RELATIONSHIP BETWEEN SQUAT AND BENCH PRESS STRENGTH AND RACQUET HEAD VELOCITY IN MALE TENNIS PLAYERS

A Thesis
by
OLUMIDE AWELEWA

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APPROVED BY:

Jeffrey M. McBride, Ph.D.
Chairperson, Thesis Committee

Caroline J. Smith, Ph.D.
Member, Thesis Committee

Mr. Travis Erickson
Member, Thesis Committee

N. Travis Triplett, Ph.D.
Chairperson, Department of Health & Exercise Science

Max C. Poole, Ph.D.
Dean, Cratis Williams Graduate School

Abstract

RELATIONSHIP BETWEEN SQUAT AND BENCH PRESS STRENGTH AND RACQUET HEAD VELOCITY IN MALE TENNIS PLAYERS

Olumide Omololu Awelewa, B.S., Kingston University, London
M.S., Appalachian State University

Chairperson: Jeffrey M. McBride, Ph.D.

Racquet head velocity is one factor commonly associated with tennis performance. The ability to generate racquet head velocity involves proper sequencing of the kinetic chain and optimal use of muscle strength. The utilization of ground reaction forces in hitting a tennis ball, reduced with Newtonian mechanics is an elastic collision. Collisions can either be elastic or inelastic. For two objects M1 and M2 (racquet and ball respectively) traveling at initial velocities U1 and U2, after collision, their final velocities will be V1 and V2. Based on the principles of conservation of momentum; a product of mass and velocity (M1U1 + M2U2 = M1V1 + M2V2). The kinetic jerk, or jolt, surge, or lurch, is the derivative of acceleration with respect to time, thus, the second derivative of velocity, or the third derivative of displacement. PURPOSE: The primary purpose of this investigation was to examine the relationship between measures of maximal strength (1RM squat and 1RM bench press) and tennis racquet head velocity. METHODS: Twenty-six male, college-aged tennis players with playing experience mean ± SD experience = (8 ± 4 years) participated in this investigation, and were grouped according to their experience (Beginner (2-5 years), n = 10; Intermediate (6-11 years), n = 9; Advanced (12+ years), n = 8). All the subjects were tested in the laboratory for 1RM squat, 1RM bench press, and vertical jump height. Racquet velocities, on serves only, were measured on court using a tri-axial accelerometer, mounted at the base of a fully customized and blinded tennis racquet. The Bluetooth© equipped accelerometer was connected to a computer containing corresponding proprietary data capture software. Maple© was used to process and calculate resultant racquet head velocities from the raw accelerometer data. Acceleration–time curves were used to calculate the acceleration derivative. Descriptive statistical analysis was executed using Pearson product-moment coefficient on SPSS. RESULTS: Racquet head velocity for the advanced players was similar to the intermediates and beginners (Beginner: 13.85 ± 1.09 ms^{-1}; Intermediate: 14.5 ± 2.19 ms^{-1}; Advanced: 14.74 ± 1.76 ms^{-1}). The rate of change of racquet acceleration was higher in advanced players compared to intermediates or beginners (Beginner: 1248.76 ± 228.73 ms^{-3}; Intermediate: 1199.2 ± 215.13 ms^{-3}; Advanced: 1539.39 ± 213.12 ms^{-3}). There were no significant differences between any of the groups in squat or bench press 1RM strength. There were no significant correlations between squat or bench press 1RM and racquet head velocity or rate of change in acceleration. CONCLUSIONS: The data suggest that racquet head velocities between male tennis players at the amateur level are similar, although the advanced players exhibited a higher rate of change of racquet acceleration. However, it appears that the higher rate of change in racquet acceleration cannot be attributed to increased leg or upper body strength. PRACTICAL APPLICATION: The existence of a definitive relationship between general measures of upper/lower body strength and tennis serve velocity, is unclear at this time. The current study suggests that advanced players may exhibit higher rates of acceleration of the racquet, possibly as a product of better kinetic chain sequencing.

Acknowledgements

This body of work would be impossible without helping hands. I am grateful for the Cratis Williams Graduate School and the Appalachian State University Office for Student Research for all of the research funding support. I also thank the faculty and Staff of the Department of Health and Exercise Sciences.

I owe much appreciation to Dr. Jeffrey McBride, Dr. Scott Collier, Dr. & Mrs. Gregory Anoufriev and Dr. Robert Johnson for their mentoring roles from my search for a place in Graduate School to a Master's degree. I especially thank Dr. Jeffrey McBride for his mentorship and encouragement in biomechanical research affairs, in addition to opening my eyes to a new world of biomechanical transducers. I remain grateful to him for trusting me with teaching and sharing my passion with his undergraduate students, an opportunity for which I swam across the ocean, an opportunity that will never be forgotten. I thank Dr. N. T. Triplett for keeping her door open for all requests; this variety rich, bespoke, research degree would be impossible without her signature. This thesis is based on her Masters' thesis. I really did stand on the shoulder of a giant.

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Lastly, I thank Dr. Scott Collier, a brilliant role model, mentor, and boss. I remember visiting Appalachian State for the first time, searching for a place to do my Master's degree. His

words to me were, “We’ll find something for you.” Little did he know that I would find a Masters degree and a purpose, balanced in the milieu of my peculiar background and education.

Dedication

For El-, the One and only who turned my ordinary, extraordinary

For Mummy & Daddy,

For Freddie,

For BASE-ette,

For Felup,

For my teachers.

For Kyle Kennedy and Emily Goodall, may the sun ever shine on your faces and endeavors.

For Mark Suggs, may chaos never know your abode.

For One,

For All,

For Beauty,

For Life.

Table of contents

Foreword

This thesis manuscript and the figures, tables, and references herein were formatted according to the author instructions for manuscript submission to the peer-reviewed journal *Journal of Strength and Conditioning Research*, published by The National Strength and Conditioning Association.

Chapter 1: Introduction

Racquet head velocity is one factor associated with tennis performance (Chow, Park, & Tillman, 2009; Reid, Whiteside, & Elliott, 2011). The ability to generate racquet head velocity involves proper sequencing of the kinetic chain and optimal use of muscle strength (Chow et al., 2009). Cross-sectional investigations have indicated that measures of maximal muscle strength in the lower and upper body relate to many sport-specific skill patterns such as golf club head velocity, tennis ball velocity, swimming start times, and baseball club velocity (Gordon, Moir, Davis, Witmer, & Cummings, 2009; Hoffman, Vazquez, Pichardo, & Tenenbaum, 2009; Kraemer et al., 1995; West, Owen, Cunningham, Cook, & Kilduff, 2011). Longitudinal investigations have also shown that strength training can result in improvements in sport-specific skills performance as well (Alvarez, Sedano, Cuadrado, & Redondo, 2012; Doan, Newton, Kwon, & Kraemer, 2006; Kraemer et al., 2003; Nimphius, Mcguigan, & Newton, 2010). However, no studies have established the relationship between upper and lower body strength and racquet head velocity in tennis. The study of this interrelation could be important in the design of training programs that equip athletes in the metamorphosis of strength gains into genuine performance gains.

Cross-sectional evidence associating maximal strength and sport-specific skill patterns continues to increase. Sleivert and Taingahue (2004) found that the one-repetitive maximal squat strength (1RM) measurement elicits kinetic and kinematic variables such as force, power, and velocity. Peak power, calculated from these variables during a countermovement jump at body mass is also a measure of explosive strength that is found at the beginning of the kinetic chain involving ground reaction forces. Significant correlations between 1RM squat strength and sprint performance were also found. Wisloff, Castagna, Helgerud, Jones, and Hoff (2004) also reported a significant correlation between 1RM and sprint times in 10m and 30m. Though the significance was remarkable, it did not account for skills such as changes in direction, which occur frequently in tennis. Jeffrey M. McBride et al. (2009) and Wisloff et al. (2004) also found a statistically significant relationship between squat strength (using the 1RM/body mass (BM) ratio) and five, ten and forty yard sprint times. The 1RM/BM ratio was used to demarcate the subject pool into elite and sub-elite groups for further analysis. While 5-yard times exhibited an insignificant relationship, the efficacy of maximal strength (in the lower body musculature) in generating the ground reaction forces needed in explosive or ballistic athletic performance was evident. Further analysis showed that the correlation was stronger in the elite group. Furthermore, (West et al., 2011), after finding a significant correlation between 1RM squat strength (predicted from 3RM) and start times, suggested that the principal athletic performance variable in swimming was sprint time governed by start time, primarily guided by ground reaction forces at the start. This indicates that the factors related to improving a skill involving jumping performance seem to be largely determined by lower body strength and muscular power. This suggests the need for longitudinal evidence investigating the variability in previous cross-sectional studies that show improvement in sport-specific skills.

