Association Between Neuromuscular Characteristics of Agility in Jumping Tasks

Lara Boman

University of South Dakota

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ASSOCIATION BETWEEN NEUROMUSCULAR CHARACTERISTICS OF AGILITY
IN JUMPING TASKS

By

Lara Boman

A Thesis Submitted in Partial Fulfillment
Of the Requirements for the
University Honors Program

Department of Kinesiology and Sport Management
The University of South Dakota

May 2018
The members of the Honors Thesis Committee appointed to examine the thesis of Lara Boman find it satisfactory and recommend that it be accepted.

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ABSTRACT

Association Between Neuromuscular Characteristics of Agility in Jumping Tasks

Lara Boman

Director: Dr. Talin Louder, PhD

This study evaluated the influence of drop height on and the statistical associations between Sheppard & Young’s (2006) three neuromuscular characteristics of agility: reactive strength, concentric strength and power, and bilateral symmetry. Nine NCAA DI women’s volleyball players completed a depth-jumping protocol at three different drop heights. Ground reaction force data was used to calculate the reactive strength index (RSI); peak and average power, peak and average force; and percent differences between the right and left lower limbs in peak and average power and force. Each neuromuscular characteristic was statistically associated with drop height, each of the other two neuromuscular characteristics, and rebound jump height. Linear regressions provided association data. The strongest association was between RSI and rebound jump height. Average force was moderately associated with RSI and weakly associated with rebound jump height. Peak power was weakly associated with RSI. This information could be used by health practitioners to better design training programs that improve vertical agility capabilities in athletes.

Keywords: reactive strength index, depth jump, volleyball
# TABLE OF CONTENTS

List of Figures ...................................................................................................................... v

List of Tables ........................................................................................................................ vi

Acknowledgements ................................................................................................................ vii

Chapter One: Introduction ..................................................................................................... 1

Chapter Two: Methods .......................................................................................................... 7

Chapter Three: Results .......................................................................................................... 15

Chapter Four: Discussion ..................................................................................................... 26

References .............................................................................................................................. 35
LIST OF FIGURES

1: Universal Components of Agility ........................................................................................................ 1
2: Mokka Force Trace .................................................................................................................................... 11
3: Reactive Strength vs. Concentric Strength and Power Linear Regressions................................... 20
4: Concentric Strength and Power vs. Bilateral Symmetry Linear Regressions......................... 22
5: Reactive Strength vs. Bilateral Symmetry Linear Regressions...................................................... 23
6: Neuromuscular Components of Agility vs. Rebound Jump Height Linear Regressions............... 25
LIST OF TABLES

1: Drop Jump Box Height and Initial Velocity......................................................... 13
2: ANOVA Main Effects.............................................................................................. 16
3: ANOVA Post-hoc Comparisons.............................................................................. 17
4: Reactive Strength vs. Concentric Strength and Power Linear Regressions.......... 19
5: Concentric Strength and Power vs. Bilateral Symmetry Linear Regressions....... 21
6: Reactive Strength vs. Bilateral Symmetry Linear Regressions............................ 23
7: Neuromuscular Components vs. Rebound Jump Height Linear Regressions........ 24
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Thank you to Dr. Christina Keller and Dr. Robin Ammon for serving as committee members. I am grateful for the time you sacrificed to meet with me throughout this project. I have also appreciated the guidance and flexibility of Dr. Scott Breuninger over the last four years. Thank you to the members of the USD women’s volleyball team for your enthusiastic participation!

I am thankful to my parents, Steve and Julie Boman, for always encouraging me to work hard, do my best and pursue what brings me joy. Thank you to A.G. Kruger III for the gifts of time and change, which have carried over to a lot more than just throwing.
Agility in sport has previously lacked a clear definition. This is problematic considering that agility is believed to influence many different movements including straight sprinting, sprinting with changes of direction, and various forms of jumping (Young, James & Montgomery, 2002). Sheppard and Young (2006) defined agility as “a rapid whole body movement with change of velocity or direction in response to a stimulus” (p. 919). Sheppard and Young (2006) also proposed that agility is influenced by two components: physical and neurocognitive (Figure 1). Within the physical component, leg muscle qualities include three neuromuscular characteristics: reactive strength, concentric strength and power, and bilateral symmetry. All three neuromuscular characteristics play important roles in agility.

