12-2021

Comparing Different Scaling Methods for Monitoring Weightlifting Performance

Jake Slaton
East Tennessee State University

Recommended Citation

Slaton, Jake, "Comparing Different Scaling Methods for Monitoring Weightlifting Performance" (2021). *Electronic Theses and Dissertations.* Paper 3984. https://dc.etsu.edu/etd/3984

Comparing Different Scaling Methods for Monitoring Weightlifting Performance

---

A thesis

presented to

the faculty of the Department of Sport, Exercise, Recreation, and Kinesiology

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Master of Science in Sport Science and Coach Education, Applied Sport Science

---

by

Jake A. Slaton

December 2021

Dr. Satoshi Mizuguchi, Chair

Dr. Kevin Carroll, Committee Member

Dr. Michael Stone, Committee Member

Keywords: weightlifting, cross-sectional area, anthropometrics, allometry, athlete monitoring

ABSTRACT

Comparing Different Scaling Methods for Monitoring Weightlifting Performance

by

Jake A. Slaton

Physiological performance has been commonly scaled for body size using various methods to scale anthropometrics, but a paucity of data exists on scaling muscle size. The aim of this thesis was to elucidate the optimal method to scale height (HT), body mass (BM), lean body mass (LBM), and muscle cross-sectional area (CSA) when scaling weightlifting performance for body size. 26 weightlifters (13 male, 13 female) participated in this study. The measurements collected were the snatch (SN), clean and jerk (CJ), isometric peak force (IPF), and countermovement jump height (CMJH). HT, LBM, BM, and vastus lateralis CSA were scaled using the ratio standard and allometry. Competition performance scaled for allometrically scaled CSA possessed greater relationships to CMJH ($r = 0.60 – 0.78$) than the ratio standard ($r = 0.56 – 0.58$). These findings suggest that allometrically scaling CSA may be superior when scaling weightlifting performance for CSA.

DEDICATION

This thesis is dedicated first and foremost to my parents, Tina Slaton and Robert Slaton, not only for their support throughout my academic endeavors, but also for being a first-hand example throughout my life of what hard work and determination looks like. At times when I felt like giving up, I thought back to how hard you both worked to provide me with an upbringing that made this level of education possible.

To my grandmother, Sarah, for her constant encouragement in my scholarly pursuits. You have been another shining example throughout my life of what grit and determination looks like. This thesis would not have been possible without your support.

Lastly, this thesis is also dedicated to Hannah. When I decided to apply to East Tennessee State University, you were nothing but supportive. You have been with me every step of the way during my graduate studies. If I ever needed someone to lift me up when I felt defeated or frustrated, you were there. I cannot thank you enough for all you have done for me over these past two years.

ACKNOWLEDGEMENTS

The author would like to first and foremost acknowledge all the athletes that participated in this study, and the sport scientists before me that helped collect this data. Gratitude is also expressed to the following people for their contributions to the completion of this thesis:

Dr. Mizuguchi, thank you for assisting me in the development of my thesis topic and the constant attention to detail during the manuscript drafting process. Your invaluable guidance on creating a well-written scientific paper will be something that I always carry with me throughout further academic pursuits.

Dr. Carroll, thank you for always being available when I needed assistance or guidance when working on this thesis - your valuable insight into the study design helped develop this investigation. Lastly, thank you for continuing as a member of this committee even as this thesis carried into the summer semester!

Dr. Stone, thank you for igniting a passion for sport science the moment I stepped into your classroom. I will always appreciate how open to scientific discussion you were whenever our paths would cross outside of the classroom. You are as excellent a teacher as you are a scientist.

TABLE OF CONTENTS

LIST OF TABLES

Chapter 1. Introduction

Weightlifting is a strength and power sport characterized by large forces generated during competition (Storey & Smith, 2012). The large forces observed during the weightlifting movements are likely associated with the lifter's maximum strength (Beckham et al., 2013). Strength has been referred to as "the ability to produce force" (Stone et al., 2002), thus maximum strength can be thought of as the ability to produce maximum force. A potential factor aiding in these high levels of force is the cross-sectional area (CSA) of the muscle involved. Suchomel and Stone (2017) observed a moderate to large relationship between vastus lateralis CSA and maximal strength measures (i.e., 1RM back squat and 1RM concentric-only half-squat), and a moderate to large relationship between vastus lateralis CSA and static jump peak power output. Both 1RM back squat (Stone et al., 2005) and static jump peak power (Carlock et al., 2004; Travis et al., 2018; Zaras et al., 2020b) have been observed to have a strong relationship to weightlifting performance. Furthermore, anthropometry (e.g., height, body mass, body composition) may also attribute to weightlifting performance. Indeed, a greater lean body mass (LBM) (Fry et al., 2006; Siahkouhian & Hedayatneja, 2010; Zaras et al., 2020b) and greater height (Ford et al., 2000; Siahkouhian & Hedayatneja, 2010) have been correlated to greater performance amongst competitive weightlifters when weight classes are not taken into account.

When assessing the athletic performance of a weightlifter, it may be necessary to scale performance variables (e.g., competitive performance and force production) to anthropometrics and CSA. Through doing so, sport scientists and weightlifting coaches can account for the contributions of body and muscle size to a lifter's performance when analyzing or monitoring a lifter's progress and capabilities. For instance, Stone et al. (2005) scaled the competitive lifts (e.g., snatch (SN) and clean and jerk (CJ)) of competitive weightlifters for height and body mass using both the ratio standard and allometric scaling methods to assess the relationship to maximal strength. Both SN and CJ had larger relationships to maximal strength when scaled using allometry as compared to the ratio standard. These findings agree with previous studies that suggested the superior method of scaling physiological variables for body size may be to allometrically scale body mass (Lietzke, 1956; Nevill et al., 1992). Scientific inquiry into the scaling of physiological performance, however, rarely attempts to scale for measures of muscle size, such as CSA. Two studies have attempted to elucidate the effects of obviating weightlifting performance for CSA (Ford et al., 2000; Funato et al., 2000). Ford et al. (2000), however, identified CSA through the use of a formula using height and weight ($\text{weight} \times \text{height}^{-3}$) rather than taking a cross-sectional measure of muscle content. Funato et al. (2000) scaled muscular strength for CSA using ultrasonography. However, only the ratio standard was utilized.

Statement of Problem

The ratio standard, or “traditional method,” simply divides a performative measurement by an anthropometric measurement; however, this may not be suitable for examining human performance. If true, this is due to the ratio standard only being deemed statistically valid if the regression model with the two variables has an intercept of 0 and a slope equivalent to the ratio standard (Winter & Nevill, 2009). To allometrically scale anthropometric variables a power function unique to a pair of a performance variable and an anthropometric variable need to be found. A common power function of 0.67, or two-thirds, is derived from the relationship between the volume and surface area of an object after the natural logarithm for each is calculated (Winter & Nevill, 2009). The same procedure of calculating a natural logarithm can be applied to a given pair of a performance variable and an anthropometric variable (Schmidt-

Nielsen, 1984). Hence, the natural log for the performative variables pertinent to weightlifting (e.g., snatch, CJ, total, and IPF) and anthropometric variables can be calculated and a power function (i.e., allometric scaling coefficient) unique to a given pair of a performance variable and an anthropometric variable can be found. Undertaking this method for the application of allometry may prove suitable for scaling weightlifting performance to measurements of muscle size and anthropometrics, key physical characteristics attributing to performance. This elucidation may aid coaches and sport scientists in effectively monitoring athlete progress in the sport of weightlifting. Therefore, the primary objective of this study is to examine the application of allometric scaling when scaling weightlifting performance to CSA.

Chapter 2. Comprehensive Review of the Literature

Introduction

The sport of weightlifting is a strength and power sport consisting of two lifts, the snatch and the clean and jerk (CJ), characterized by the high power outputs achieved during their execution (Garhammer, 1993). The production of these high power outputs can likely be attributed to the superior peak forces (Beckham et al., 2013; Funato et al., 2000; McBride et al., 1999; Stone et al., 2005), rate of force development (Beckham et al., 2013; Haff et al., 2005; Zaras et al., 2020b), and peak velocities (McBride et al., 1999) weightlifters are capable of generating. Additionally, a weightlifter's maximal strength has been observed to possess a positive relationship with weightlifting performance (Beckham et al., 2013; Carlock et al., 2004; Funato et al., 2000; Haff et al., 2005; Lucero et al., 2019; Stone et al., 2005). Stone et al. (2002) referred to strength as "the ability to produce force," therefore, a weightlifter's maximal strength can be considered their ability to produce maximum force.

The strength contributing to weightlifting success may be facilitated by the skeletal muscle architecture (i.e., muscle thickness, fascicle length and angle, cross-sectional area) (Ford et al., 2000; Funato et al., 2000; Häkkinen & Keskinen, 1989; Zaras et al., 2020a,b) of the involved muscles. Indeed, the architecture of skeletal muscle is partly responsible for its force-producing properties (Aagaard et al., 2001; Blazevich et al., 2009; Maffiuletti et al., 2016), thus, training-induced alterations to the structure of the muscle may in part determine the change in a lifter's force production capabilities. Muscle architecture and its relationship with various characteristics essential to success in sport has been researched extensively due to the noninvasive methods (e.g., ultrasonography, dual energy x-ray absorptiometry (DEXA), magnetic resonance imaging (MRI), computerized tomography (CT)) utilized. Additionally, examining muscle architecture may provide additional insight into the physical mechanisms underpinning weightlifting performance that common anthropometric methods (i.e., height, body composition) do not.

Although a wealth of research has examined the relationship of muscle's architecture and force-generating abilities, there is a paucity of research examining the relationship of muscle architecture specifically to weightlifting performance (Di Naso et al., 2012; Ford et al., 2000; Funato et al., 2000; Zaras et al., 2020a,b). The relationships elucidated within these studies have, however, presented equivocal findings. Therefore, the aim of this review is to examine the elucidations made in research studies examining the relationship of muscle architecture features to physical performance characteristics associated with weightlifting performance.

Muscle Thickness

Images of skeletal muscle captured using ultrasonography can be used to measure the thickness of the muscle by measuring the distance between the deep aponeurosis and superficial aponeurosis (Blazevich et al., 2003; Blazevich & Giorgi, 2001; Brechue & Abe, 2002; Kawakami et al., 1995; Wells et al., 2014; Zaras et al., 2020a,b). Muscle thickness has been observed to increase as a result of extended (5-16wks) resistance training, with increases observed in the vastus lateralis (Blazevich et al., 2003; Timmins et al., 2016; Wells et al., 2014), rectus femoris (Blazevich et al., 2003) and triceps brachii (Blazevich & Giorgi, 2001; Kawakami et al., 1995). These findings, however, have not been observed in longitudinal studies examining the training adaptations occurring in competitive weightlifters. For instance, Suarez et al. (2019) observed no significant changes in the vastus lateralis muscle thickness of collegiate weightlifters across 20 weeks of training. Similarly, Zaras et al. (2020a) examined the changes in vastus lateralis muscle thickness in elite weightlifters throughout 16 weeks of training and observed no significant changes. A possible explanation for the discrepancy in training-induced muscle thickness increases may be due to the training history of the participants. The participants in the resistance training studies seeing longitudinal increases in muscle likely did not have the extensive and intensive resistance training history characteristic of competitive weightlifters (Storey & Smith, 2012). Indeed, the resistance training experience of the weightlifters participating in the studies by Suarez et al. (2019) and Zaras et al. (2020a) was 5.4-10.7 years. It has been postulated that experienced weightlifters are near, or have reached, the upper limit of possible muscle growth (Ford et al., 2000), therefore, there may be paucity of muscle morphology throughout the training process.

Research examining muscle thickness and weightlifting performance is very limited, with only one such study existing to the author's knowledge. Zaras et al. (2020b) collected vastus lateralis and vastus intermedius muscle thickness of eight well-trained female weightlifters. Vastus lateralis thickness possessed moderate relationships with the snatch (r=0.430), CJ (r=0.337), and weightlifting total (WT) (r=0.381). Conversely, the relationships between vastus intermedius thickness and the snatch (r=0.151), CJ (r=0.094), and WT (r=0.121) were found to be trivial. Although large relationships between muscle thickness and weightlifting performance were not observed, the research group did find countermovement jump (CMJ) power to possess a large and moderate relationship with vastus lateralis (r=0.540) and vastus intermedius thickness (r=0.428), respectively. CMJ power has been observed to possess strong relationships with the snatch (r=0.76-0.93) and CJ (r=0.76-0.90), making it a potentially useful predictor of performance within weightlifters (Carlock et al., 2004; Zaras et al., 2020b).