For all correlation studies, it is difficult to assess whether the observed relationships are markers of each other or causative, that is, an increase in one variable directly corresponds to a positive change in the other. Recent longitudinal studies have explored the aforementioned correlational interrelations through the design of training studies. For example, Kraemer et al. (2003) reported that, of the tennis players that were tested, the periodized group elicited significant increases in jump height, serve, forehand, and backhand ball velocities compared to the non-periodized group of tennis players. Ball velocity is the kinetic and kinematic result of the elastic collision between the string-bed and the ball. Ideally, a strategic placement of wireless accelerometers at the center of mass of the racquet should provide data for the calculation of axial velocities, acceleration, power and impact based on Newton's laws (Chow et al., 2009). Alvarez et al. (2012) found that an improvement in barbell squat in an 18-week study coincided with marked improvements in ball velocity. This was also congruent with the earlier observations reported by (Doan et al., 2006).

Sport-specific improvements in training studies are not only limited to squat strength training and leg press. Just like tennis, rowing requires lower and upper body strength and in a review, Lawton, Cronin, and McGuigan (2011) emphasized improvements in rowing performance spanning sub-elite to elite rowers. Finally, Hermassi et al. (2011) hypothesized that "elite handball players who supplemented their normal in-season handball training with an 8-week program of heavy biweekly resistance exercises for both the lower and the upper limbs would enhance their muscular strength and power without compromising other factors critical to handball performance (throwing velocity, sprinting, and jumping abilities)". (p. 2425). The findings supported the hypothesis with substantial gains in sport-specific skills.

Other factors involve the utilization of ground reaction forces. The utilization of ground reaction forces in hitting a tennis ball, reduced with Newtonian mechanics is an elastic collision. Collisions can either be elastic or inelastic. For two objects M1 and M2 (racquet and ball, respectively) traveling at initial velocities U1 and U2, after collision, their final velocities were V1 and V2. Based on the principles of conservation of momentum; a product of mass and velocity:

$$M1U1 + M2U2 = M1V1 + M2V2$$

A successful shot should result in M2V2 >> M1V1 with M1V1 tending to zero in the recovery phase of the shot cycle as V1 tends to zero. Thus U1 is important because it is the only variable under the absolute control of the player. The same is also true if the equation above is written for axial velocity components. Technique is a matter of impact, impact that is eventually transferred to the ball from the generated ground reaction force to the racquet through the hips, shoulders, elbows and wrists via the kinetic chain. If the magnitude of the time variable in the impact equation is too high, M1 and M2 will combine to form a new mass M and a new much lower velocity V.

To our knowledge no investigation has examined the relationship between measures of maximal strength (1RM squat and 1RM bench press) and tennis racquet head velocity. It is hypothesized that there is a direct positive relationship between the 1RM squat strength and racquet velocity.

Chapter 2: Experiment
Methods

The subjects consisted of 18-25 year old male tennis players with no existing injuries, selected from the community and screened based on their United States Tennis Association (USTA) rating. The rating is based on the ratio between the number of matches won or lost and has been used to predict skill level. They were recruited through word of mouth and email announcement for the student body of Appalachian State University.

To participate, the subjects had to be players, with no recent orthopedic surgery or injury, USTA rated at least 3.5 to strive for sample homogeneity (Kraemer et al., 2003; Kraemer et al., 1995; Parchmann & McBride, 2011). Players rated ≥ 3.5 had at least 4 years of playing competitive tennis and some experience with weight training as preparation. This means familiarity with the protocols that were used in the study. There was no minimum requirement for strength. The participants were allowed to play on court at their leisure as usual except 24 hours before testing. Prior to being informed of any participatory risk, the subjects were given a written consent form approved by the Institutional Review Board at Appalachian State University to read and sign.

Procedure

The participants met the principal investigator in the Neuromuscular Lab for the first session and then on a tennis court (within a week) for the second session. Session one consisted of the informed consent (Appendix A), anthropometry, tennis history, tennis experience, resistance training experience, and other contact details. Anthropometric measures including height, body mass, and grip circumference were recorded, followed by vertical jump and 1RM (Bench and Squat) tests. Upon completion, the second meeting date for the racquet velocity test was scheduled. Within a week, they were instructed to play on court at their leisure as usual except 24 hours prior to testing. Subjects who were unable to schedule the first and second session within the allotted maximum time of one week had to reschedule. Certified personnel supervised the subjects during the tests to fulfill all program protocols. The principal investigator was present for all tests until successful 1RM attempts, including a complete range of motion of the exercise, for each individual was attained.

1RM Squat.

The back squat 1RM data were acquired using procedures established in prior research (Cormie, McBride, & McCaulley, 2007; Winchester, Erickson, Blaak & McBride, 2005). This included a warm-up of 4-6 repetitions at 30% of estimated 1RM, 3-4 repetitions at 50% 1RM, 2-3 repetitions at 70% 1RM, and 1 repetition at 90% of 1RM. The subjects had up to four attempts to achieve a true 1RM (Winchester et al., 2005). Each set was interspersed by five minutes of rest.

1RM Bench Press.

The 1RM strength of the participants were obtained for a free-weight bench press according to the methods described by (Kraemer et al., 1995). Two warm-up sets of 2–5 repetitions at approximately 50% and 80% of perceived 1RM were performed, separated by a 1-minute rest interval. Finally, 3–4 attempts at 1RM, separated by 3–5-min rest intervals.

Jump Height.

Jump height was measured using a Vertec vertical jump tester (Sports Imports, Hilliard, OH). Standing reach was determined while each participant stood flat-footed, reaching maximally with the dominant hand. Then five trials were performed and the highest vertical jump height (difference between total jump height and standing reach) were recorded.

Racquet Velocity.

Racquet velocities were evaluated using a tennis (Delsys Trigno Wireless System) wireless accelerometer/gyroscope amalgamated apparatus. The accelerometer/gyroscope is mounted inside a rugged polymer measuring 35mm by 23mm by 11mm and weighing 6g in total. It assays data at a rate of 1 kHz and is connected by Bluetooth to a computer with its corresponding proprietary software. The accelerometer was mounted at the base of the racquet (Yonex USA, Torrance, CA), for all participants.

The racquet was customized (string and grip) and blinded (blacked-out graphics) to reduce racquet bias, which is common in tennis players. The racquet was comprised of high modulus graphite and titanium amalgam, weighed 350g, with a standardized grip circumference, 690mm in length, 581cm^2 head size, and 1.2mm (18 gauge) string circumference (Topspin, Hürth, Germany) strung at 26.4kg (259N) tension in a 16 X 18 pattern.

Racquet Velocity on court.

The racquet velocity measurement protocol was explained again to the participants, highlighting the presence of the accelerometer, attached to the base of the blinded racquet. They were also told that the racquet would feel different from their regular racquet and deliberately so for all participants, because the racquet is an apparatus in an experiment. The unfamiliar grip circumference, calculated by taking the average circumference for all the participants was also explained. They were specifically told that, "This is a maximal tennis serve test. Serve as fast and as hard as you can to the service box on the opposite side of the net. Only the serves that go in the box will be counted." The participants underwent 5 minutes of the regular pre-match warm-up protocol as stated by the International Tennis Federation. This included tennis-specific activities that activate the appropriate muscles, stimulate the neural pathways, and enhance appropriate motor unit activation for the serve. For example, practicing "dummy strokes" with the correct footwork, with or without the racquet, on the court, gradually increasing the intensity. Line judges were present on all sides of the court to indicate whether the serves were in or out. Racquet velocities were recorded for the serve on a tennis court in accordance with prior research (Chow et al., 2009; Elliott, Marsh, & Blanksby, 1986; Elliott, Marshall, & Noffal, 1995; Kraemer et al., 2003; Kraemer et al., 1995). This included three successful maximal effort trials; the peak velocities were recorded for analysis.