Figure 1. Universal components of agility modified from Young, et al., 2002 (Sheppard & Young, 2006, p. 921).
Reactive strength takes into account how the athlete’s body absorbs force, with elastic properties and neuroreflexive pathways allowing muscle to produce greater force in response to impact. The stretch-shortening cycle (SSC) plays a vital role in the process of absorbing and redirecting force. Muscles lengthen eccentrically upon absorption of force (e.g. landing from a jump or planting to change direction), and energy is absorbed and stored elastically. Energy can then be released during contraction to produce a more powerful takeoff (Flanagan & Comyns, 2008). Jump landing impacts can activate the Golgi Tendon Organ (GTO), a protective neuromuscular mechanism, or the muscle spindle reflex, which is believed to enhance muscle performance in SSC movements. The GTO responds to increased muscle tension, or stress, by reducing tension in the agonist muscle while potentiating tension in the antagonist. On the other hand, the muscle spindles respond to increased magnitude and rate of muscle strain by increasing tension and contraction in the agonist muscle. This allows muscle to produce greater force in response to impact (Flanagan & Comyns, 2008). The magnitude of the effect of the GTO vs. muscle spindles influences the reactive capabilities of athletes.

The reactive strength index (RSI) is the most commonly utilized assessment of reactive strength (Louder, 2017), and was originally developed to measure explosiveness in athletes. The RSI is computed as the ratio between jump height and ground contact time in a drop jump to determine how effectively an athlete is able to utilize absorbed force to quickly produce a powerful action. The depth jump is the most commonly utilized movement skill for assessing RSI. Performing a depth jump requires an athlete to step off a plyometric box, impact the ground with the
feet (or foot), and perform an immediate maximal effort vertical rebound jump. Higher rebound jump heights and lower ground contact times are proportional with higher RSI scores. An athlete who possesses good neuromuscular reactivity is able to absorb the energy of an impact quickly and then direct energy into an explosive, maximal effort rebound jump. This ability carries over into sport where agile movements that require quick and powerful reactions to external stimuli can influence success (Sheppard & Young, 2006).

Strength is defined as the maximum amount of active and passive force production capacity for any given muscle contraction velocity. Strength is the foundation of power - maximizing force production at various contraction velocities (eccentric, isometric, concentric) increases the power output of muscle tissue. Concentric strength is a measure of the contractile force a muscle produces, while concentric power is the product of contractile force and the velocity of muscle contraction. Each of these quantifies the ability of an athlete to create motion of their body or objects in the environment with varying force and speed. The more concentric strength and power an athlete possesses, the more effectively they should be able to move their body and change the horizontal and vertical direction of body movement. A powerful athlete can quickly produce the forces necessary to cut and change movement direction, to start and stop movement, or to jump. For instance, prior research has associated increased strength and power levels with low to moderate increases in straight sprint speed and other measures of horizontal agility (Sheppard & Young, 2006).
Bilateral symmetry is a measure of strength and power imbalances between left and right limbs. Injury, intrinsic physical irregularity, training history, or demands of sport can produce performance differences in the capabilities of right and left limbs. Differences in strength and power between the right and left legs have been observed to affect the ability of an individual to change direction of movement horizontally (Young et al., 2002). Additionally, prior research suggests that bilateral asymmetry may influence risk for lower extremity injury in sport (Paterno, Huang, Thomas, Hewett, & Schmitt, 2017). Paterno et al. (2017) showed that low levels of symmetry in plyometric activities predicted future ACL injuries in adolescent athletes. Research has also suggested that bilateral symmetry influences physical functioning in clinical populations (Skelton, Kennedy, & Rutherford, 2002). For example, Skelton et al. (2002) found that older adults with bilateral lower limb power asymmetries had an increased fall risk.

Research has attempted to quantify the contribution of Sheppard and Young's neuromuscular qualities (reactive strength, concentric strength and power, bilateral symmetry) to agility, as measured by a variety of tasks focused on horizontal agility such as straight sprinting and sprinting with varying changes of direction (Young et al., 2002). However, to the author's knowledge, studies have yet to include all three neuromuscular qualities in a single experimental investigation of jumping mechanics or investigate statistical associations between components. Sports such as volleyball, basketball, football, gymnastics, and high jumping in track and field place a high level of importance on vertical jumping, with vertical jump performance often viewed as a reliable predictor of lower extremity muscle power.
Therefore, it is important to understand the applications of agility in the vertical dimension.