Muscle thickness has also been examined in other strength and power sports such as track and field throwing (Zaras et al., 2016) and powerlifting (Brechue & Abe, 2002). Brechue and Abe (2002) did not observe any significant relationships between muscle thickness and powerlifting performance. The research group postulated that poor relationships existed between muscle thickness and powerlifting performance due to the level of powerlifting skill possessed by the study's participants. Indeed, the study included multiple world and national champions, with the participants having an average of nine years and therefore they may have achieved the upper limit of muscle accumulation possible. Zaras et al. (2016) examined the relationship vastus lateralis muscle thickness possessed with isometric rate of force development (IRFD) at different time bands (i.e., 0-50ms, 0-100ms, 0-150ms, 0-200ms, 0-250ms), isometric peak force (IPF) and maximal strength (i.e., 1-repetition maximum (1RM) back squat and hang power clean) among competitive shot put, discus, hammer, and javelin throwers in a longitudinal training study. The research group observed muscle thickness to possess significantly large relationships with IPF (r=0.636-0.848), hang power clean (r=0.713), RFD50 (r=0.645-0.651), RFD100 (r=0.734-0.832), RFD150 (r=0.816-0.875), RFD200 (r=0.806-0.839), and RFD250 (r=0.776-0.835). Of note is the relationship of muscle thickness to RFD at the later time bands since competitive throwing movements are executed in 150-240ms (Zaras et al., 2016). Similar to weightlifting movements, competitive throwing movements require high peak forces produced as quickly as possible at the launching point of a loaded projectile (e.g., throwing instrument, barbell) (Bartlett, 1992). Furthermore, RFD at later time bands (>100ms) is believed to be determined by maximal muscle strength (Kavvoura et al., 2018), thus the high peak forces generated <240ms in competitive throwing (Zaras et al., 2016) and weightlifting (Garhammer, 1991) may be facilitated by the thickness of the involved muscle groups.

The relationship of muscle thickness to performative variables (e.g., maximum strength, RFD, CMJ) in strength and power athletes (e.g., weightlifters, throwers) is likely due to the distinctive mechanistic factors responsible for the increase in pennate muscle thickness. Blazevich et al. (2006) observed an increase in fascicle angle and no change in fascicle length accompanied increases in vastus lateralis and rectus femoris muscle thickness when athletes completed five weeks of squat training. Conversely, athletes undertaking sprint/jump training with no resistance training experienced a decrease in fascicle angle and increase in fascicle length, but still increased their muscle thickness. Hence, morphological changes in fascicle angle and fascicle length may be contributory to increases in muscle thickness. However, an increase in fascicle angle is a commonly observed adaptation to long-term (e.g., 14-16 weeks) resistance training (Aagaard et al., 2001; Folland & Williams, 2007; Kawakami et al., 1995) and therefore is likely responsible for any changes in muscle thickness observed in competitive weightlifters.

There is a plethora of research examining the relationship of muscle thickness to human performance, namely resistance training. Additionally, multiple studies have attempted to elucidate the morphological changes in muscle thickness that are induced by resistance training. Muscle thickness possesses relationships with multiple performative characteristics (e.g., CMJ, RFD, IPF, maximal strength) that have been linked to weightlifting performance, thus it may be an important component of a weightlifter’s skeletal muscle structure. Applying these findings to competitive weightlifting should be done with caution, however, as muscle thickness possesses equivocal relationships with direct metrics of weightlifting performance (e.g., snatch, CJ, WT). There is a paucity of research examining the relationship of muscle thickness to weightlifting performance (Zaras et al., 2020b) and longitudinal changes in muscle thickness within competitive weightlifters (Suarez et al., 2019; Zaras et al., 2020a). Future research should aim to elucidate the difference in the muscle thickness of competitive weightlifters at different skill levels and different training ages. Additionally, further research may be necessary to better determine the contribution of muscle thickness to weightlifting performance.

Fascicles in Pennate Muscle

The angle and length of the fascicles of pennate muscle can also be measured using ultrasonography. Using ultrasound imaging, fascicle angle (FAN) is measured as the angle at which the measured fascicles insert into the deep aponeurosis of muscle. The entire length of the fascicles, however, often cannot be captured within the field-of-view provided by ultrasonography. Therefore, fascicle length (FL) can be estimated using the following trigonometric function: $FL = d \cdot sin\theta^{-1}$, where d is the distance between the deep aponeurosis and superficial aponeurosis measured at the point of fascicle insertion (i.e., muscle thickness at the given insertion), and θ is the FAN of the fascicle being measured. FAN and FL are interrelated structural components of pennate muscle partly responsible for the muscle's force-velocity relationship through the distinctive characteristics of each measurement. Furthermore, morphological changes in FAN and FL may be impacted differently based on training regimen (Blazevich et al., 2003) and muscle action (Blazevich et al., 2007; Franchi et al., 2014).

Fascicle Angle

Increases in FAN have been observed as an adaptation to resistance training within the pennate muscles that are exercised (Aagaard et al., 2001; Blazevich et al., 2003, 2007; Blazevich & Giorgi, 2001; Franchi et al., 2014; Kawakami et al., 1995). Conversely, longitudinal studies (e.g., 16-20 weeks) investigating training-induced changes in competitive weightlifters (Suarez et al., 2019; Zaras et al., 2020a) and throwers (Zaras et al., 2016) have not observed significant changes in FAN. A possible explanation for this discrepancy is the training history of the study participants. In the studies that have observed resistance training-induced increases in FAN, all but one included participants with no history of resistance training; Blazevich et al. (2003) included athletes (e.g., soccer, netball, rugby) with at least 3 months of resistance training experience. The extended training history (average of 5.4-10.7 years) of the competitive weightlifters likely led to an attenuation of any significant morphological changes to FAN across the training period. The pennate muscles of these well-trained individuals may be nearing a “critical” FAN, where the fascicles may be reaching their maximum angle of pennation. For instance, Brechue and Abe (2002) observed negative relationships between FAN and performance within a sample of high-level powerlifters (average of 9 years training history). The authors determined that the participants’ superior levels of fat-free mass accumulation meant that the participants had neared a “critical” FAN, thereby explaining the unexpected negative relationships between FAN and powerlifting performance. Superior levels of force production are paramount to powerlifting success and therefore force production is a sought after adaptation in powerlifting (Travis et al., 2020), similar to weightlifting (Stone et al., 2005). Hence, experienced weightlifters may also be nearing a “critical” FAN, thus explaining the lack of significant longitudinal change observed by Suarez et al. (2019) and Zaras et al. (2020a). Additionally, Zaras et al. (2020a,b) observed equivocal relationships between FAN and weightlifting performance. The vastus lateralis FAN of well-trained female weightlifters possessed moderate relationships with the snatch (r=0.459), CJ (r=0.436), and weightlifting total (r=0.448) (Zaras et al., 2020b). It should be noted that levels of significance were not measured for these relationships. Furthermore, when the FAN of elite-level male weightlifters was measured as part of a 16-week training period, Zaras et al. (2020a) found insignificant relationships between weightlifting total and vastus lateralis FAN at the beginning (r=0.250, p=0.633) and end (r=0.771, p=0.073) of the training period. Similar to the experienced powerlifters investigated by Brechue and Abe (2002), the homogeneity in the extensive training history of the weightlifters examined by Zaras et al. (2020a,b) may be resultant in the participants nearing a critical FAN as a product of the intensive/extensive resistance training employed by weightlifters (Storey & Smith, 2012), and thereby resulting in less individual variance at the competitive level possessed by these weightlifters.

An increase in FAN is determined by an addition to sarcomeres in parallel within the muscle fiber’s myofibrils as a result of muscle hypertrophy (Stone et al., 2007). The addition of sarcomeres in parallel results in the packing of muscle fiber along the connective tissue/tendon and thereby increases the FAN of the muscle. This has a distinct effect on the force properties of the contracting muscle; sarcomeres in parallel allow for each sarcomere to act independently, allowing for the force generated by the myofibril’s cross-bridges to be additive during contraction (Stone et al., 2007). Consequently, the increase in FAN may result in a greater mechanical disadvantage of the fibers in regards to their line of pull to tendon and therefore an increase in FAN is a trade-off between muscle fiber packing and mechanical disadvantage (Folland & Williams, 2007). However, it has been postulated that the optimal FAN of pennate muscle is 45^{o} (Alexander & Vernon, 1975) therefore, if the critical FAN of pennate muscle is ~30^{o} as hypothesized by Brechue and Abe (2002) then increases in FAN should contribute to increased strength.

Resistance training that elicits increases in FAN, and thereby maximal strength/force, should be implemented with competitive weightlifters so that they may reach their maximal FAN. The current literature investigating changes in FAN within competitive weightlifters

(Suarez et al., 2019; Zaras et al., 2020a) may have found no significant training-induced changes due to the extensive resistance training history of the participants; furthermore, this may also be responsible for insignificant relationships when FAN is directly correlated to performance in strength and power sports (e.g., weightlifting and powerlifting) (Brechue & Abe, 2002; Zaras et al., 2020a,b). Additionally, there is a need for more longitudinal and cross-sectional studies examining FAN and weightlifting performance, as there is currently a paucity of literature investigating the subject. Future studies should aim to examine FAN at different levels of talent and training history in order to produce a more robust knowledge of FAN's contributions to weightlifting performance.

Fascicle Length

The distinct plasticity of a pennate muscle's fascicles can also extend to fascicle length (FAL). Increases in FAL are believed to be a morphological adaptation to training protocols that are high-velocity, low-force (Blazevich et al., 2003). This adaptation may be determined by the force-velocity properties of muscle. Indeed, longer fascicles have a greater shortening velocity than shorter fibers (Sacks & Roy, 1982), therefore, the muscle's fascicles may lengthen as an adaptation to increase fiber contraction velocity. This adaptation is evident in sprinters, as a greater FAL possesses a positive relationship with sprint performance in male (Kumagai et al., 2000) and female (Abe et al., 2001) sprinters; additionally, sprinters possess a greater FAL than distance runners (Abe et al., 2000). A greater FAL is achieved through the addition of sarcomeres in series, which results in an increase in the velocity of fascicle contraction due to the lengthening of the fascicle (Stone et al., 2007). Indeed, assuming that all sarcomeres within a given fascicle contract simultaneously, displacement will increase in proportion to the number of sarcomeres in series, and thereby maximal velocity will increase (Wickiewicz et al., 1983). Since the snatch and CJ in weightlifting are ballistic movements that require high levels of power output (Garhammer, 1991, 1993), and therefore require an element of velocity for competitive success, morphological changes in FAL may affect weightlifting performance.