Data acquisition and Statistical Analysis.

The proprietary software that was bundled with the accelerometer was used for data acquisition. The equipment was connected on court to the electricity mains and the accelerometers were connected to the antenna box by Bluetooth. The accelerometers were calibrated (for the x, y, and z directions) then affixed to the base of the handle of the tennis racquet without adding any significant mass to the racquet. The data were collected as described above and the resulting file was opened in a spreadsheet for graphing.

Graphing the data in a spreadsheet showed a clipping of the accelerometer data at the maxima. A fraction (about one-hundredths of a second) of the G-forces generated by the racquet were outside the range of the accelerometer. This phenomenon was not apparent during pilot testing. The previous prototype was built to prevent this by adding mass to the middle of the racquet, making it 700 grams but it was eventually reduced to its current mass to remove any possibility of shoulder injury to the participants.

To calculate the missing data, three proven mathematical techniques (conic sections, matrices, and differential calculus) were combined and applied to calculate the missing data (maximal racquet head velocity and its derivatives). Given that the racquet was moving in a parabolic path, an equation can be written for its displacement, velocity, and acceleration vectors using three points on the curve. Each point was resolved into a second-degree polynomial equation. These equations were combined into a 4 X 3 matrix and solved using an augmented matrix method. The resulting equation was written in standard completing the square form to disclose the required maxima. The data were split into three groups based on the experience of the participants; beginner, intermediate, and advanced.

Descriptive statistical analyses were executed using Pearson product-moment coefficient. Statistical power was ascertained for the sample size based on Kraemer et al., (2003). This meant that a sample size of thirty participants would be adequate. Significance in this study was defined as $p \leq 0.05$.

Results

Thirty-three men initially responded whereas 27 men completed the entire study. Six participants completed the first session in the laboratory but were absent for the second session. Table 1 provides basic descriptives for all participants who completed both sessions.

The sample pool were relatively healthy. Their combined experience (mean ± SD) was 8 ± 4 years and they were grouped according to their experience (Beginner (2-5 years), n = 10; Intermediate (6-11 years), n = 9; Advanced (12+ years), n = 8). Five of the participants in the advanced group were National Collegiate Athletic Association (NCAA) tennis players at Appalachian State University. All participants met the selection criteria for tennis experience, some having as much as eighteen years of playing experience. Tennis experience was a self-reported variable. Another variable called the NTRP (National Tennis Rating Program), an objective alternative to the self-report, based on the ratio between matches won and lost, was collected. However, very few of the participants reported an NTRP rating because they forgot or never registered for the program. There was one participant with a disproportionately high racquet velocity score and a disproportionately low 1RM squat that was excluded as an outlier.

Contrary to a priori hypothesis, racquet head velocity for the advanced players was similar to the intermediates and beginners (Beginner: 13.85 ± 1.09 ms^{-1}; Intermediate: 14.5 ± 2.19 ms^{-1}; Advanced: 14.74 ± 1.76 ms^{-1}). The rate of change of racquet acceleration was significantly higher in advanced players compared to intermediates or beginners (Beginner: 1248.76 ± 228.73 ms^{-3}; Intermediate: 1199.2 ± 215.13 ms^{-3}; Advanced: 1539.39 ± 213.12 ms^{-3}). There were no significant differences between any of the groups in squat or bench press 1RM (data).

Pearson product moment correlation indicated no significant correlation between squat or bench press 1RM and racquet head velocity (r = 0.18; r = 0.097, respectively); (Table 2).

Similar results were also observed between squat or bench press 1RM and rate of change of racquet acceleration (r = -0.104; r = -0.064, respectively) (Table 2). However, the only significant correlation was between the rate of change of racquet acceleration and tennis experience (r = 0.546, p=0.004).

Descriptives: Mean ± SD (N=26 if not otherwise noted)			
	Beginner	Intermediate	Advanced
	(N=9)	(N=9)	(N=8)
Tennis Experience (years)	4 ± 1	8 ± 2	14 ± 3
Body Mass (kg)	76.9 ± 13.6	78.6 ± 21	77.2 ± 6.9
Height (m)	1.78 ± 0.74	1.78 ± 0.96	1.81 ± 0.61

Table 1. Physical characteristics of male college-age tennis players.

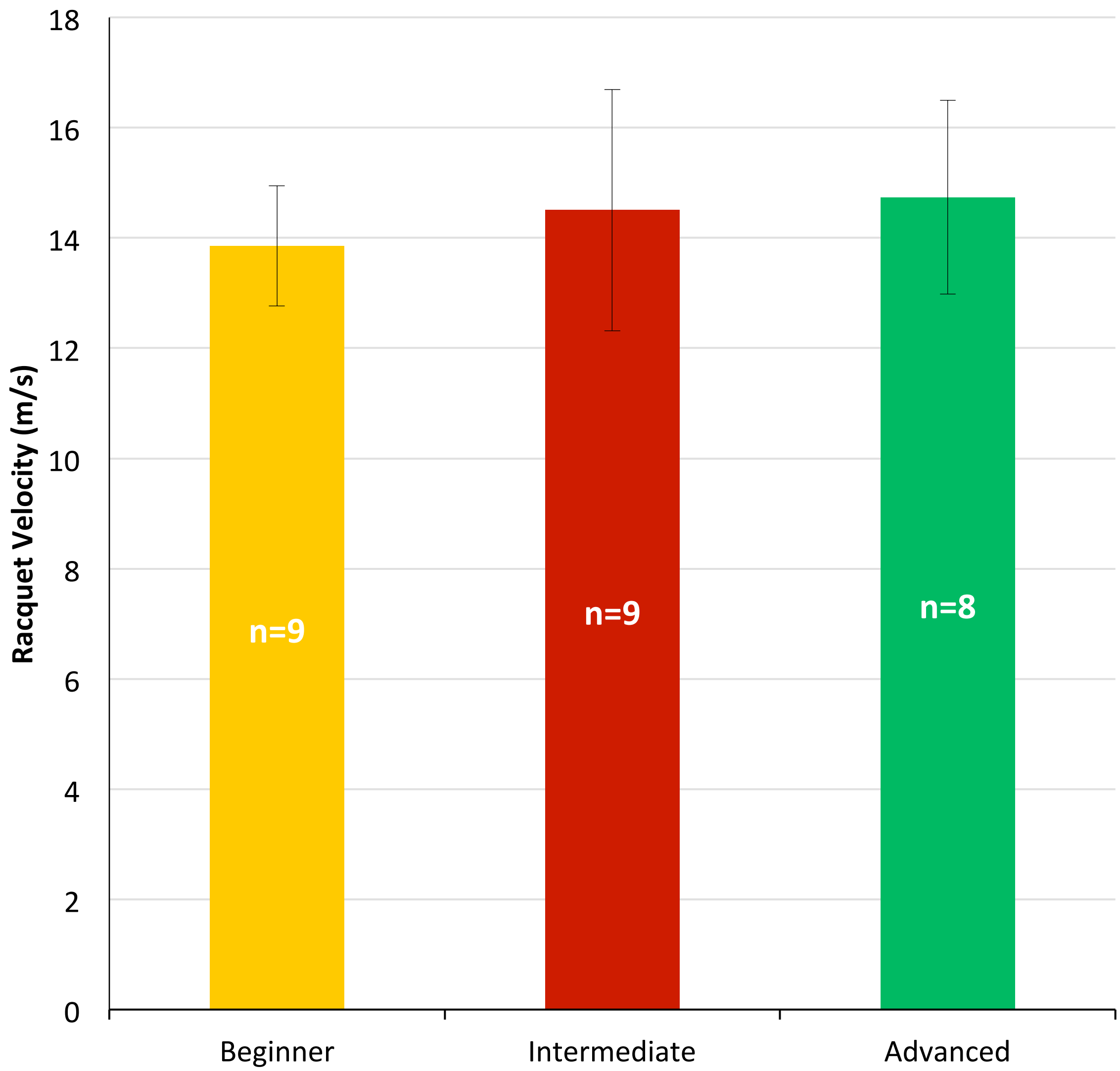

Figure 1. Resultant velocity values for male college-age tennis players.

