CHAPTER 5

CONCLUSIONS

In this dissertation, I set out to investigate lower body muscle architecture in athletes in two different but related ways. The majority of previous research has focused on comparison of architecture between groups, correlation of architecture to performance metrics, and regression of a performance measure onto a model that includes a measure of muscle architecture as a predictor variable. As has been previously mentioned, this research is limited in scope due to both the low number and limited availability of elite and well-trained athletes. Still, considerable work has been accomplished in elucidating the differences in these variables and relationships with various factors of sport performance. Furthermore, this area of study is still relatively young, and considering the possible impact of observing novel differences and creating a more robust “map” of muscle structure in athletes, is a worthwhile area of investigation with a high potential for impacting athletes, coaches, and sport scientists, as well as athlete monitoring and talent identification efforts.

This investigation has been laid out in two parts to afford the space to address related research questions with appropriately different research methodologies. First, I sought to expand what is known about differences in muscle architecture between athletes of different sports and between males and females. Specifically, the purpose of this first study was to observe and compare muscle architecture variables (MT, PA, FL, and FL_{rel} of the VL and LG muscle) between competitive athletes of different sports and sexes. Secondarily, we sought to draw exploratory inferences about muscle architecture based on known metabolic, kinetic, and kinematic aspects of each sport and comment on their efficacy and practicality for use as monitoring and talent identification variables. This hypothesis-generating study aimed to contribute to establishing normative data and uncover sport and gender differences for comparison to future monitoring efforts and to facilitate insights into the landscape of muscle architecture variables in diverse samples of athletes.

Second, I aimed to elucidate differences in muscle architecture between athletes of different strength and jumping ability in different sports. Therefore, the purpose of the second study was specifically to examine differences in physical characteristics, muscle architecture, jumping ability, and strength and power output between athletes of different strength and jumping abilities in two metabolically different sports. The aim of this second study was to narrow the focus to just two unique samples of athletes while widening the scope of investigation to include relevant performance variables in order to translate empirical knowledge to practical knowledge.

Muscle Architecture Comparisons

A trend was observed for both VL and LG muscle architecture supporting the notion that architectural differences between sports are at least partially driven by metabolic differences. Statistically significant differences were observed for sex in VL MT and PA, and in LG MT and FL, and for sport in VL MT, FL, and FL_{rel}, and in LG MT. Statistically significant interaction effects between sex and sport were seen for LG PA and FL_{rel}. Architectural differences were observed between sports with diverging sport-specific demands (e.g. cross-country and weightlifting), and similarities were observed between sports with more similar demands (e.g. basketball, tennis, and soccer).

Based on this study, muscle architecture characteristics may be associated with unique metabolic, kinetic, or kinematic demands of each sport, as do both the magnitude and direction of differences between males and females. For example, it was observed that for LG PA, sex differences for soccer athletes (males having a larger LG PA) are the opposite of those found in weightlifting, tennis, and cross-country athletes (females having a larger LG PA), while for basketball athletes there is no difference. Caution should be taken applying these results to talent identification purposes, as there is high inter-individual variation within sports, a problem that may be inflated in less competitive athletes. Muscle architecture may hold the most promise as an indicator of the direction of morphological adaptation to prescribed training, allowing sport scientists to adjust training content and quantity based on resultant architectural changes and desirable physical characteristics for each sport. Future research should focus on the time course of change in muscle architecture during normal sport and resistance training to determine relationships to training parameters and whether those parameters differ between sports or sexes.

What remains unknown is whether the general architectural profile of each sample of athletes may be due to years of sport-specific training, inherited genotype, or both. Finally, due to both the presence of sport by sex interaction effects in the LG muscle architecture, and the high degree of inter-individual variation for each architectural parameter, it was recommended that practitioners utilize muscle architecture measures primarily as longitudinal observation tools that may offer explanatory value to concurrent performance testing.

Peak Force, Muscle Architecture, and Peak Power

The results of this second study showed that STR BSB athletes were leaner and more muscular than WEA athletes, while STR SOC athletes were heavier also more muscular than their WEA counterparts, but with similar BF% levels. Coaches in more anaerobic sports should select players with low BF% and greater FFM relative to other male athletes, as these athletes are also likely to be stronger and jump higher. In contrast, coaches in more aerobic sports should be aware of a possible BF% threshold that may exist between 7.1% to 8.6%, above which more aerobic athletes will experience deleterious effects to performance.

In light of the finding that baseball athletes are generally heavier than soccer athletes regardless of strength level or jumping ability, baseball athletes are encouraged to take a long-term approach in the development of fat-free mass beginning in the early years of training, and continuing during each consecutive preparatory phase of the annual training cycle. The goal of this training should be to maximize long-term strength potential by improving the architectural properties of the musculature (namely increasing CSA and FL).

Strength level did not differentiate between high and low jumpers in soccer athletes, nor did stronger soccer athletes have greater power output. It was suggested that this could be due in part to the negative effects that concurrent training has on early time-force characteristics, and partly because the individuals included in the study may not have been the best representations of highly competitive soccer athletes. Moreover, the sample of soccer athlete may have been too homogenous in the variables of interest to determine the true relationships between strength and the other variables. Greater strength did show a relationship with high jumpers and power outputs for baseball athletes. Based on these different patterns between sports, coaches of more aerobic athletes should rely on direct measures of jumping or neuromuscular ability if that is of interest, whereas for more anaerobic athletes, relative strength levels may be indicative of jump performance and power output.

Finally, this study together with the findings from Abe’s group (Abe et al., 2000), confirmed the hypothesis that more aerobic athletes in general have greater VL PA, while more anaerobic athletes in general have greater VL FL. This finding also validates the trend observed from the first study, namely that the architectural profile of each sport is largely dependent upon the unique metabolic demands of that sport.

Limitations

The findings of this research are primarily restricted to collegiate athletes. It is known that well-trained athletes may respond differently to stressors than trained athletes, and that truly elite athletes can represent outliers even among their sub-elite peers. Because this data was conducted with competitive collegiate athletes, the muscle architecture values for each sport and sex may be different than those in a truly elite or less well-trained sample of athletes. Most likely, athletes of the same sport and sex with greater levels of competitiveness will display muscle architecture that is more similar than the current sample due to competitive pressures of each sport selecting for desired athletic abilities and sport-specific training driving adaptation toward those abilities.

Recommendations for Future Research

Future research should investigate changes in muscle architecture throughout a competitive season, as well as over the course of a collegiate athletics career. These data would be valuable in assessing the contribution from training and genetics to the resultant observed characteristics, as well as the percent change between these variables and other monitoring data. To date, three recent studies have examined the time-course of muscle architecture changes in athletes during a competitive season (Jajtner et al., 2013; Nimphius et al., 2012; Zaras et al., 2016), but each of them have reported on a single sex and sport group. In athletes for whom resistance training may lay outside of sport-specific metabolic parameters, it is difficult to isolate the effects of either mode (sport or resistance) of training on observed changes in muscle architecture. Therefore, future investigations could track muscle architecture in weightlifters, powerlifters, and bodybuilders along with training data to determine how the manipulation of training variables such as volume and intensity affect subsequent structural adaptations in muscle fascicles.

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