There is little research investigating the relationship of FAL to weightlifting performance within competitive weightlifters. The FAL measurements in a sample of well-trained female weightlifters possessed moderate to large relationships with the snatch ($r=0.517$), CJ ($r=0.414$), and weightlifting total ($r=0.464$), however, these findings should be interpreted with caution as the authors did not examine the levels of significance these relationships possessed (Zaras et al., 2020b). Training-induced changes in the FAL of competitive weightlifters have been investigated longitudinally (Suarez et al., 2019; Zaras et al., 2020a); although both studies did not observe significant changes across the 16-20 weeks of training. Suarez et al. (2019) observed a moderate increase in the FAL of experienced collegiate weightlifters across the 20-week training period ($d=0.70$, [-0.30 to 1.68]); similarly, the elite male weightlifters investigated by Zaras et al. (2020a) experienced a moderate increase in FAL ($g=0.492$) after 16 weeks of training. A possible explanation for these moderate increases in FAL (albeit statistically insignificant) is the shift toward higher velocity training throughout the training cycle, a common practice when implementing periodized training (Fleck, 1999). For instance, Zaras et al. (2016) measured the changes in the performance and FAL of competitive track and field throwers after 10 weeks of periodized training. Post-training measurements revealed FAL to have significantly increased by 13.41 ± 16.15%. This increase in FAL coincided with significant increases in isometric leg press RFD time bands (50, 100, 150, 200, 250ms), which may explain the change in relationship FAL possessed with RFD. No significant relationships were observed between FAL and RFD at pre-training, however, post-training measurements revealed FAL to possess strong relationships with RFD_{100} (r=0.601), RFD_{150} (r=0.613), RFD_{200} (r=0.682), and RFD_{250} (r=0.683). Additionally, the authors observed FAL to possess a significant relationship with shot put performance at pre- and post-training measurements. The increase in FAL and its relationship with RFD can likely be attributed to the shift to higher velocity training toward the end of the 10-week training regimen. As the athletes shifted to higher velocity training, they may have added sarcomeres in series and thereby increased the shortening velocity of the muscle through an increase in FAL. Similar to weightlifting, competitive throwing is a ballistic movement that requires the projection of a weighted implement. Conversely, however, the weighted implement in weightlifting can reach upward of 35-fold heavier than in competitive throwing. Therefore, the ability of the muscles involved in competitive throwing to contract with a high velocity may be more pertinent to throwing performance, thus it can be expected that FAL would have a greater relationship to throwing performance as compared to weightlifting performance. Nevertheless, a greater FAL may still be practical for strength and power sports involving heavy weighted implements. Indeed, Brechue and Abe (2002) found the FAL of the triceps long head and vastus lateralis to have a significant relationship with back squat (r=0.45; r=0.50, respectively), bench press (r=0.52; r=0.56, respectively), and deadlift (r=0.56; r=0.54, respectively) performance among high-level competitive powerlifters. Interestingly, powerlifting is a sport characterized by the high-force/low-velocity produced during the competitive lifts (Garhammer, 1993) (e.g., back squat, bench press, deadlift), and therefore it could be hypothesized that a greater FAL would not correlate to greater performance. However, Brechue and Abe (2002) postulated that the extensive powerlifting experience (9-year mean) of the involved subjects likely meant they had reached a "critical" FAN (see ***Fascicle Angle***), therefore, in order for the subjects to continue accumulating fat-free mass (FFM) they must add sarcomeres in series and thereby increasing FAL. Hence, the authors observing a significant relationship between triceps long head and vastus lateralis FAL and FFM (r=0.59; r=0.63, respectively).

While FAL and performance findings in sports such as throwing (Zaras et al., 2016) and powerlifting (Brechue & Abe, 2002) may provide insight into how FAL may affect weightlifting performance, applying these findings must be done with caution. Although weightlifting shares similarities to such strength and power sports as throwing and powerlifting, it still possesses distinct kinematic and kinetic differences. Future research examining the relationship of FAL and weightlifting performance should aim to include subjects with a greater array of training duration; additionally, longitudinal studies should possibly aim to examine training-induced changes in FAL across multiple training cycles to gain greater insight into morphological changes.

Cross-Sectional Area

Skeletal muscle anatomical cross-sectional area (ACSA) is a macroscopic muscle architecture measurement used to determine whole muscle size. ACSA has been measured using magnetic resonance imaging (MRI) (Aagaard et al., 2001; Kawakami et al., 1995; Maden-Wilkinson et al., 2020), ultrasonography (Blazevich et al., 2003, 2007; Blazevich & Giorgi, 2001; Funato et al., 2000; Ikai & Fukunaga, 1968; Suarez et al., 2019; Zaras et al., 2020a,b), and anthropometric formulas (Ford et al., 2000). An increase in ACSA is a customary adaptation to resistance training (Aagaard et al., 2001; Maden-Wilkinson et al., 2020) that may facilitate maximal strength (Miller et al., 1992; Ikai & Fukunago, 1968; Schantz, 1983; Suchomel & Stone, 2017) and vertical jumping (Suchomel & Stone, 2017; Zaras et al., 2020b), making it a sought-after adaptation in competitive weightlifters. The contribution of ACSA to greater muscular performance can be attributed to the hypertrophying of the involved muscle fibers.

Indeed, continuous resistance training results in the hypertrophying of muscle fibers (Staron et al., 1990), and more importantly, the fast-twitch type IIA muscle fibers. The performance of international- and national-level male weightlifters possessed a very strong relationship with type IIA percent content (r=0.94) and type IIA percent fiber area (r=0.84) (Fry et al., 2003), therefore, an increase in type IIA muscle fiber content may be the facilitating factor to an increase in ACSA, however, there is a paucity of research examining the relationship of skeletal muscle ACSA to weightlifting performance. Suarez et al. (2019) measured the ACSA of the vastus lateralis of collegiate competitive weightlifters throughout a 20-week training cycle. The authors observed a significant increase in ACSA after the strength-endurance block (d=1.90, [0.53 to 3.21]), followed by a significant decrease (d= -1.61, [-2.82 to -0.34]) in the subsequent strength-power block of training. Thereafter, ACSA did not significantly change, however, upon the conclusion of the 20-week training cycle, ACSA values were significantly higher (d= 1.19, [0.06 to 2.27]) than they had been prior to the training cycle. Additionally, it was observed that rate of force development (RFD) values initially had an inverse relationship with ACSA during the strength-endurance block, followed by a rebound and then eventually post-training values greater than pre-training values. When coupling these findings with the RFD values, Suarez et al. (2019) postulated that the initial increase in ACSA during the strength-endurance block may largely be attributed to edema-producing muscle damage that was produced as a result of the strenuous, high-volume training characteristic of the strength-endurance block. Indeed, Damas et al. (2016) observed initial increases in ACSA to primarily be a product of muscle swelling. Hence, the accumulative muscle damage produced during the strength-endurance block may have attenuated RFD capabilities (Hornsby et al., 2017).

Recently, Zaras et al. (2020a) investigated the relationship of quadriceps muscle architecture and performance in well-trained female weightlifters. Total ACSA of the quadriceps muscle group (i.e., vastus lateralis, vastus intermedius, vastus medialis, rectus femoris) possessed large to very large relationships with the snatch (r= 0.732), CJ (r= 0.680), and weightlifting total (r= 0.706). When examining each individual quadricep muscle, however, the relationships to weightlifting performance were equivocal: the vastus lateralis and vastus medialis possessed small to moderate relationships with weightlifting performance (r= 0.271-0.361; r=0.137-0.241, respectively) , and conversely the vastus intermedius and rectus femoris possess large relationships with weightlifting performance (r= 0.593-0.624; r= 0.565-0.610, respectively). Funato et al. (2000) also investigated the relationship of ACSA to muscle performance among the elbow flexors/extensors and knee flexors/extensors of elite senior and college weightlifters. The key findings observed within this study was the lack of any significant difference of ACSA between the elite senior and collegiate weightlifters, and the elite senior weightlifters possessing a significantly greater ratio of force to ACSA (F/ACSA). The authors postulated that these findings were a result of the significantly greater training experience of the elite senior weightlifters when compared to the collegiate weightlifters (10.2±1.3 years; 5.8±0.3 years, respectively). Similar to the concept of a critical FAN (see ***Fascicle Angle***), there may be an upper limit for an individual's ACSA achieved once the upper limit of the involved muscle fibers are reached. Once the critical ACSA is reached, it may be more pertinent for weightlifters to focus on the ability of the given muscle to produce force.

A small, but important, amount of research exists examining skeletal muscle ACSA and how it may facilitate weightlifting performance. Future research should aim to include larger subject groups, subject groups with differing training experience, or subject groups utilizing different training methods in an effort to provide practitioners with greater insight into ACSA and weightlifting performance. Furthermore, it may be beneficial to examine ACSA and muscle fiber composition within the same study, thus hopefully providing a better understanding of morphological changes of ACSA.

Ultrasonography Instrumentation

In recent years, the use of ultrasonography to examine muscle architecture has grown in popularity among researchers. This rise in usage can likely be contributed to ease of use and cost-efficiency compared to other instruments used for measuring muscle architecture (i.e., MRI, DEXA, CT). As with the implementation of any instrument, its validity and reliability must be investigated. Cartwright et al. (2013) assessed the validity of ultrasonography by comparing the nerve CSAs and muscle thicknesses obtained through ultrasound with the actual nerve CSAs and muscle thicknesses of human cadavers; the ultrasound measurements presented strong relationships with the actual measurements of the nerves ($r = 0.968$, $P<0.001$) and muscles ($r = 0.985$, $P < 0.001$). These findings are in line with Scott et al. (2012), who found ultrasound measurements of quadriceps femoris ASCA to possess a high agreement with ASCA obtained from MRI. Additionally, a systematic review examining the validity and reliability of muscle ultrasound use on older adults found ultrasonography to possess a high validity (ICC = 0.92-0.999) (Nijholt et al., 2017). Nijholt et al. (2017) also found the inter-rater reliability of muscle thickness and ACSA measured through ultrasound to be sufficient, with ICC scores ranging from 0.88 to 0.998 in the studies reviewed. Muscle ultrasonography has also exhibited strong test-retest reliability levels when measuring muscle thickness (ICC = 0.88-0.998) (Cartwright et al., 2013; Wallwork et al., 2007). The test-retest reliability regarding the measurements associated with the fascicles of pennate muscle (e.g., FAL and FAN), however, possess a greater range of reliability scores. A systematic review by Kwah et al. (2013) found the test-retest reliability to range from moderate to very high for both FAL (ICC = 0.62-0.99) and FAN (ICC = 0.51-1.00). The authors noted that the FAL and FAN reliability likely increases when large limbs are measured in a relaxed state. Additionally, measurements of FAL obtained through ultrasound should be interpreted with caution as length is often estimated through trigonometric function using MT and FAN.

One concern with muscle ultrasonography is the reliability between multiple experimenters. Ultrasound requires the experimenter to use a handheld probe to examine the architecture of muscle; procedural aspects such as probe orientation (Klimstra et al., 2007) have been observed to affect muscle architecture measurements. Ultrasound, however, has demonstrated sufficient inter-rater reliability levels when the same protocol is used. The systematic review by Kwah et al. (2013) investigating inter-rate reliability of FAL and FAN obtained from ultrasound presented high to very high ICC scores of 0.80 to 0.97 and 0.8, respectively; however, few studies have investigated the inter-rate reliability of FAL and FAN obtained from ultrasonography. Additionally, ultrasonographic measurements of muscle thickness have been found to possess sufficient inter-rater reliability levels. Indeed, Cartwright et al. (2013) demonstrated a very high inter-rater reliability score (ICC = 0.996) when measuring muscle thickness within human cadavers. These findings are supported by Wallwork et al. (2007), who observed the inter-rater reliability of muscle thickness measurements performed by a novice and experience ultrasound technician to range from high to very high (ICC = 0.85-0.97). Furthermore, the collection of ACSA using ultrasound imaging has demonstrated very high levels of inter-rater reliability (ICC = 0.963 – 0.991).

Conclusion

A paucity of research exists pertaining to muscle architecture and weightlifting performance, therefore weightlifting coaches and sport scientists should aim to disseminate muscle morphology research and apply it to the sport of competitive weightlifting. A major component of training for weightlifting is high intensity resistance training (Storey & Smith, 2012) to increase force-generating capabilities, a pertinent component of the competitive movements (snatch and clean and jerk). The subsequent architectural adaptations to this training style have been observed thoroughly in non-competitive weightlifter populations (e.g., field athletes, resistance trained subjects, untrained subjects) – MT (Blazevich et al., 2003; Blazevich & Giorgi, 2001; Kawakami et al., 1995; Timmins et al., 2016; Wells et al., 2014), FAN (Aagaard et al., 2001; Blazevich et al., 2003, 2007; Blazevich & Giorgi, 2001; Franchi et al., 2014; Kawakami et al., 1995), and ACSA (Aagaard et al., 2001; Maden-Wilkinson et al., 2020) were observed to increase with resistance training. Conversely, the velocity component of the high peak powers produced during the weightlifting movements may increase the weightlifter's FAL. Indeed, Suarez and colleagues (2019) observed a trend toward an increase in the FAL of collegiate weightlifters as they neared competition. Additionally, MT may be of particular importance to weightlifting performance, as it can increase via an increase in either FAN or FAL (Blazevich et al., 2003), hence, it may be necessary to examine FAN and FAL changes when MT is examined. These adaptations remain poorly investigated in competitive weightlifters, with only two longitudinal studies in current existence (Suarez et al., 2019; Zaras et al., 2020a). Furthermore, cross-sectional analysis of muscle architecture measurements and weightlifting performance remains equivocal due to the paucity of research investigating the subject. These equivocal longitudinal and cross-sectional findings support the need for further research investigating muscle architecture in competitive weightlifters. Future findings may assist in the athletic monitoring of weightlifters by weightlifting coaches and assist in the identification of potential weightlifting talent. Hence, it is of the utmost importance for sport scientists to continue investigating the relationship of muscle architecture to performative tests (e.g., vertical jumping, isometric/dynamic strength testing) and competitive performance (snatch and clean and jerk) performed by competitive weightlifters.