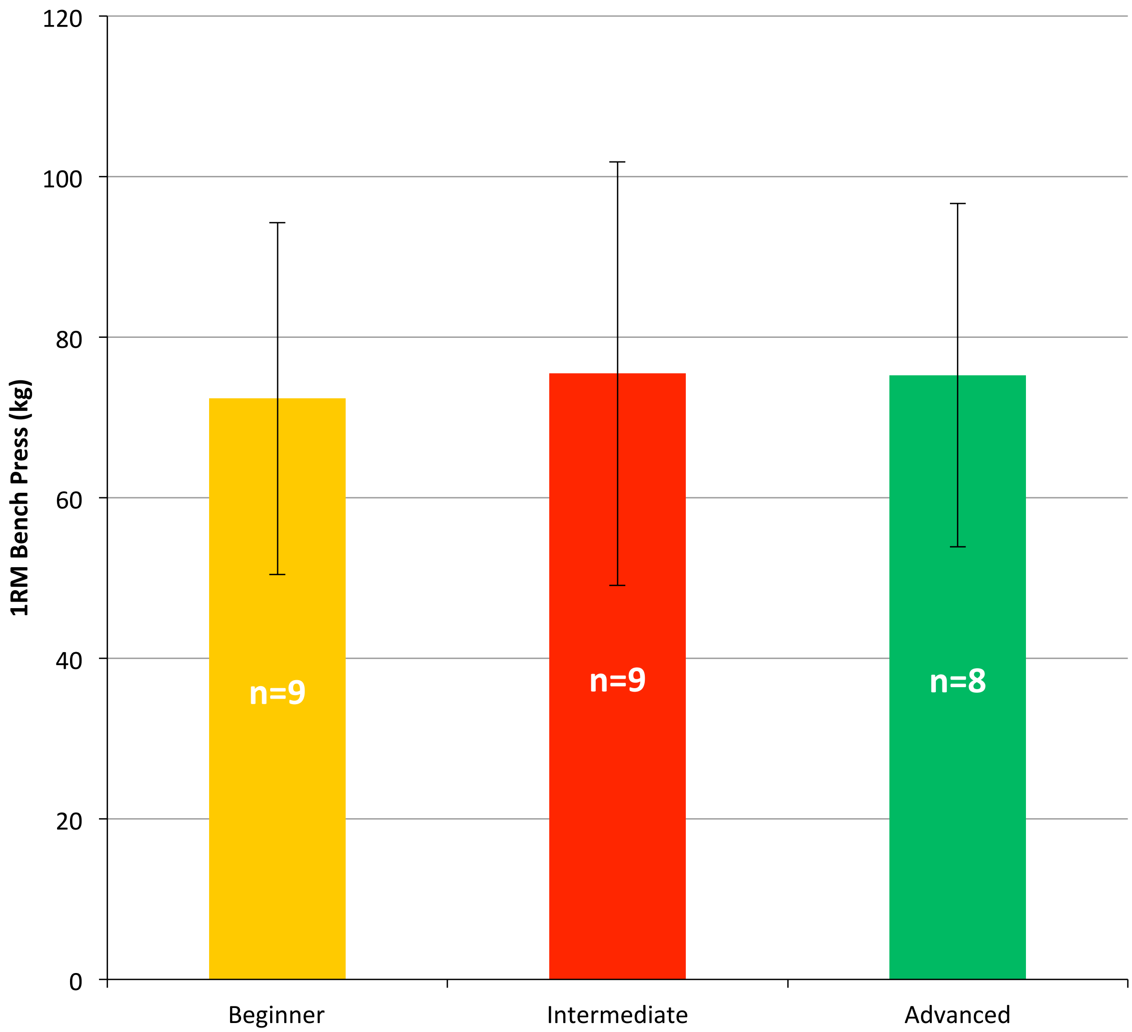

Figure 2. 1RM Bench press values for male college-age tennis players.

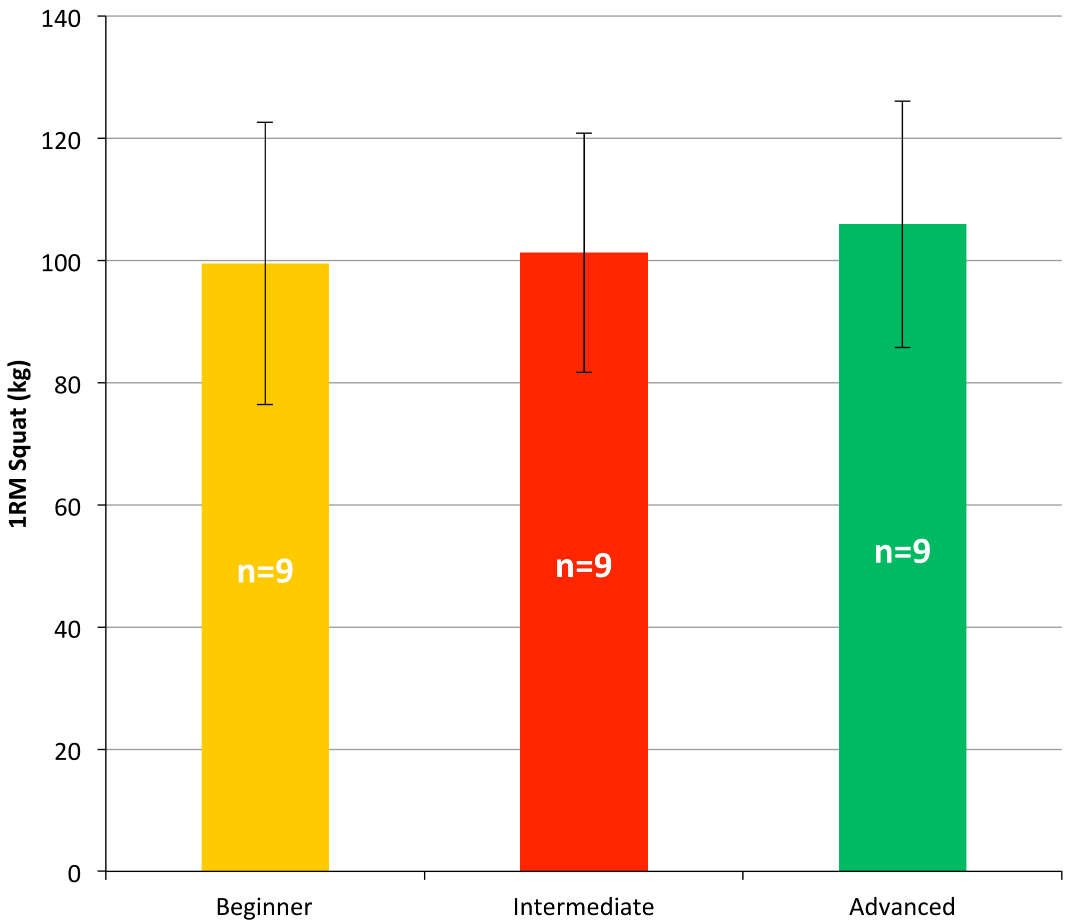

Figure 3. 1RM Squat values for male college-age tennis players.

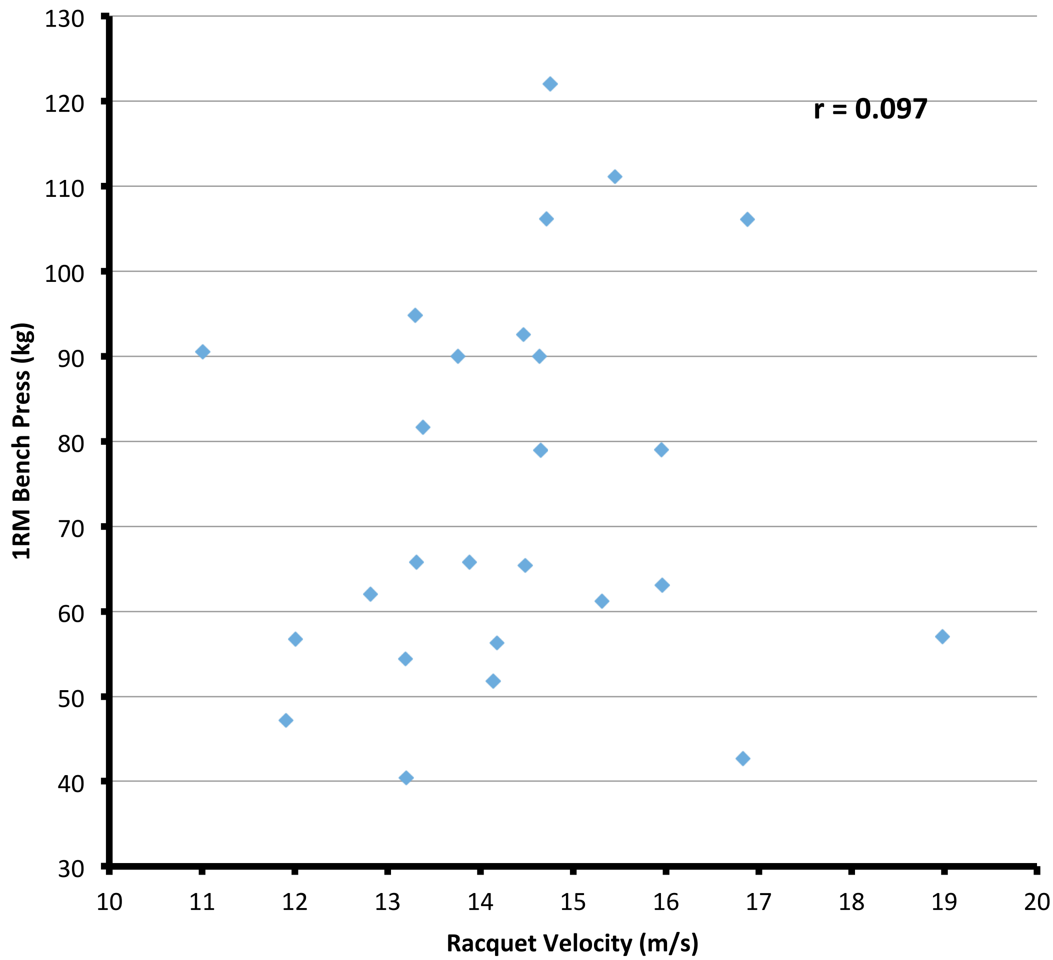

Figure 4. Correlation between 1RM Bench Press and Racquet Velocity for male college-age tennis players.

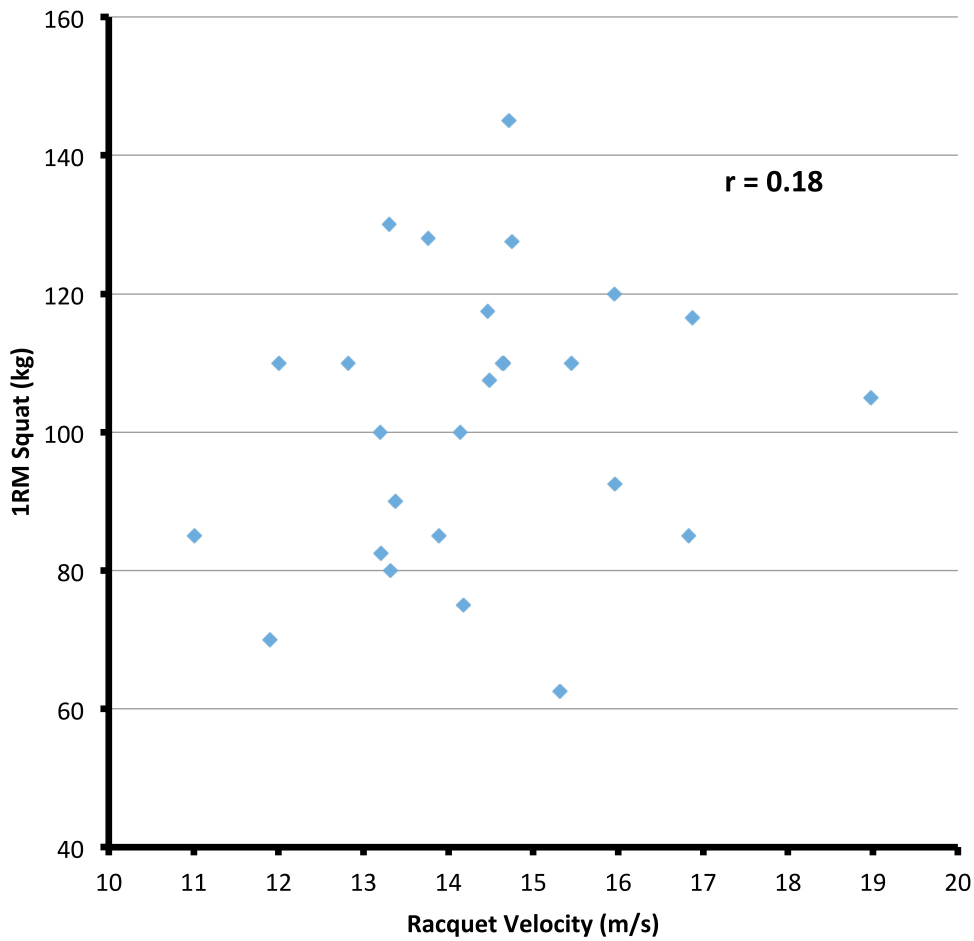

Figure 5. Correlation between 1RM Squat and Racquet Velocity for male college-age tennis players.