Chapter 3.

COMPARING DIFFERENT SCALING METHODS FOR MONITORING WEIGHTLIFTING PERFORMANCE

Original Investigation

Jake A. Slaton[1], Satoshi Mizuguchi[1], Kevin M. Carroll[1], Michael H. Stone[1]

[1]Center of Excellence for Sport Science and Coach Education, Department of Sport, Exercise, Recreation, and Kinesiology, East Tennessee State University, Johnson City, TN 37614, USA

Corresponding Author:

Jake A. Slaton

Phone: +1-770-843-6679

Email: jakeslaton95@gmail.com

Abstract

Physiological performance has been commonly scaled for body size using various methods to scale anthropometrics, but a paucity of data exists on scaling muscle size when scaling performance. The aim of this thesis was to elucidate the optimal method to scale height (HT), body mass (BM), lean body mass (LBM), and vastus lateralis muscle cross-sectional area (CSA) when scaling weightlifting performance for body size. Athlete monitoring data from 26 competitive weightlifters (13 male, 13 female) was used for this study. The measurements collected were the snatch (SN), clean and jerk (CJ), isometric peak force (IPF), and countermovement jump height (CMJH). HT, LBM, BM, and CSA were scaled using the ratio standard and allometry; unique power functions for each anthropometric variable and CSA were developed for the use of allometry. Competition performance scaled for allometrically scaled CSA possessed better relationships to CMJH (r = 0.60 – 0.78) than the ratio standard (r = 0.56 – 0.58). Performance scaled for ratio standard scaled HT, BM, LBM possessed better relationships to CMJH than when allometry was used. These findings suggest that allometrically scaling CSA may be optimal when scaling weightlifting performance for CSA.

Keywords: weightlifting; cross-sectional area; anthropometrics; allometry; athlete monitoring

Introduction

Weightlifting is a strength and power sport characterized by large forces generated during competition [1]. The large forces observed during the weightlifting movements are likely associated with the lifter's maximum strength [2]. Strength has been referred to as "the ability to produce force," thus maximum strength can be thought of as the ability to produce maximum force" [4]. A potential factor aiding in these high levels of force is the cross-sectional area (CSA) of the muscle involved. Suchomel and Stone [5] observed a moderate to large relationship between vastus lateralis CSA measured at 50% of the distance between the greater trochanter and the lateral condyle of the tibia and maximal strength measures (i.e., 1RM back squat and 1RM concentric-only half-squat), and a moderate to large relationship between vastus lateralis CSA and static jump peak power output. Both 1RM back squat [3] and static jump peak power [6–8] have been observed to have a strong relationship to weightlifting performance. Furthermore, anthropometry (e.g., height, body mass, body composition) may also attribute to weightlifting performance. Indeed, a greater lean body mass (LBM) [7–9] and greater height [10,11] have been correlated to greater performance amongst competitive weightlifters when weight classes are not taken into account.

When assessing the athletic performance of a weightlifter, it may be necessary to scale performance variables (e.g., competitive performance and force production) to anthropometrics and CSA. Through doing so, sport scientists and weightlifting coaches can account for the contributions of body and muscle size to a lifter's performance when comparing lifters of different sizes or monitoring a lifter's progress and capabilities. For instance, Stone et al. [3] scaled the competitive lifts (e.g., snatch (SN) and clean and jerk (CJ)) of competitive weightlifters for height and body mass using both the ratio standard and allometric scaling methods to assess the relationship to maximal strength. Both SN and CJ possessed larger relationships to maximal strength when scaled using allometry as compared to the ratio standard. These findings agree with previous studies that suggested the superior method of scaling strength variables for body size may be to allometrically scale body mass [12,13]. Conversely, Markovic and Sekluic [14] observed allometric scaling using uniquely derived power functions failed to sufficiently scale weightlifting performance for body mass, with the scaling method favoring middle-weight lifters. However, it should be noted the authors did not include any athletes with a body mass greater than 105kg, thereby excluding any super heavyweight lifters. This may have led to an error in allometric power function derivation, as super heavyweights may benefit the most from performance scaling using allometry due to their greater body fat composition [11]. Scientific inquiry into the scaling of physiological performance, however, rarely attempts to scale for measures of muscle size, such as CSA. Two studies have attempted to elucidate the effects of obviating weightlifting performance for CSA [11,15]. However, Ford et al. [11] identified CSA through the use of a formula using height and weight (weight $\times$ height^{-3}) rather than taking a cross-sectional measure of muscle content. Funato et al. [15] scaled muscular strength for CSA using ultrasonography. However, only the ratio standard was used.

The ratio standard, or “traditional method,” simply divides a performative measurement by an anthropometric measurement; however, this may not be suitable for examining human performance. If true, this is due to the ratio standard only being deemed statistically valid if the regression model with the two variables has an intercept of 0 and a slope equivalent to the ratio standard [16]. To allometrically scale anthropometric variables a power function unique to a pair of a performance variable and an anthropometric variable need to be found. A common power function of 0.67, or two-thirds, is derived from the relationship between the volume and surface area of an object after the natural logarithm for each is calculated [16]. The same procedure of calculating a natural logarithm can be applied to a given pair of a performance variable and an anthropometric variable [17]. Hence, the natural log for the performative variables pertinent to weightlifting (e.g., snatch, CJ, total, and IPF) and anthropometric variables can be calculated and a power function (i.e., allometric scaling coefficient) unique to a given pair of a performance variable and an anthropometric variable can be found. Undertaking this method for the application of allometry may prove suitable for scaling weightlifting performance to measurements of muscle size, a key physical characteristic attributing to performance. Furthermore, developing unique power functions for anthropometric variables may further refine the use of allometry when analyzing weightlifting performance. This elucidation may aid coaches and sport scientists in effectively monitoring athlete progress in the sport of weightlifting. Therefore, the primary objective of this study is to compare the ratio standard method and allometry method when using anthropometrics and muscle size to scale weightlifting performative measures.

Materials and Methods

This study analyzed athlete monitoring data previously collected as part of an ongoing athlete monitoring program. Anthropometric (i.e., ultrasonography and body composition) and performance (i.e., isometric mid-thigh pull (IMTP), countermovement jump (CMJ), and competition results) data was collected post-competition at the end of the athletes' macrocycles where they had been "peaked" for optimal competition performance. Competitions for all athletes took place on a single day of a given weekend (i.e., Friday, Saturday, or Sunday). The Monday after competition consisted of a low intensity active recovery training session. Ultrasound and body composition measurements were obtained on the subsequent Tuesday, with

CMJ and IMTP performed on the subsequent Wednesday. The competition results selected for use in this study were chosen from the competition where the athlete performed the greatest weightlifting total (WT).

To derive unique power functions for allometric scaling, natural logarithms of all variables were used to create general linear models. Statistically significant power functions were then used to compare allometric scaling to the ratio standard to examine which method may better scale for a given anthropometric variable when correlating a weightlifting-specific fitness quality measure and a weightlifting-specific performance measure. For this comparison, CMJ jump height (JH) was chosen as a weightlifting-specific fitness quality measure because it appears that CMJ JH is a correlate of weightlifting performance [6–8].

Athletes

Data was collected from 26 competitive weightlifters (13 female, 13 male) involved in the athlete monitoring program (Table 1). Inclusion criteria required an athlete to have completed both a snatch (SN) and a clean and jerk (CJ) in a competition they had peaked for. Additionally, the athlete must have completed all post-competition testing. The level of competition among the 26 athletes ranged from USA Weightlifting University National Championships to the USA Weightlifting Senior National Championships during their time within the monitoring program.

Table 1. Athlete Characteristcs

Sex	Age (yrs)	BM (kg)	BF %	HT (cm)	CSA (cm^2)	SN (kg)	CJ (kg)	IPF (N)
Female	20.5 ± 2.3	64.8 ± 8.6	20.4 ± 4.0	158.5 ± 4.9	34.0 ± 5.3	68.8 ± 7.4	88.3 ± 8.8	3742.7 ± 671.2
Male	22.3 ± 2.2	90.7 ± 9.9	13.3 ± 4.7	171.3 ± 6.7	46.0 ± 9.9	117.3 ± 18.5	149.8 ± 24.7	5617.6 ± 1839.0
All	21.4 ± 2.5	77.7 ± 20.2	16.8 ± 5.6	164.9 ± 8.7	40.0 ± 9.9	93.0 ± 28.0	119.0 ± 35.9	4680.2 ± 1671.9

Notes: Expressed as mean ± SD. Female (n = 13). Male (n = 13). BM = body mass. BF = body fat. HT = height. CSA = cross-sectional area. SN = snatch. CJ = clean and jerk. IPF = isometric peak force. N = newtons.

Hydration

Prior to all testing sessions, athlete hydration levels were measured through urine specific gravity (USG) using a handheld refractometer (Atago 4410 PAL-10S, Tokyo, Japan). If USG was scored ≥ 1.020, athletes were instructed to rehydrate until USG scored below 1.020. Hydration testing was utilized to control for any effect dehydration may have on athlete performance [18] and test measurements.

Ultrasonography

Vastus lateralis (VL) CSA was measured using a 7.5 MHz ultrasound probe (LOGIQ P6, General Electric Healthcare, Wauwatosa, WI, USA). All measurements were collected in the standing position in accordance with guidelines previously outlined [19]. Three panoramic images of the VL were collected at mid-femur on the athlete's right leg. Mid-femur was identified as the halfway point between the greater trochanter and lateral epicondyle of the femur. It should be noted that while multi-site ultrasonographic CSA images may potentially provide greater insight into the muscle's architecture, multiple multi-site studies have found the VL mid-belly's CSA to statistically increase after multi-joint resistance training [20–22]. Furthermore, the ultrasound imagery was collected as part of a routine athlete monitoring program. Thus, a single-site protocol was chosen to fit the imaging process with the lifters' practice and competition schedule. The three images were measured using the ultrasound's measurement tool by outlining the connective tissue surrounding the muscle tissue of the VL; thereafter, the mean of the three measurements was obtained and used as the athlete's CSA measurement.

Body Composition and Anthropometry

Body mass (BM) (kg) was obtained from a digital scale (Tanita Corporation, Arlington Heights, IL, USA) with the athlete minimally clothed; a stadiometer (Rice Lake Weighing Systems, Rice Lake, WI, USA) was used to obtain athlete height (cm). BM and HT both have been found to be related to weightlifting performance, with greater HT and BM correlating to a greater WT [10,11]. Additionally, lean body mass (LBM) has been observed to possess a positive relationship with weightlifting performance [9]. LBM (kg) was calculated from skinfold calipers (Cambridge Instruments, Cambridge, MD, USA) using a 7-site skinfold body density equation and body fat percentage equation [23,24]. Body composition and anthropometry testing were performed the Tuesday morning after competition for all athletes. All skinfold caliper measurements were collected by the same investigator in an attempt to collect reliable skinfold measurements [25].

Warm-Up

Prior to CMJ and IMTP testing, athletes performed a standardized warm-up protocol of 25 jumping jacks followed by four sets of five dynamic mid-thigh clean pull repetitions. The first set was performed with a 20kg barbell; the subsequent three sets were performed with 60kg (male) and 40kg (female) with approximately one-minute rest between sets.

Countermovement Jumping

CMJ trials were performed on dual force plates (Rice Lake Weighing Systems, Rice Lake, WI, USA; 1000Hz sampling rate). Athletes performed the CMJ holding a PVC pipe across their upper back. Athletes completed two warm-up jumps at 50% and 75% perceived effort prior to the first CMJ trial. Athletes were permitted to self-select countermovement depth. Following the warm-up jumps, athletes began their CMJ trials. A minimum of two trials were completed. Jump height (JH) was calculated from flight time and analyzed using custom LabView software (National Instruments, Austin, TX, USA). If the JH of the two trials were greater than 2cm apart, a subsequent CMJ trial was performed. This criterion was implemented as necessary until the athletes performed two CMJ trials less than 2 cm apart in JH. The mean of the two greatest JH (less than 2 cm apart) was used for athlete JH.