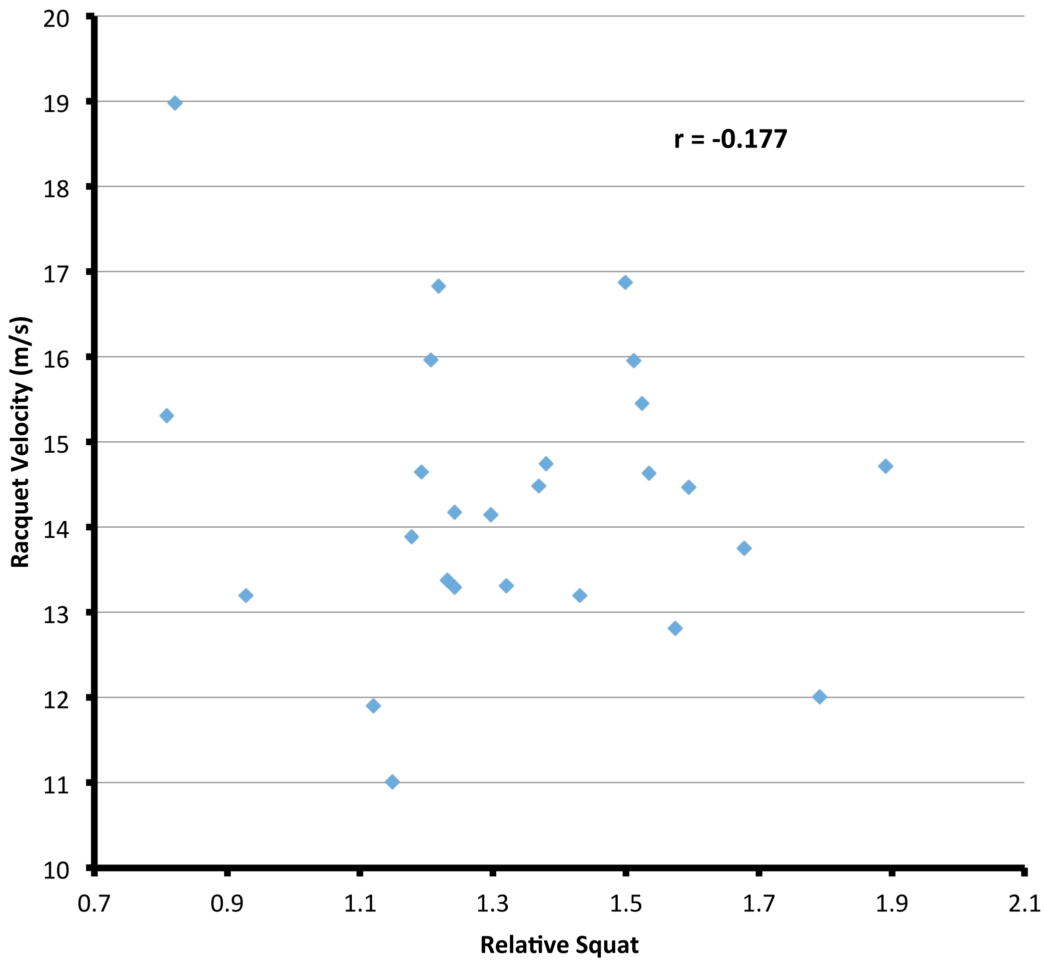

Figure 6. Correlation between Relative Squat and Racquet Velocity for male college-age tennis players.

Three participants with a relative squat score of less than 1 were identified. These were probably a result of limited weightlifting experience, incongruent with actual tennis experience. Data from an isometric squat performed on a force plate could also be used but it was beyond the scope of this study.

Chapter 3: Discussion

While recent tennis accelerometry projects have yielded a myriad of methods for measuring racquet kinematics, their methods remain unclear and the software, proprietary. Many of these methods and data are patented, given their importance to the business model of their respective manufacturers. In this study, we explored the profile of the tri-axial accelerometer, built into a tennis racquet to form an ergometer. Previous work in the Neuromuscular & Biomechanics Laboratory at Appalachian State University, provided the groundwork for the project.

The kinetic chain has been found to be pivotal in all vertebrates for the transfer of forces from one cardinal end of the musculoskeletal system to the other (Kibler, 1995).

The main finding of this study was that racquet head velocities between male tennis players at the amateur level are similar, although the advanced players exhibited a higher rate of change of racquet acceleration. It appears that the higher rate of change in racquet acceleration cannot be attributed to increased leg or upper body strength. Girard, Micallef, & Millet (2005) found that despite elite tennis players exhibiting improved vertical forces and lower extremity co-ordination, compared to beginners and intermediates, the P_{max} (maximum power) value on countermovement jumps were similar. Thus advanced players in this study may have exhibited higher rates of acceleration of the racquet, possibly as a product of better kinetic chain sequencing.

The Pearson-product indicated the correlation ($r = 0.55$, $r^2 = 0.30$) between tennis experience and the rate of change of racquet acceleration (jerk) suggesting that the advanced players are marginally better at transmuting ground reaction forces, through the lower and upper body, into racquet acceleration, compared to their less experienced counterparts. While most results suggested a small and insignificant correlation, a number of studies suggested significant improvements in ball velocity after periodized training (Alvarez et al., 2012;

Hermassi et al., 2011; Kraemer et al., 2003; Parchmann & McBride, 2011; Schache et al., 2011; Sleivert & Taingahue, 2004; Wells, Elmi, & Thomas, 2009; West et al., 2011; Wisloff et al., 2004).

The interrelation between 1RM squat/relative 1RM squat (lower body strength) and racquet head kinematics was based on plausible longitudinal and cross-sectional evidence, suggesting significant improvements in post-training performance and strong 1RM: performance correlation (Alvarez et al., 2012; McBride, Triplett-McBride, Davie, & Newton, 2002; Schache et al., 2011). Unfortunately, the main limitation of this study is that an eighteen-year variance in tennis experience did not necessarily mean a comparable variance in lower body strength values.

The interrelation between 1RM bench/relative 1RM bench (upper body strength) and racquet head velocity in tennis was included in this study to investigate how strongly the upper body musculature featured in the kinetic chain. Kibler (1995) suggested the strong influence of localized deep musculature in the shoulder (13%), elbow (21%) and wrist (15%). The Pearson product correlation from our results ($r = 0.097$) is in agreement.

The interrelation between vertical jump height and racquet head kinematics in tennis should be a product of improved kinetic chain, stretch-shortening cycle and lower body strength in the advanced players compared to the intermediates and the beginners. In a review by Kibler (2005), 54% of the kinetic energy on serve was reported to be from the trunk/leg. Girard et al. (2005) also reported a definitive use of ground reaction forces, on a force plate, in elite layers compared to the others. Rigorous inclusion/exclusion criteria in this study with respect to relative 1RM strength could have yielded results congruent with the above studies.

The interrelation between upper/lower body strength and racquet head velocity in tennis should inform the design of training programs involving the metamorphosis of strength gains into genuine performance gains. This is important for athletes translating from amateur to professional tennis. The ability to consistently generate maximal racquet head velocity efficiently is essential for long rallies, games, matches, seasons, and sustainable success in professional tennis.

In conclusion, the existence of a definitive relationship between general measures of upper/lower body strength and serve velocity, is currently unclear. The inclusion/exclusion criteria were based on previous studies that showed a significant increase in ball velocity after improvements in 1RM following periodized training in advanced players (Kraemer et al., 2003). Future studies, especially a training study, could improve the exclusion criteria using relative 1RM, thus giving a better statistical distribution of strength in the participants. As the study of tennis ball kinematics transitions into racquet kinematics, further studies could also investigate the effect of periodized training on racquet velocity and strength using the accelerometry methods in this study. The limitation of accelerometry is its data plenitude, which exposes research design to validity problems. More sophisticated mathematical and computational methods are needed for future analysis to draw clear conclusions that translate to practical application, particularly in the analysis of kinematic jerk, a relatively unknown variable in accelerometry.

REFERENCES

Alvarez, M. A. R. Í. A., Sedano, S., Cuadrado, G., & Redondo, J. C. (2012). Effects of an 18-week strength training program on low-handicap golfers' performance. *The Journal of Strength & Conditioning Research*, *26*(4), 1110-1121.

Chow, J. W., Park, S. A., & Tillman, M. D. (2009). Lower trunk kinematics and muscle activity during different types of tennis serves. *BMC Sports Science, Medicine and Rehabilitation*, *1*(1), 24.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2007). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of applied biomechanics*, *23*(2), 103.

Doan, B. K., Newton, R. U., Kwon, Y. H., & Kraemer, W. J. (2006). Effects of physical conditioning on intercollegiate golfer performance. *J Strength Cond Res, 20*(1), 62-72. doi: 10.1519/r-17725.1

Elliott, B., Marsh, T., & Blanksby, B. (1986). A three-dimensional cinematographic analysis of the tennis serve. *International Journal of Sport Biomechanics*, *2*(4), 260-271.

Elliott, B. C., Marshall, R. N., & Noffal, G. J. (1995). Contributions of upper limb segment rotations during the power serve in tennis. *Journal of Applied Biomechanics*, *11*, 433-442.

International Tennis Federation. (2014). *Warming up*. Retrieved from http://www.itftennis.com/scienceandmedicine/injury-clinic/injury-prevention/warming-up

Girard, O. L. I. V. I. E. R., Micallef, J. P., & Millet, G. P. (2005). Lower-limb activity during the power serve in tennis: effects of performance level. *Med Sci Sports Exerc*, *37*(6), 1021-1029.

Gordon, B. S., Moir, G. L., Davis, S. E., Witmer, C. A., & Cummings, D. M. (2009). An investigation into the relationship of flexibility, power, and strength to club head speed in male golfers. *J Strength Cond Res, 23*(5), 1606-1610. doi: 10.1519/JSC.0b013e3181a3c39d

Hermassi, S., Chelly, M. S., Tabka, Z., Shephard, R. J., & Chamari, K. (2011). Effects of 8-week in-season upper and lower limb heavy resistance training on the peak power, throwing velocity, and sprint performance of elite male handball players. *The Journal of Strength & Conditioning Research*, *25*(9), 2424-2433.

Hoffman, J. R., Vazquez, J., Pichardo, N., & Tenenbaum, G. (2009). Anthropometric and performance comparisons in professional baseball players. *The Journal of Strength & Conditioning Research*, *23*(8), 2173-2178.

Kibler, W. B. (1995). Biomechanical analysis of the shoulder during tennis activities. *Clinics in sports medicine, 14*(1), 79-85.

Kibler, W. B. (2009). The 4000-watt Tennis Player: Power Development for Tennis. *Medicine & Science in Tennis*, *14*, 5-8.

Kraemer, W. J., Hakkinen, K., Triplett-McBride, N. T., Fry, A. C., Koziris, L. P., Ratamess, N. A., ... Knuttgen, H. G. (2003). Physiological changes with periodized resistance training in women tennis players. *Medicine and science in sports and exercise*, *35*(1), 157-168.

Kraemer, W. J., Triplett, N. T., Fry, A. C., Koziris, L. P., Bauer, J. E., Lynch, J. M., . . . Knuttgen, H. G. (1995). An in-depth sports medicine profile of women college tennis players. *Journal of Sport Rehabilitation, 4*(2), 79-98.

Lawton, M. T. W., Cronin, J. B., & McGuigan, M. R. (2011). Strength testing and training of rowers. *Sports Medicine*, *41*(5), 413-432.

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (2002). The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed. *The Journal of Strength & Conditioning Research*, *16*(1), 75-82.

McBride, J. M., Blow, D., Kirby, T. J., Haines, T. L., Dayne, A. M., & Triplett, N. T. (2009). Relationship between maximal squat strength and five, ten, and forty yard sprint times. *The Journal of Strength & Conditioning Research*, *23*(6), 1633-1636.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2010). Relationship between strength, power, speed, and change of direction performance of female softball players. *The Journal of Strength & Conditioning Research*, *24*(4), 885-895.

Parchmann, C. J., & McBride, J. M. (2011). Relationship between functional movement screen and athletic performance. *J Strength Cond Res, 25*(12), 3378-3384. doi: 10.1519/JSC.0b013e318238e916

Reid, M., Elliott, B., & Alderson, J. (2007). Shoulder joint loading in the high performance flat and kick tennis serves. *British Journal of Sports Medicine*, *41*(12), 884-889.

Reid, M., Elliott, B., & Alderson, J. (2008). Lower-limb coordination and shoulder joint mechanics in the tennis serve. *Medicine+ Science in Sports+ Exercise*, *40*(2), 308.

Reid, M., Whiteside, D., & Elliott, B. (2011). Serving to different locations: Set-up, toss, and racket kinematics of the professional tennis serve. *Sports Biomech, 10*(4), 407-414.

Schache, A. G., Blanch, P. D., Dorn, T. W., Brown, N. A., Rosemond, D., & Pandy, M. G. (2011). Effect of running speed on lower limb joint kinetics. *Med Sci Sports Exerc*, *43*(7), 1260-1271.

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European journal of applied physiology*, *91*(1), 46-52.

Wells, G. D., Elmi, M., & Thomas, S. (2009). Physiological correlates of golf performance. *The Journal of Strength & Conditioning Research*, *23*(3), 741-750.

West, D. J., Owen, N. J., Cunningham, D. J., Cook, C. J., & Kilduff, L. P. (2011). Strength and power predictors of swimming starts in international sprint swimmers. *The Journal of Strength & Conditioning Research*, *25*(4), 950-955.

Winchester, J. B., Erickson, T. M., Blaak, J. B., & McBride, J. M. (2005). Changes in bar-path kinematics and kinetics after power-clean training. *J Strength Cond Res, 19*(1), 177-183. doi: 10.1519/14023.1

Wisloff, U., Castagna, C., Helgerud, J., Jones, R., & Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine, 38*(3), 285-288.

APPENDICES

APPENDIX A

Consent to Participate in Research

Information to Consider About this Research

Relationship Between Squat Strength and Racquet Head Velocity in Tennis.

Principal Investigator: Dr. Jeffrey. M. McBride

Department: Health, Leisure, and Exercise Science

Contact Information: (828) 202-3937 mcbridejm@appstate.edu

Lead Graduate Student: Olumide O. Awelewa

What is the purpose of this research?

Racquet velocity and ball velocity are the two main factors that are associated with improved tennis performance. Previous research shows that resistance training can result in the improvement ofthese factors. Increases in 1 repetitive maximum(1RM) squat strength correlates to increases in sport-specific performance such as ball velocity in tennis and club velocity in golf and baseball. The purpose of this study is to determine the relationship between squat strength and racquet head velocity in tennis players. The study investigators intend to publish these results in a peer-reviewed scientific journal in hopes that the information will lead to further research and ultimately help tennis players improve their training and performance.

Why am I being invited to take part in this research?

You are being asked to participate in this research study because:

- you are a male tennis player rated 3.5 or more according to the United States Tennis Association. This usually means at least 2 years of playing experience.
- you are aged 18-25 years old
- youare one of approximately 30 healthy volunteers
- you have not had an orthopedic (joint) surgery or injury within the last year

What will I be asked to do?

The Appalachian State University's Institutional Review Board (Jeffrey M. McBride et al.) has approved all study procedures. We will thoroughly explain all study procedures (below) to you, but at any time, please feel free to ask any of the study personnel any questions you may have. Briefly, your participation in this research study will include 3 sessions, a consent session and two testing sessions, each lasting approximately 2 hours. The first (consent) and second (test) session will take place at the Neuromuscular Biomechanics laboratory. The third and last session were on the tennis courts on Rivers Street at Appalachian State University, Boone, North Carolina.

In an individual face-to-face meeting with a member of our research team, you were asked to sign this informed consent document and to complete a brief survey (the Appalachian ACSM/AHA) to assess your functional health, well-being, and to ensure that you are able to perform exercise safely. Next you will complete a series of physical function tests to assess your:

- Racquet velocity
- 1 repetitive maximum (1RM) back squat strength
- 1 repetitive maximum (1RM) bench press
- Countermovement jump height

You are allowed to play on court at your leisure as usual except 48 hours prior to testing.Experienced and certified strength and conditioning specialists will individually supervise you during the tests to fulfill all test protocols.You will need to hold back from performing strenuous resistance training for 48 hours before the testing session.

The tests include:

- Height and Body mass measurement.

- *Racquet Velocity* – Racquet velocities were recorded for the serve on the tennis courts at Appalachian State University. You will undergo a standardized warm up by taking several "dummy strokes" with the correct footwork, with or without a racket, on the court, gradually increasing the intensity until you are comfortable with the test racquet (Yonex USA, Torrance, CA). Data were recorded asyouserve with the same brand, ITF (Federation) regulation sized balls, successfully into the opposite service box. Three trial shots werecollected for data and the maximum velocity were recorded for analysis.

- *1RM Squat* –The one repetition maximum in the back squat (1RM) will include a warm-up of 4-6 repetitions at 30% of your estimated 1RM, 3-4 repetitions at 50% 1RM, 2-3 repetitions at 70% 1RM and 1 repetitions at 90% of 1RM. You will then have up to 4 attempts to reach a true 1RM. The load prescription will depend on the research assistant's recommendation. Youweregin the squat by standing with your feet shoulder width apart, barbell positioned on your upper back. You will squat down to 80 degrees as determined by the researchers, then return to the standing position. Rest periods of 5 minutes were given between all sets. All exercises were performed with either body weight alone or a barbell and weight plates while standing on a SS Performance weightlifting platform.

- *1RM Bench Press.* Your 1RM strength were obtained for a free-weight bench press according to the methods described by previous research. Two warm-up sets of 2–5 repetitions at approximately 50 and 80% of perceived 1RM were performed separated by a 1-minute rest interval. Then, three-to-four attempts separated by 3-to 5-min rest intervals were performed until a 1RM is attained. The same investigator will judge all tests until successful 1RM attempts, including complete range of motion of the exercise are attained.