Isometric Mid-Thigh Pull (IMTP)

IMTP trials were performed while standing on dual force plates (Rice Lake Weighting Systems, Rice Lake, WI, USA; 1000Hz sampling rate) within a custom-built power-rack. Athletes were positioned in the IMTP and knee angle was assessed and adjusted to be 120-135 degrees with a handheld goniometer while maintaining a vertical torso in order to best simulate the power position achieved during a clean [26]. Subsequently, athletes performed warm-up pulls, separated by a brief rest, at 50% and 75% effort. The athletes were secured to the IMTP bar with lifting straps and athletic tape to obviate for hand grip strength. For each trial, athletes were instructed to get into position, apply slight tension on the barbell to remove any slack from the body. Once a steady force trace was observed, the athlete performed a maximal IMTP at the cessation of the command “3, 2, 1, pull” while provided with verbal encouragement to apply maximal effort. At the occurrence of a plateau or decline in the force tracing, the athlete was instructed to stop pulling. Two trials were performed by each athlete with a third trial required if the two initial trials exhibited a difference greater than 200N. Subsequent trials were required until the 200N criterion was met. The two trials with the greatest peak force (IPF) that met the 200N criterion were selected and analyzed using custom LabView software (National

Instruments, Austin, TX, USA); subsequently, the IPF of the two selected trials were averaged and the mean was used for this study.

Competition Results

Three attempts in both the SN and CJ were performed by athletes during competition. The greatest SN and CJ performed were summated to obtain the WT. All competitions were USAW sanctioned events, and all lifts were judged by USAW certified referees.

Statistical Analyses

In order to obtain the power functions for each anthropometric variable, each performance and anthropometric variable underwent natural logarithm transformations; subsequently, the natural logarithm of each independent variable (e.g., performance), dependent variable (e.g., anthropometry and CSA), and sex in the form of a dummy variable were used to build a general linear model. An interaction effect between sex and anthropometric variables was investigated by including an interaction term between the two. A statistically significant slope of a model provided a unique power function for the subsequent comparison between allometric scaling and the ratio standard. Pearson's r was used to assess the effect size of a relationship between the scaling methods and CMJ JH, a weightlifting-specific fitness quality measurement. The following scale was used to interpret effect sizes: 0.0-0.1 (trivial), 0.1-0.3 (weak), 0.3-0.5 (moderate), 0.5-0.7 (strong), 0.7-0.9 (very strong), and 0.9-1.0 (nearly perfect) [27]. Zou's 95% confidence interval was used to compare scaling method correlations [28]. The alpha criterion for null hypothesis testing was set at $p = 0.05$. For all analyses, the assumptions of general linear model were considered. When any assumptions except independence of error were violated, bootstrapping was applied to ensure sufficient accuracy for model parameter estimates and 95%

confidence intervals. If independence of error was violated, generalized least squares was applied. Statistical analyses were performed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA) and RStudio (Version 3.6.3; RStudio, Inc, Boston, MA, USA).

Results

Sex Effect

The interaction term between athlete anthropometric variables and sex displayed no statistically significant interaction effect. As a result, the sex effect was excluded in the subsequent analyses.

Deriving Power Functions for Allometric Scaling

All dependent variables possessed statistically significant relationships with all independent variables (Table 2). Furthermore, the slope of each model reached statistical significance, which suggested likely presence of a unique power function for each anthropometric variable.

Comparison of Scaling Methods

SN, CJ, and WT scaled by CSA, HT, LBM, and BM were statistically significantly correlated to CMJ JH ($r = 0.57$-0.79) under both scaling methods (Table 3). The lone IPF scaling to reach statistical significance was with HT ($r = 0.47$) using the ratio standard. SN, CJ, and WT divided simply by LBM possessed statistically significant better correlations with CMJ JH than the correlations of those divided by allometrically scaled LBM. Additionally, SN and WT divided by allometrically scaled CSA possessed statistically significant better correlations with CMJ JH than those simply divided by CSA. Furthermore, a general trend was observed where scaling CSA using allometry produced larger correlations with CMJ JH; conversely, all other anthropometric variables produced larger correlations when scaled using the ratio standard, albeit LBM was the lone anthropometric variable to possess a statistically significant difference between the two correlations.

Table 2. Natural Logarithm Models

	Independent Variables			
Dependent Variables	lnCSA	lnHT	lnBM	lnLBM
lnIPF				
R^2	0.49***	0.68***	0.71***	0.68***
Slope	0.87***	4.84***	1.09***	1.03***
Intercept	5.20***	-16.30***	3.67***	4.13***
95% CI - Slope	0.50, 1.24	3.45, 6.23	0.80, 1.39	0.73, 1.33
lnSnatch				
R^2	0.55***†	0.68***	0.62***	0.84***
Slope	0.58***	4.75***	1.05***	1.13***
Intercept	2.38***	-19.77***	-0.06	-0.19
95% CI - Slope	0.36, 0.80	3.37, 6.13	0.74, 1.36	0.92, 1.34
lnCJ				
R^2	0.60***	0.68***	0.69***	0.85***
Slope	0.94***	4.72***	1.05***	1.12***
Intercept	1.31*	-19.32***	0.20	0.09
95% CI - Slope	0.61, 1.26	3.37, 6.07	0.75, 1.34	0.92, 1.33
lnWT				
R^2	0.54***†	0.69***	0.69***	0.85***
Slope	0.55***	4.73***	1.05***	1.13***
Intercept	3.32***	-18.84***	0.77	0.65
95% CI - Slope	0.34, 0.76	3.39, 6.08	0.75, 1.35	0.93, 1.33

Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. †pseudo R^2 . CI: confidence interval.

Table 3. Correlation Comparisons of CMJH and Scaling Methods

	95% CI	Ratio Standard r	Allometry r
SN:CSArs v. SN:CSAa	-0.45, -0.06*	0.58**	0.78***
CJ:CSArs v. CJ:CSAa	-0.15, 0.07	0.56**	0.60**
WT:CSArs v. WT:CSAa	-0.45, -0.05*	0.58**	0.78***
IPF:CSArs v. IPF:CSAa	-0.17, 0.01	0.22	0.29
SN:HTrs v. SN:HTa	-0.02, 0.46	0.79***	0.61***
CJ:HTrs v. CJ:HTa	-0.04, 0.45	0.78***	0.61***
WT:HTrs v. WT:HTa	-0.04, 0.45	0.79***	0.62***
IPF:HTrs v. IPF:HTa	-0.05, 0.56	0.47*	0.22
SN:LBMrs v. SN:LBMa	0.03, 0.31*	0.69***	0.57**
CJ:LBMrs v. CJ:LBMa	0.03, 0.31*	0.69***	0.57**
WT:LBMrs v. WT:LBMa	0.06, 0.34*	0.71*	0.57**
IPF:LBMrs v. IPF:LBMa	-0.01, 0.07	0.13	0.10
SN:BMrs v. SN:BMa	-0.07, 0.16	0.69***	0.66***
CJ:BMrs v. CJ:BMa	-0.07, 0.16	0.69***	0.66***
WT:BMrs v. WT:BMa	-0.07, 0.16	0.70***	0.67***
IPF:BMrs v. IPF:BMa	-0.03, 0.17	0.34	0.28

Note: CMJH = countermovement jump height rs = ratio standard. a = allometry. SN = snatch. CJ= clean and jerk. WT = total. IPF = isometric peak force. CSA = cross-sectional area. HT = height. LBM = lean body mass. BM = body mass. *p < 0.05, **p < 0.01, ***p < 0.001.

Discussion

The intent of this study was to contribute to athlete monitoring in the sport of weightlifting when monitoring muscle size and anthropometry in order to identify a superior scaling method when scaling performance to anthropometrics. To accomplish this, the relationship of weightlifting performance to muscle size and anthropometrics that have been scaled using the ratio standard and allometry was compared. The main inferences are that scaling performance to CSA may be better done using allometry, whereas scaling to LBM, BM, and HT might be sufficiently performed using either method.

When considering a common weightlifting fitness quality such as CMJ JH [6–8], allometry is likely superior to the ratio standard when accounting for individual differences in CSA. After scaling weightlifting performance measures (e.g., SN, CJ, WT, & IPF) using allometrically scaled CSA, CMJ JH is likely to be a better indicator of weightlifting performance as compared to ratio standard scaled CSA. This inference can be supported by the statistically greater correlation coefficients with CMJ JH for allometrically scaled CSA (Table 3). This finding indicates that when attempting to assess the relationship of a lifter's CSA to their athletic performance, it may be advised to use allometrically scaled CSA. The superior results may reflect the likely non-linear relationship of body mass and weightlifting total scaled to CSA, as seen in high-level weightlifters [11]. The body mass of heavier weightlifters has a lesser relative fraction of muscle tissue, partially due to the upper limit of myofiber accruement achieved [29]. This would result in a non-linear relationship between the proportion of CSA to body mass. Ford et al. [11] observed weightlifting total scaled to CSA decreased beyond the 83kg and 64kg weight classes for men and women, respectively. The authors inferred that at body masses above these weight classes, weightlifters' body masses consist of a greater portion of body fat. If true, this inference adheres to the *surface law* that postulates the surface area of a body correlates to its volume allometrically scaled with a power function of 0.67; essentially, as a body's volume increase, its surface area decreases in proportion [17]. Therefore, identifying a power function specific to CSA and applying it during allometric scaling may account for the non-linear pattern of weight lifted scaled to CSA and body mass when monitoring weightlifter performance.

The observed use of allometry as a likely superior method to obviate individual differences in CSA elucidates the potential benefit of employing the scaling of performative characteristics of weightlifting to muscle CSA when monitoring athlete performance and development. Previously, a study investigated the muscle CSA and its force generating capabilities in elite- and collegiate-level weightlifters [15]. The study group observed the elite-level group to possess a statistically greater force per unit of CSA (F/CSA) than the collegiate-level group; however, no statistically significant group difference existed in muscle CSA. It should be noted that Funato et al. [15] measured force from unilateral single-joint isolated muscle actions; conversely, the performance variables scaled for CSA in the current study were bilateral multiple-joint muscle actions performed during competition (e.g., SN, CJ, WT), and are more representative of the competitive lifts (e.g., IPF from IMTP). Nonetheless, Funato and colleagues' findings support the potential benefit of scaling performance to CSA.

Scaling weightlifting performance to LBM when using the ratio standard might be superior to allometrically scaled LBM; the statistically greater correlation coefficient between CMJ JH and weightlifting performance scaled to ratio standard LBM supports this inference (Table 3). These current results observed between CSA scaling methods and anthropometry scaling methods (BM, LBM, and HT) may be thought of as confounding since CSA may be considered part of the athlete's LBM and BM, and likely some molecular factors responsible for the upper limit of CSA accruement are also responsible for the upper limit of bone growth [30] and thus HT. For instance, protein kinase-B (Akt) is one of many intracellular regulators contributing to both skeletal muscle [31] and bone growth [32]. Indeed, it is believed that growth factors such as insulin growth factor-1 and growth hormone are regulated by pleiotropic genes that control for both bone and muscle growth [33]. Therefore, it may be assumed, within limits, that HT and CSA possess a relationship through shared intracellular molecular pathways. However, the contrasting relationship of CSA scaling methods and body size scaling methods to a common fitness quality, such as CMJ JH, can possibly be attributed to CSA being a body part measurement as opposed to measurements (e.g., LBM, BM, HT) representing the body as a whole. Specific body parts that act as primary movers during the lifts, such as the knee extensor muscles (e.g., vastus lateralis), may not possess the same relationships to weightlifting performance as whole-body measurements. The 0.67, or two-thirds, power function that appears to be common for allometrically scaling body size measurements when examining physiological performance [34] may still be applicable when allometrically scaling weightlifter anthropometry and muscle size (e.g., CSA). Additionally, the 0.67 power function may be applicable when allometrically scaling CSA since the 95% confidence intervals for natural logarithm transformed CSA contains 0.67, however, further research into muscle size allometry is needed to support this inference.

It should be noted that there may be potential sources of error in the investigation's attempt to elucidate best practices for scaling weightlifting performance. For example, this study inferred that the ratio standard may be the better method for scaling weightlifting performance by LBM (Table 3). This inference, however, may be a type 1 statistical error; allometrically scaled body size is thought to be superior to ratio standard scaled body size when scaling physiological variables [12,34]. Indeed, the common power function to scale body size is 0.67; this power function has been observed to scale better when scaling physiological parameters for body size [34,35]. The equivocal findings between the current study and these previous studies may be due to the use of LBM as an anthropometric variable; typically, studies examining anthropometric allometry use BM rather than LBM [3,12,35]. Furthermore, although using skinfold measurements as a tool to estimate body fat composition has displayed high test-retest reliability [36], it still presents a greater measurement error than the gold standard of dual x-ray absorptiometry (DEXA) [37]. Hence, LBM estimation accuracy may not have been as optimal compared to alternative methods for assessing body composition, possibly resulting in the scaling of LBM with the ratio standard displaying better correlation coefficients to weightlifting performance. Therefore, we advise readers to interpret this finding with caution. Another potential source of error is only obtaining CSA from a single landmark of the vastus lateralis. While often more practical in athlete monitoring, this approach may not fully convey muscle CSA, as resistance-training induced muscle growth is intra-muscularly inhomogeneous [38]. These regional differences in muscle growth appear to be influenced in part by muscle action type [20,21], range of motion [22], and mode of exercise [39,40]. Nonetheless, multiple studies have observed statistically significant increases in VL mid-belly CSA after multi-joint resistance training [20–22]. Still, applying the scaling methodology of the current study to various regions of the muscle of interest may provide better insight into the optimal protocol for scaling muscle size.