- *Jump Height.* Jump height were measured using a Vertec vertical jump tester (Sports Imports, Hilliard, OH). Standing reach were determined while you stand flat-footed, reaching up maximally with the dominant hand. Three trials were performed and the highest vertical jump height (difference between total jump height and standing reach) were recorded.

What are possible harms or discomforts that I might experience during the research?

Injury potential with the racquet velocity test, bench press, jump height and back squat is no more than that of any other type of cardiovascular/resistance training exercise or other general type of exercise; which includes muscle strains or pulls. While resistance exercise and tennis training is relatively safe even for elderly individuals, there are some risks associated with any exercise activity. To the best of our knowledge, the risk of harm and discomfort from participating in this research study is no more than you would experience in everyday life. While these risks are minimal, you may experience dizziness and lightheadedness while performing or following the exercise. These symptoms should subside within 2-3 minutes. For your safety and to help minimize these risks, youwere monitored and supervised by trained and certified research personnel at all times. You may also feel tired immediately after or experience muscle soreness the days following the resistance exercise testing sessions. These symptoms should resolve without any intervention.

What are possible benefits of this research?

You will learn how to maximize your current training techniques/programs for goals specific to tennis performance. You will also gain a better understanding of the Forehand, Backhand and serve strokes of your game.

What are possible societal benefits of this research?

By participating in this research, it could increase the readily available knowledge base on tennis; inspire future scientists who are tennis enthusiasts to build on this knowledge base using advanced research techniques and technology. Ultimately, to dispel false anecdotal information about the game of tennis and other sports involving the use of ground reaction forces.

Will I be paid for taking part in the research?

You will not be paid for the time you volunteer while being in this research study.

What if I get sick or hurt while participating in this research study?

In the rare event of an injury during functional testing, standard emergency procedures were followed. The Campus Health Centeris located within a few minutes. If you need emergency care while you are performing procedures involved in the research study, it were provided to you. If you get hurt or sick when you are not performing procedures involved in the research study, you should call your doctor or call 911 in an emergency. If your illness or injury could be related to the research, tell the doctors or emergency room staff about the research study, the name of the Principal Investigator, and provide a copy of this consent form if possible. Call the Principal Investigator, Dr. Jeffrey. M. McBride, at (828) 202-3937 as soon as you can because we need to know that you are hurt or ill.

There are procedures in place to help attend to your injuries or provide care for you. Costs associated with this care were billed in the ordinary manner, to you or your insurance company. However, insurance companies, Medicare, and Medicaid may not pay bills that are related to research costs. You should check with your insurance about this and talk to the Principal Investigator if you have concerns.

How will you keep my private information confidential?

Your information were combined with information from other people taking part in the study. When we write up the study to share it with other researchers, we will write about the combined information. You will not be identified in any published or presented materials. Only the research personnel associated with this study, including the Principal Investigator, study coordinator, research assistants, and all other research staff, will have access to information that can identify you as a participant. Your identity and the personal information we collect about you were kept strictly confidential.

Information on subjects were kept in the Neuromuscular and Biomechanics Laboratory, which has limited public access. In addition, all identifying information were kept in the Neuromuscular and Biomechanics Laboratory in a locked filing cabinet, and informed consent were kept in a locked filing cabinet in a separate location from the data. All computers containing subject information are also password protected. No persons not associated with the study will have access to any subject information. The data were kept for 3 years.

Photography and Video Recording Authorization

With your permission, still pictures/video recordings taken during the study may be used in research presentations of the findings of the study. Please indicate whether or not you agree to havingstill pictures/video recordings used in research presentations by reviewing the authorization below and signing if you agree.

Authorization

I hereby release discharge, and agree to save harmless Appalachian State University, its successors, assigns, officers, employees or agents, any person(s) or corporations (s) for whom it might be acting, and any firm publishing and/or distributing any photograph or video footage produced as part of this research, in whole or in part, as a finished product from and against any liability as a result of any distortion, blurring, alteration, visual or auditory illusion, or use in composite form, either intentionally or otherwise, that may occur or be produced in the recording, processing, reproduction, publication or distribution of any photograph, videotape, or interview, even should the same subject me to ridicule, scandal, reproach, scorn or indignity. I hereby agree that the photographs and video footage may be used under the conditions stated herein without blurring my identifying characteristics.

Participant's Name (PRINT) Signature Date

Whom can I contact if I have a question?

The people conducting this study were available to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator, Jeffrey M. McBride, at (828) 202-3937 or mcbridejm@appstate.edu. If you have questions about your rights as someone taking part in research, contact the Appalachian Institutional Review Board Administrator at 828-262-2130 (days), through email at irb@appstate.edu or at Appalachian State University, Office of Research and Sponsored Programs, IRB Administrator, Boone, NC 28608.

Do I have to participate?

Your participation in this research is completely voluntary. If you choose not to volunteer or withdraw from the study at any time, there were no penalty and you will not lose any benefits or rights you would normally have. If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. There were no penalty and no loss of benefits or rights if you decide at any time to stop participating in the study.
This research project has been approved on 8/19/2014 by the Institutional Review Board (Jeffrey M. McBride et al.) at Appalachian State University. This approval will expire on 8/18/2015 unless the IRB renews the approval of this research.

I have decided I want to take part in this research. What should I do now?

If you have read this form, had the opportunity to ask questions about the research and received satisfactory answers, and want to participate, then sign the consent form and keep a copy for your records.

____

Participant's Name (PRINT) Signature Date

APPENDIX B

ID:

Relationship Between Squat Strength and Racquet Head Velocity in Tennis

<table>
<tr><td colspan="2">Name</td><td colspan="2">M / F

Right or Left Handed</td></tr>
<tr><td colspan="2">Email</td><td>Mobile</td><td>USTA NTRP Rating</td></tr>
<tr><td>DOB</td><td>Age</td><td colspan="2">Preferred Day and Time of testing</td></tr>
<tr><td>Do you play other sports apart from Tennis? Y / N</td><td>Years of Tennis experience</td><td colspan="2">Years of Resistance training experience</td></tr>
</table>

Notes

Anthropometry	
Height (m)	
Body Mass (kg)	
Grip Circumference (m)	

APPENDIX C

ID:

Relationship Between Squat Strength and Racquet Head Velocity in Tennis

Note: The order in which these were performed were randomized.

ID:

ween Squat Strength and Racquet Head Velocity in Tennis

n which these will be performed will be randomized.

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Comments
np						
locity						
						• 2-5 repetitions at 50% of estimated 1RM (______) • 2-5 repetitions at 80% of estimated 1RM (______) • 3-4 attempts at achieving true 1RM
						• Warm up 4-6 repetitions at 30% of estimated 1RM. • 3-4 repetitions at 50% of estimated 1RM (______) • 2-3 repetitions at 70% of estimated 1RM (______) • 1 repetitions at 90% of estimated 1RM (______) • 3-4 attempts at achieving true 1RM

Vita

Olumide Omololu Olawale Awelewa was born in Ondo Town, Ondo State, Nigeria. He has lived in numerous places across 3 continents with his family, from Ondo Town to Akure, Ondo State where his father was a businessman and his mother a midwife. Olumide emigrated with his family to the UK at age 16 and attended The Princess Margaret Royal Free School in Windsor, Berkshire where he was voted Head Boy of the school by students, faculty, and staff. After his undergraduate in Aerospace Engineering at the prestigious Queen Mary College, University of London and Sports Science at Kingston University, London with a study abroad scholarship at Grand Valley State University, Michigan, he moved to the mountains in Boone, North Carolina for graduate school. At Appalachian State University, Olumide began pursuing a Master of Science in Exercise Science (research concentration), completing his research thesis in the spring of 2015. In 2015, he will commence research towards his Doctor of Philosophy at the Universita degli Studi di Roma, Italy. Olumide plans to teach, research, write and mentor students.