Conclusion

The findings of the current study should be interpreted with caution, and further research may be necessary before applying unique power functions to bodily measurement, primarily due to the lack of evidence or investigation into examining scaling techniques for muscle CSA. Additionally, future studies may want to investigate these scaling methods specifically within male athletes and female athletes. Indeed, sex may influence the power functions used for allometry as Ford et al. [11] observed female weightlifters to be taller than their male counterparts when equalized for body mass. Furthermore, maximal strength may contribute to performance to a somewhat lesser extent for female weightlifters [3], thereby possibly influencing the relationship of performance to anthropometrics and muscle size. Nonetheless, the current observation did not indicate any sex interaction effect; however, this may differ in studies with a larger sample size. Allometrically scaling muscle size may provide weightlifting coaches and sport scientists with a more effective method when employing ultrasound images of CSA in an athlete monitoring program and may provide a better insight into the impact muscle morphology has on weightlifting performance when attempting to scale performance, specifically the competition lifts, for muscle size. This approach may be increasingly necessary the more experienced a weightlifter is in the sport of weightlifting. Based on the findings of this study, practitioners desiring to implement such monitoring protocols can utilize a uniquely derived power function. The 95% confidence intervals of the slopes provide an estimated range within which an effective power function can be identified; the ranges elucidated in the current study for allometrically scaling CSA are 0.34 to 1.26 across all performance variables (i.e., SN, CJ, WT, and IPF). The common power function of 0.67 utilized for body size allometry falls within this 95% confidence interval, and therefore may also be the first choice when allometrically scaling CSA.

References

1. Storey, A.; Smith, H.K. Unique Aspects of Competitive Weightlifting. *Sports Med* **2012**, *42*, 769–790.
2. Beckham, G.K.; Mizuguchi, S.; Carter, C.; Sato, K.; Ramsey, M.; Lamont, H.; Hornsby, G.; Haff, G.; Stone, M. Relationships of Isometric Mid-Thigh Pull Variables to Weightlifting Performance. *J. Sports Med. Phys. Fitness* **2013**, *53*, 10.
3. Stone, M.H.; Sands, W.A.; Pierce, K.C.; Carlock, J.; Cardinale, M.; Newton, R.U. Relationship of Maximum Strength to Weightlifting Performance. *Med. Sci. Sports Exerc.* **2005**, *37*, 1037–1043.

4. Stone, M.H.; Moir, G.; Glaister, M.; Sanders, R. How Much Strength Is Necessary? *Phys. Ther. Sport* **2002**, *3*, 88–96, doi:10.1054/ptsp.2001.0102.
5. Suchomel, T.; Stone, M. The Relationships between Hip and Knee Extensor Cross-Sectional Area, Strength, Power, and Potentiation Characteristics. *Sports* **2017**, *5*, 66, doi:10.3390/sports5030066.
6. Carlock, J.M.; Smith, S.L.; Hartman, M.J.; Morris, R.T.; Ciroslan, D.A.; Pierce, K.C.; Newton, R.U.; Harman, E.A.; Sands, W.A.; Stone, M.H. The Relationship between Vertical Jump Power Estimates and Weightlifting Ability: A Field-Test Approach. *J. Strength Cond. Res.* **2004**, *18*, 534, doi:10.1519/R-13213.1.
7. Travis, S.K.; Goodin, J.R.; Beckham, G.K.; Bazyler, C.D. Identifying a Test to Monitor Weightlifting Performance in Competitive Male and Female Weightlifters. *Sports* **2018**, *6*, 1–12.
8. Zaras, N.; Stasinaki, A.-N.; Spiliopoulou, P.; Hadjicharalambous, M.; Terzis, G. Lean Body Mass, Muscle Architecture, and Performance in Well-Trained Female Weightlifters. *Sports* **2020**, *8*, 67, doi:10.3390/sports8050067.
9. Fry, A.C.; Ciroslan, I.D.; Fry, M.D.; Leroux, I.C.D.; Schilling, B.K.; Chiu, L.Z.F. Antrhopometric and Performance Variables Discriminating Elite American Junior Men Weightlifters. *Jouranl Strength Cond. Res.* **2006**, *20*, 861–866.
10. Siahkouhian, M.; Hedayatneja, M. Correlations of Anthropometric and Body Composition Variables with the Performance of Young Elite Weightlifters. *J. Hum. Kinet.* **2010**, *25*, doi:10.2478/v10078-010-0040-3.

11. Ford, L.E.; Detterline, A.J.; Ho, K.K.; Cao, W. Gender- and Height-Related Limits of Muscle Strength in World Weightlifting Champions. *J. Appl. Physiol.* **2000**, *89*, 1061–1064, doi:10.1152/jappl.2000.89.3.1061.
12. Lietzke, M.H. Relation between Weight-Lifting Totals and Body Weight. *Science* **1956**, *124*, 486–487.
13. Crewther, B.T.; Kilduff, L.P.; Cook, C.J.; Cunningham, D.J.; Bunce, P.J.; Bracken, R.M.; Gaviglio, C.M. Scaling Strength and Power for Body Mass Differences in Rugby Union Players. *J Sports Med Phys Fit.* **2012**, *52*, 27–32.
14. Markovi, G.; Sekuli, D. Modeling the Influence of Body Size on Weightlifting and Powerlifting Performance. *Coll Antropol* **2006**, 7.
15. Funato, K.; Kanehisa, H.; Fukunaga, T. Differences in Muscle Cross-Sectional Area and Strength between Elite Senior and College Olympic Weight Lifters. *J. Sports Med. Phys. Fitness* **2000**, *40*, 312–318.
16. Winter, E.M.; Nevill, A.M. Scaling: Adjusting for difference in body size. In *Kinanthropometry and Exercise Physiology Laboratory Manual*; Routledge, 2009; Vol. 1, pp. 300–314.
17. Schmidt-Nielsen, K. *Scaling, Why Is Animal Size so Important?*; Cambridge University Press, 1984;
18. Judelson, D.A.; Maresh, C.M.; Farrell, M.J.; Yamamoto, L.M.; Armstrong, L.E.; Kraemer, W.J.; Volek, J.S.; Spiering, B.A.; Casa, D.J.; Anderson, J.M. Effect of Hydration State on Strength, Power, and Resistance Exercise Performance. *Med. Sci. Sports Exerc.* **2007**, *39*, 1817–1824.

19. Wagle, J.; Carroll, K.; Cunanan, A.; Taber, C.; Wetmore, A.; Bingham, G.; DeWeese, B.; Sato, K.; Stuart, C.; Stone, M. Comparison of the Relationship between Lying and Standing Ultrasonography Measures of Muscle Morphology with Isometric and Dynamic Force Production Capabilities. *Sports* **2017**, *5*, 88, doi:10.3390/sports5040088.
20. Franchi, M.V.; Atherton, P.J.; Reeves, N.D.; Flück, M.; Williams, J.; Mitchell, W.K.; Selby, A.; Beltran Valls, R.M.; Narici, M.V. Architectural, Functional and Molecular Responses to Concentric and Eccentric Loading in Human Skeletal Muscle. *Acta Physiol.* **2014**, *210*, 642–654, doi:10.1111/apha.12225.
21. Housh, D.J.; Housh, T.J.; Johnson, G.O.; Chu, W.K. Hypertrophic Response to Unilateral Concentric Isokinetic Resistance Training. *J. Appl. Physiol.* **1992**, *73*, 65–70, doi:10.1152/jappl.1992.73.1.65.
22. McMahon, G.E.; Morse, C.I.; Burden, A.; Winwood, K.; Onambélé, G.L. Impact of Range of Motion during Ecologically Valid Resistance Training Protocols on Muscle Size, Subcutaneous Fat, and Strength. *J. Strength Cond. Res.* **2014**, *28*, 245–255, doi:10.1519/JSC.0b013e318297143a.
23. Jackson, A.S.; Pollock, M.L.; Ward, A. Generalized Equations for Predicting Body Density of Women. *Med. Sci. Sports Exerc.* **1980**, *12*, 175–181.
24. Jackson, A.S.; Pollock, M.L. Generalized Equations for Predicting Body Density of Men. *Br. J. Nutr.* **1978**, *40*, 497–504.
25. Kispert, C.P.; Merrifield, H.H. Interrater Reliability of Skinfold Fat Measurements. *Phys. Ther.* **1987**, *67*, 917–920, doi:10.1093/ptj/67.6.917.

26. Beckham, G.K.; Sato, K.; Santana, H.A.P.; Mizuguchi, S.; Haff, G.G.; Stone, M.H. Effect of Body Position on Force Production during the Isometric Midthigh Pull. *J. Strength Cond. Res.* **2018**, *32*, 48–56, doi:10.1519/JSC.0000000000001968.
27. Hopkins, W.G. A New View of Statistics. 2006.
28. Zou, G.Y. Toward Using Confidence Intervals to Compare Correlations. *Psychol. Methods* **2007**, *12*, 399.
29. Brechue, W.F.; Abe, T. The Role of FFM Accumulation and Skeletal Muscle Architecture in Powerlifting Performance. *Eur. J. Appl. Physiol.* **2002**, *86*, 327–336, doi:10.1007/s00421-001-0543-7.
30. Thompson, W.R.; Rubin, C.T.; Rubin, J. Mechanical Regulation of Signaling Pathways in Bone. *Gene* **2012**, *503*, 179–193.
31. Lim, C.H.; Luu, T.S.; Phoung, L.Q.; Jeong, T.S.; Kim, C.K. Satellite Cell Activation and MTOR Signaling Pathway Response to Resistance and Combined Exercise in Elite Weight Lifters. *Eur. J. Appl. Physiol.* **2017**, *117*, 2355–2363, doi:10.1007/s00421-017-3722-x.
32. Choi, S.-C.; Kim, S.-J.; Choi, J.-H.; Park, C.-Y.; Shim, W.-J.; Lim, D.-S. Fibroblast Growth Factor-2 and -4 Promote the Proliferation of Bone Marrow Mesenchymal Stem Cells by the Activation of the PI3K-Akt and ERK1/2 Signaling Pathways. *Stem Cells Dev.* **2008**, *17*, 725–736, doi:10.1089/scd.2007.0230.
33. Bonewald, L.F.; Kiel, D.P.; Clemens, T.L.; Esser, K.; Orwoll, E.S. Forum on Bone and Skeletal Muscle Interactions: Summary of the Proceedings of an ASBMR Workshop. *J. Bone Miner. Res.* **2013**, 9.

34. Nevill, A.M.; Ramsbottom, R.; Williams, C. Scaling Physiological Measurements for Individuals of Different Body Size. *Eur. J. Appl. Physiol.* **1992**, *65*, 110–117, doi:10.1007/BF00705066.
35. Nevill, A.M.; Holder, R.L. Modelling Maximum Oxygen Uptake: A Case-Study in Non-Linear Regression Model Formulation and Comparison. *J. R. Stat. Soc. Ser. C Appl. Stat.* **1994**, *43*, 653–666, doi:10.2307/2986263.
36. Jackson, A.S.; Pollock, M.L. Practical Assessment of Body Composition. *Phys. Sportsmed.* **1985**, *13*, 76–90, doi:10.1080/00913847.1985.11708790.
37. Bilsborough, J.C.; Greenway, K.; Opar, D.; Livingstone, S.; Cordy, J.; Coutts, A.J. The Accuracy and Precision of DXA for Assessing Body Composition in Team Sport Athletes. *J. Sports Sci.* **2014**, *32*, 1821–1828, doi:10.1080/02640414.2014.926380.
38. Zabaleta-Korta, A.; Fernández-Peña, E.; Santos-Concejero, J. Regional Hypertrophy, the Inhomogeneous Muscle Growth: A Systematic Review. *Strength Cond. J.* **2020**, *42*, 94–101, doi:10.1519/SSC.0000000000000574.
39. Wakahara, T.; Fukutani, A.; Kawakami, Y.; Yanai, T. Nonuniform Muscle Hypertrophy: Its Relation to Muscle Activation in Training Session. *Med. Sci. Sports Exerc.* **2013**, *45*, 2158–2165, doi:10.1249/MSS.0b013e3182995349.
40. Escamilla, R., F.; Fleisig, G., S.; Zheng, N.; Barrentine, S., W.; Wilk, K., E.; Andrews, J., R. Biomechanics of the Knee during Closed Kinetic Chain and Open Kinetic Chain Exercises. *Med. Sci. Sports Exerc.* **1998**, *30*, 556–569.

Chapter 4. Summary and Future Investigations

The objective of this thesis was to investigate the utility of allometrically scaling CSA when scaling weightlifting performance for muscle size. Performance, anthropometric, and ultrasound data was collected from 26 competitive weightlifters and used to carry out this study. For allometric scaling, unique power functions were derived by creating a linear regression model using the natural logarithm of each dependent variable (CSA, HT, BM, LBM) and independent variable (IPF, SN, CJ, WT). The slope of each model was used as the power function when allometrically scaling the dependent variable. Each independent variable was scaled for each dependent variable and correlated to CMJH, a fitness quality that has been observed to possess a relationship with weightlifting performance (Carlock et al., 2004; Travis et al., 2018). We observed that performance scaled to allometrically scaled CSA may possess better relationships to CMJH as compared to the traditional method of ratio standard scaling (Table 3). Conversely, when scaling performance to HT, BM, and LBM the ratio standard may possess better relationships to CMJH as opposed to allometry. As mentioned before, insight provided from this investigative may allow sport scientists and weightlifting coaches the ability to appropriately implement sound athlete monitoring protocols, thus allowing for an accurate method to track athletic performance and progress. To this study group's knowledge, this is the first study to investigate the use of allometry when scaling weightlifting performance for CSA.

Athlete monitoring, the foundation of sport science, is the tracking of fatigue management and program efficacy (Suarez et al., 2020) as a means to enhance athletic performance. Elucidating the optimal scaling methods that accounts for the contribution of body zie to performance allows sport scientists to better monitor program efficacy in the sport of weightlifting. HT, BM, and LBM have all been identified to attribute to weightlifting performance (Ford et al., 2000; Fry et al., 2006; Siahkouhian & Hedayatneja, 2010), however, these measurements of body size do not possess a completely linear relationship to performance (Ford et al., 2000). Hence, the use of allometric scaling when scaling physiological performance for body size is commonly used when elucidating the relationship of performance to specific fitness qualities, such as weightlifting performance and maximal strength (Stone et al., 2005). While the use of different scaling methods for body size measurements has been extensively investigated in weightlifting, the literature examining the scaling of weightlifting performance for CSA is scarce (Ford et al., 2000; Funato et al., 2000). Furthermore, there is no literature investigating the use of allometry for scaling CSA.

The findings of this thesis posit that scaling weightlifting performance for CSA may be best undertaken using allometry. However, this is the first study to investigate and discover the efficacy of allometrically scaling CSA. While a potentially beneficial method to employ within an athlete monitoring protocol, we recommend further investigations like the current study be undertaken to further access the efficacy of allometrically scaling CSA. The current sample also contained individuals with a wide array of size (54.0 – 147.3kg BM). Since weightlifting is a weight class sport, it may be beneficial to investigate the current study protocols using a sample of weightlifters that possess greater BM homogeneity. Nonetheless, this thesis elucidated promising findings when allometrically scaling CSA, thus future research should be carried out further examining the topic.

References

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A.-M., Wagner, A., Magnusson, S. P., Halkjaer-Kristensen, J., & Simonsen, E. B. (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: Changes in muscle architecture. *The Journal of Physiology*, *534*(2), 613–623. https://doi.org/10.1111/j.1469-7793.2001.t01-1-00613.x

Abe, T., Fukashiro, S., Harada, Y., & Kawamoto, K. (2001). Relationship between sprint performance and muscle fascicle length in female sprinters. *Journal of Physiological Anthropology and Applied Human Science*, *20*(2), 141–147.

Abe, T., Kumagai, K., & Brechue, W. F. (2000). Fascicle length of leg muscles is greater in sprinters than distance runners. *Medicine and Science in Sports and Exercise*, *32*(6), 1125–1129.

Alexander, R. M., & Vernon, A. (1975). The dimensions of knee and ankle muscles and the forces they exert. *J. Hum. Move. Stud.*, *1*, 115–123.

Bartlett, R. M. (1992). The biomechanics of the discus throw: A review. *Journal of Sports Sciences*, *10*(5), 467–510. https://doi.org/10.1080/02640419208729944

Beckham, G. K., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., Hornsby, G., Haff, G., & Stone, M. (2013). Relationships of isometric mid-thigh pull variables to weightlifting performance. *The Journal of Sports Medicine and Physical Fitness, 53*(5), 10.

Beckham, G. K., Sato, K., Santana, H. A. P., Mizuguchi, S., Haff, G. G., & Stone, M. H. (2018). Effect of body position on force production during the isometric midthigh pull. *The*

Journal of Strength & Conditioning Research, *32*(1), 48–56. https://doi.org/10.1519/JSC.0000000000001968

Bilsborough, J. C., Greenway, K., Opar, D., Livingstone, S., Cordy, J., & Coutts, A. J. (2014). The accuracy and precision of DXA for assessing body composition in team sport athletes. *Journal of Sports Sciences*, *32*(19), 1821–1828. https://doi.org/10.1080/02640414.2014.926380

Blazevich, A. J., Cannavan, D., Coleman, D. R., & Horne, S. (2007). Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol*, *103*, 1565–1575.

Blazevich, A. J., Cannavan, D., Horne, S., Coleman, D. R., & Aagaard, P. (2009). Changes in muscle force–length properties affect the early rise of force in vivo. *Muscle & Nerve*, *39*(4), 512–520.

Blazevich, A. J., Gill, N. D., Bronks, R., & Newton, R. U. (2003). Training-specific muscle architecture adaptation after 5-wk training in athletes: *Medicine & Science in Sports & Exercise*, *35*(12), 2013–2022. https://doi.org/10.1249/01.MSS.0000099092.83611.20

Blazevich, A. J., & Giorgi, A. (2001). Effect of testosterone administration and weight training on muscle architecture: *Medicine & Science in Sports & Exercise*, *33*(10), 1688–1693. https://doi.org/10.1097/00005768-200110000-00012

Bonewald, L. F., Kiel, D. P., Clemens, T. L., Esser, K., & Orwoll, E. S. (2013). Forum on bone and skeletal muscle interactions: Summary of the proceedings of an ASBMR workshop. *Journal of Bone and Mineral Research*, 9.

Brechue, W. F., & Abe, T. (2002). The role of FFM accumulation and skeletal muscle architecture in powerlifting performance. *European Journal of Applied Physiology*, *86*(4), 327–336. https://doi.org/10.1007/s00421-001-0543-7

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., Newton, R. U., Harman, E. A., Sands, W. A., & Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: A field-test approach. *The Journal of Strength and Conditioning Research*, *18*(3), 534. https://doi.org/10.1519/R-13213.1

Cartwright, M. S., Demar, S., Griffin, L. P., Balakrishnan, N., Harris, J. M., & Walker, F. O. (2013). Validity and reliability of nerve and muscle ultrasound. *Muscle & Nerve*, *47*(4), 515–521. https://doi.org/10.1002/mus.23621

Choi, S.-C., Kim, S.-J., Choi, J.-H., Park, C.-Y., Shim, W.-J., & Lim, D.-S. (2008). Fibroblast growth factor-2 and -4 promote the proliferation of bone marrow mesenchymal stem cells by the activation of the PI3K-Akt and ERK1/2 signaling pathways. *Stem Cells and Development*, *17*(4), 725–736. https://doi.org/10.1089/scd.2007.0230

Crewther, B. T., Kilduff, L. P., Cook, C. J., Cunningham, D. J., Bunce, P. J., Bracken, R. M., & Gaviglio, C. M. (2012). Scaling strength and power for body mass differences in rugby union players. *J Sports Med Phys Fitness*, *52*(1), 27–32.

Di Naso, J. J., Pritschet, B. L., Emmett, J. D., Owen, J. D., Willardson, J. M., Beck, T. W., DeFreitas, J. M., & Fontana, F. E. (2012). Comparing thigh muscle cross-sectional area and squat strength among national class Olympic weightlifters, power lifters, and bodybuilders. *International SportMed Journal*, *13*(2), 48–57.

Escamilla, R., F., Fleisig, G., S., Zheng, N., Barrentine, S., W., Wilk, K., E., & Andrews, J., R. (1998). Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. *Medicine & Science in Sports & Exercise*, *30*(4), 556–569.

Fleck, S. J. (1999). Periodized strength training: A critical review. *Journal of Strength and Conditioning Research*, *13*(1), 82–89.

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: Morphological and neurological contributions to increased strength. *Sports Medicine*, *37*(2), 145–168. https://doi.org/10.2165/00007256-200737020-00004

Ford, L. E., Detterline, A. J., Ho, K. K., & Cao, W. (2000). Gender- and height-related limits of muscle strength in world weightlifting champions. *Journal of Applied Physiology*, *89*(3), 1061–1064. https://doi.org/10.1152/jappl.2000.89.3.1061

Franchi, M. V., Atherton, P. J., Reeves, N. D., Flück, M., Williams, J., Mitchell, W. K., Selby, A., Beltran Valls, R. M., & Narici, M. V. (2014). Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiologica*, *210*(3), 642–654. https://doi.org/10.1111/apha.12225

Fry, A. C., Ciroslan, I. D., Fry, M. D., Leroux, I. C. D., Schilling, B. K., & Chiu, L. Z. F. (2006). Antrhopometric and performance variables discriminating elite American junior men weightlifters. *Jouranl of Strength and Conditioning Research*, *20*(4), 861–866.

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003). Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. *Journal of Strength and Conditioning Research*, *17*(4), 746–754.

Funato, K., Kanehisa, H., & Fukunaga, T. (2000). Differences in muscle cross-sectional area and strength between elite senior and college Olympic weight lifters. *Journal of Sports Medicine and Physical Fitness*, *40*(4), 312–318.

Garhammer, J. (1991). A comparison of maximal power outputs between elite male and female weightlifters in competition. *International Journal of Sport Biomechanics*, *7*(1), 3–11.

Garhammer, J. (1993). A review of power output studies of Olympic and powerlifting: Methodology, performance prediction, and evaluation. *Journal of Strength and Conditioning Research*, *7*(2), 76–89.

Haff, G. G., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Kawamori, N., Jackson, J. R., Morris, R. T., Sands, W. A., & Stone, M. H. (2005). Force-time curve characteristics of dynamic and isometri muscle actions of elite women Olympic weightlifters. *Journal of Strength and Conditioning Research*, *19*(4), 741–748.

Häkkinen, K., & Keskinen, K. L. (1989). Muscle cross-sectional area and voluntary force production characteristics in elite strength- and endurance-trained athletes and sprinters. *European Journal of Applied Physiology and Occupational Physiology*, *59*(3), 215–220. https://doi.org/10.1007/BF02386190

Hopkins, W. G. (2006). *A new view of statistics.* https://www.sportsci.org/resource/stats/effectmag.html

Hornsby, W., Gentles, J., MacDonald, C., Mizuguchi, S., Ramsey, M., & Stone, M. (2017). Maximum strength, rate of force development, jump height, and peak power alterations in weightlifters across five months of training. *Sports*, *5*(4), 78. https://doi.org/10.3390/sports5040078

Housh, D. J., Housh, T. J., Johnson, G. O., & Chu, W. K. (1992). Hypertrophic response to unilateral concentric isokinetic resistance training. *Journal of Applied Physiology*, *73*(1), 65–70. https://doi.org/10.1152/jappl.1992.73.1.65

Ikai, M., & Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Internationale Zeitschrift Für Angewandte Physiologie Einschliesslich Arbeitsphysiologie*, *26*(1), 26–32.

Jackson, A. S., & Pollock, M. L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, *40*(3), 497–504.

Jackson, A. S., & Pollock, M. L. (1985). Practical assessment of body composition. *The Physician and Sportsmedicine*, *13*(5), 76–90. https://doi.org/10.1080/00913847.1985.11708790

Jackson, A. S., Pollock, M. L., & Ward, A. (1980). Generalized equations for predicting body density of women. *Medicine and Science in Sports and Exercise*, *12*(3), 175–181.

Judelson, D. A., Maresh, C. M., Farrell, M. J., Yamamoto, L. M., Armstrong, L. E., Kraemer, W. J., Volek, J. S., Spiering, B. A., Casa, D. J., & Anderson, J. M. (2007). Effect of hydration state on strength, power, and resistance exercise performance. *Medicine and Science in Sports and Exercise*, *39*(10), 1817–1824.

Kavvoura, A., Zaras, N., Stasinaki, A.-N., Arnaoutis, G., Methenitis, S., & Terzis, G. (2018). The importance of lean body mass for the rate of force development in taekwondo athletes and track and field throwers. *Journal of Functional Morphology and Kinesiology*, *3*(43), 20.

Kawakami, Y., Abe, T., Kuno, S.-Y., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European Journal of Applied Physiology and Occupational Physiology*, *72*(1–2), 37–43. https://doi.org/10.1007/BF00964112

Kispert, C. P., & Merrifield, H. H. (1987). Interrater reliability of skinfold fat measurements. *Physical Therapy*, *67*(6), 917–920. https://doi.org/10.1093/ptj/67.6.917

Klimstra, M., Dowling, J., Durkin, J. L., & MacDonald, M. (2007). The effect of ultrasound probe orientation on muscle architecture measurement. *Journal of Electromyography and Kinesiology*, *17*(4), 504–514. https://doi.org/10.1016/j.jelekin.2006.04.011

Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology*, *88*(3), 811–816. https://doi.org/10.1152/jappl.2000.88.3.811

Lietzke, M. H. (1956). Relation between weight-lifting totals and body weight. *Science*, *124*, 486–487.

Lim, C. H., Luu, T. S., Phoung, L. Q., Jeong, T. S., & Kim, C. K. (2017). Satellite cell activation and mTOR signaling pathway response to resistance and combined exercise in elite weight lifters. *European Journal of Applied Physiology*, *117*(11), 2355–2363. https://doi.org/10.1007/s00421-017-3722-x

Lucero, R. A., Fry, A. C., LeRoux, C. D., & Hermes, M. J. (2019). Relationships between barbell squat strength and weightlifting performance. *International Journal of Sports Science & Coaching*, *14*(4), 562–568. https://doi.org/10.1177/1747954119837688

Maden-Wilkinson, T. M., Balshaw, T. G., Massey, G. J., & Folland, J. P. (2020). What makes long-term resistance-trained individuals so strong? A comparison of skeletal muscle morphology, architecture, and joint mechanics. *Journal of Applied Physiology*, *128*(4), 1000–1011.

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: Physiological and methodological considerations. *European Journal of Applied Physiology*, *116*(6), 1091–1116. https://doi.org/10.1007/s00421-016-3346-6

Markovi, G., & Sekuli, D. (2006). Modeling the influence of body size on weightlifting and powerlifting performance. *Coll. Antropol.*, 7.

McBride, J. M., Triplett-Mcbride, T., Davie, A., & Newton, R. U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Jouranl of Strength and Conditioning Research*, *13*(1), 58–66.

McMahon, G. E., Morse, C. I., Burden, A., Winwood, K., & Onambélé, G. L. (2014). Impact of range of motion during ecologically valid resistance training protocols on muscle size, subcutaneous fat, and strength. *Journal of Strength and Conditioning Research*, *28*(1), 245–255. https://doi.org/10.1519/JSC.0b013e318297143a

Nevill, A. M., & Holder, R. L. (1994). Modelling maximum oxygen uptake: A case-study in non-linear regression model formulation and comparison. *Journal of the Royal Statistical Society. Series C (Applied Statistics)*, *43*(4), 653–666. https://doi.org/10.2307/2986263

Nevill, A. M., Ramsbottom, R., & Williams, C. (1992). Scaling physiological measurements for individuals of different body size. *European Journal of Applied Physiology and Occupational Physiology*, *65*(2), 110–117. https://doi.org/10.1007/BF00705066

Nijholt, W., Scafoglieri, A., Jager-Wittenaar, H., Hobbelen, J. S. M., & Schans, C. P. van der. (2017). The reliability and validity of ultrasound to quantify muscles in older adults: A systematic review. *Journal of Cachexia, Sarcopenia and Muscle*, *8*(5), 702–712. https://doi.org/10.1002/jcsm.12210

Sacks, R. D., & Roy, R. R. (1982). Architecture of the hind limb muscles of cats: Functional significance. *Journal of Morphology*, *173*(2), 185–195. https://doi.org/10.1002/jmor.1051730206

Schmidt-Nielsen, K. (1984). *Scaling, why is animal size so important?* Cambridge University Press.

Siahkouhian, M., & Hedayatneja, M. (2010). Correlations of anthropometric and body composition variables with the performance of young elite weightlifters. *Journal of Human Kinetics*, *25*(1). https://doi.org/10.2478/v10078-010-0040-3

Staron, R. S., Malicky, E. S., Leonardi, M. J., Falkel, J. E., Hagerman, F. C., & Dudley, G. A. (1990). Muscle hypertrophy and fast fiber type conversions in heavy resistance-trained women. *European Journal of Applied Physiology and Occupational Physiology*, *60*(1), 71–79. https://doi.org/10.1007/BF00572189

Stone, M. H., Moir, G., Glaister, M., & Sanders, R. (2002). How much strength is necessary? *Physical Therapy in Sport*, *3*(2), 88–96. https://doi.org/10.1054/ptsp.2001.0102

Stone, M. H., Sands, W. A., Pierce, K. C., Carlock, J., Cardinale, M., & Newton, R. U. (2005). Relationship of maximum strength to weightlifting performance. *Medicine and Science in Sports and Exercise*, *37*(6), 1037–1043.

Stone, M. H., Stone, M., & Sands, W. A. (2007). Biomechanics of resistance training. In *Principles and Practice of Resistance Training* (pp. 45–60). Human Kinetics.

Storey, A., & Smith, H. K. (2012). Unique aspects of competitive weightlifting. *Sports Med*, *42*(9), 769–790.

Suarez, D. G., Harden, N. G., Perkins, A., D'Amato, J. S., Almugathawi, I. F., & Stone, M. H. (2020). Athlete monitoring for barbell strength sports: A review with practical recommendations for implementation. *Professional Strength & Conditioning*, *58*, 23–35.

Suarez, D. G., Mizuguchi, S., Hornsby, W. G., Cunanan, A. J., Marsh, D. J., & Stone, M. H. (2019). Phase-specific changes in rate of force development and muscle morphology throughout a block periodized training cycle in weightlifters. *Sports*, *7*(6), 129. https://doi.org/10.3390/sports7060129

Suchomel, T., & Stone, M. (2017). The relationships between hip and knee extensor cross-sectional area, strength, power, and potentiation characteristics. *Sports*, *5*(3), 66. https://doi.org/10.3390/sports5030066

Thompson, W. R., Rubin, C. T., & Rubin, J. (2012). Mechanical regulation of signaling pathways in bone. *Gene*, *503*(2), 179–193.

Timmins, R. G., Shield, A. J., Williams, M. D., Lorenzen, C., & Opar, D. A. (2016). Architectural adaptations of muscle to training and injury: A narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. *British Journal of Sports Medicine*, *50*(23), 1467–1472. https://doi.org/10.1136/bjsports-2015-094881

Travis, S. K., Goodin, J. R., Beckham, G. K., & Bazyler, C. D. (2018). Identifying a test to monitor weightlifting performance in competitive male and female weightlifters. *Sports*, *6*(46), 1–12.

Travis, S. K., Mujika, I., Gentles, J. A., Stone, M. H., & Bazyler, C. D. (2020). Tapering and peaking maximal strength for powerlifting performance: A review. *Sports*, *8*(9), 125. https://doi.org/10.3390/sports8090125

Wagle, J., Carroll, K., Cunanan, A., Taber, C., Wetmore, A., Bingham, G., DeWeese, B., Sato, K., Stuart, C., & Stone, M. (2017). Comparison of the relationship between lying and standing ultrasonography measures of muscle morphology with isometric and dynamic force production capabilities. *Sports*, *5*(4), 88. https://doi.org/10.3390/sports5040088

Wakahara, T., Fukutani, A., Kawakami, Y., & Yanai, T. (2013). Nonuniform muscle hypertrophy: Its relation to muscle activation in training session. *Medicine & Science in Sports & Exercise*, *45*(11), 2158–2165. https://doi.org/10.1249/MSS.0b013e3182995349

Wallwork, T. L., Hides, J. A., & Stanton, W. R. (2007). Intrarater and interrater reliability of assessment of lumbar multifidus muscle thickness using rehabilitative ultrasound imaging. *Research Report*, 11.

Wells, A. J., Fukuda, D. H., Hoffman, J. R., Gonzalez, A. M., Jajtner, A. R., Townsend, J. R., Mangine, G. T., Fragala, M. S., & Stout, J. R. (2014). Vastus lateralis exhibits non-homogenous adaptation to resistance training. *Muscle & Nerve*, *50*, 785–793.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. *Clinical Orthopaedics and Related Research*, *179*, 275–283.

Winter, E. M., & Nevill, A. M. (2009). Scaling: Adjusting for difference in body size. In *Kinanthropometry and Exercise Physiology Laboratory Manual* (3rd ed., Vol. 1, pp. 300–314). Routledge.

Zabaleta-Korta, A., Fernández-Peña, E., & Santos-Concejero, J. (2020). Regional hypertrophy, the inhomogeneous muscle Growth: A systematic review. *Strength & Conditioning Journal*, *42*(5), 94–101. https://doi.org/10.1519/SSC.0000000000000574

Zaras, N. D., Stasinaki, A.-N. E., Methenitis, S. K., Krase, A. A., Karampatsos, G. P., Georgiadis, G. V., Spengos, K. M., & Terzis, G. D. (2016). Rate of force development, muscle architecture, and performance in young competitive track and field throwers. *The Journal of Strength & Conditioning Research*, *30*(1), 81–92.

Zaras, N., Stasinaki, A.-N., Spiliopoulou, P., Arnaoutis, G., Hadjicharalambous, M., & Terzis, G. (2020). Rate of force development, muscle architecture, and performance in elite weightlifters. *International Journal of Sports Physiology and Performance*.

Zaras, N., Stasinaki, A.-N., Spiliopoulou, P., Hadjicharalambous, M., & Terzis, G. (2020). Lean body mass, muscle architecture, and performance in well-trained female weightlifters. *Sports*, *8*(5), 67. https://doi.org/10.3390/sports8050067

Zou, G. Y. (2007). Toward using confidence intervals to compare correlations. *Psychological Methods*, *12*(4), 399.

VITA

JAKE A. SLATON

Education:	M.S. Sport Science and Coach Education, East Tennessee State University, Johnson City, Tennessee, 2021
	B.S. Kinesiology, University of North Georgia, Dahlonega, Georgia, 2019
Professional Experience:	Clinical Research Coordinator II, Sports Performance And Research Center, Emory University School of Medicine, Flowery Branch, Georgia, 2021 – Present
	Weightlifting Coach, Power & Grace Performance, Suwannee, Georgia, 2021 – Present
	Personal Trainer, Peak Strength & Fitness, Buford, Georgia, 2014-2019
Publications:	Ishida, A., Suarez, D. G., Travis, S. K., **Slaton, J. A.**, White, J. B., Bazyler, C. D., & Stone, M. H. (in press). Intra- and inter-session reliability of isometric squat, mid-thigh pull and squat jump in resistance-trained individuals. *Journal of Strength and Conditioning Research*.
	Suarez, D. G., Carroll, K. M., **Slaton, J. A.**, Rochau, K. G., Davis, M. W., & Stone, M. H. (2020). Utility of a shortened isometric midthigh pull protocol for assessing rapid force production in athletes. *Journal of Strength and*

	Conditioning Research. Ahead of print.
	Walsh, D. J., Palevo, G., Polascik, M., & **Slaton, J**. (2020). Physiological differences of US army cadets during a loaded and unloaded 6-mile ruck march. *Journal of Exercise Physiology Online*, *23*(1), 79-87.
Professional Certifications:	National Strength and Conditioning Association, Certified Strength and Conditioning Specialist, 2020
	USA Weightlifting, Level 1, 2014
Honors and Awards:	East Tennessee State University Scholarship Athlete, Weightlifting, 2019-2021