This knowledge could potentially help coaches and health care providers to specify agility training for maximizing athletic performance and functional movement ability. An understanding of what components to train to improve vertical agility could allow practitioners to develop effective training programs for athletes' needs. For example, a strength coach may be able to better choose between training methods (e.g. powerlifting vs. Olympic lifting; high reps and low weight vs. low reps and high weight; the addition of single-leg exercises) when designing a training cycle focused on improving vertical agility. In a clinical sense, a physical therapist overseeing an athlete’s return to play could add exercises focusing on key characteristics to rehab to improve vertical agility before return to play. Therefore, the purpose of the present study was to evaluate the influence of drop height on and the statistical associations between Sheppard and Young’s (2006) neuromuscular characteristics of agility.
Hypotheses

It was expected that the strongest associations would be observed for comparisons of reactive strength, peak and average power measurements, and rebound jump height. Previous research has correlated reactive strength with performance in horizontal agility activities such as straight sprint speed and sprint change of direction speed (Young et al., 2002). Also, it was expected that there would be moderate associations between concentric strength and power measures and corresponding bilateral symmetry measurements. Finally, it was expected that the weakest associations would be observed between bilateral symmetry and reactive strength as well as bilateral symmetry and rebound jump height.
CHAPTER TWO

Methods

Subjects

Nine members of a Division I NCAA women’s volleyball team participated in this study (mean (SD); age: 20.0 (1.4) years; height: 1.8 (0.1) m; mass: 77.5 (6.6) kg). At the time of data collection, all athletes were fully cleared by the university’s athletic training staff for participation and were undergoing a uniform spring training protocol that involved up to 20 hours per week of volleyball team training, volleyball skills sessions, and weightlifting. Additionally, participants were excluded from the study if they were not between the ages of 18 and 35, had sustained a lower extremity injury within the prior 12 months, or were otherwise contraindicated from safely completing maximal effort depth jumps.

Prior to participation, participants were provided an informed consent document that was approved by the University Institutional Review board. All participants provided consent through signature prior to participation.

Experimental Design

A cross-sectional experimental design addressed the purpose(s) of the present investigation.

Procedures

Participants were asked to attend a single data collection, lasting approximately one hour. Prior to testing, each participant performed a standard, team-specific warm-up that included a series of dynamic stretches focusing on hip mobility. Prior to data collection, participants were affixed with 10 wireless
electromyography sensors and 20 infrared reflective markers. Following the placement of markers, participants were asked to perform 30 total Maximal Voluntary Isometric Contractions (MVIC; three trials for each of the following bilateral muscles: gluteus maximus, rectus femoris, biceps femoris, tibialis anterior, and medial gastrocnemius). The MVIC process lasted approximately 15 minutes and involved a moderate amount of isolated muscle exertion. Data corresponding with the electromyography sensors and infrared reflective markers were not used to address the purpose of the present study.

Following the collection of MVIC data, participants were asked to complete a standard depth jumping protocol. Depth jumping is the most commonly used plyometric exercise to evaluate Sheppard and Young's neuromuscular qualities, especially reactive strength (Flanagan & Comyns, 2008). Participants were asked to complete three successful trials of depth jumping at heights of 15 inches (0.3810 m), 21 inches (0.5334 m), and 27 inches (0.6858 m) above the laboratory floor. Heights were chosen by decreasing jump heights used in a previous study of Division I men's basketball players (Louder, 2017) after communication with the volleyball team's strength and conditioning staff. Depth jumps were performed from a plyometric box positioned above and centered in relation to two in-ground tri-axial force platforms (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Order of the three drop heights was randomized, and all jumps at a specific height were performed successively to minimize transition time.

For each trial of depth jumping, participants were asked to step up on the plyometric box and center themselves in a standing position above the force
platforms. Participants were then given the following standard verbal cue: “You will hop forward off the box, land with one foot on each of two adjacent force platforms, and immediately perform a maximal effort vertical jump upwards as quickly as possible.” To maximize the ecological validity of results, arm motion was not restricted during the performance of depth jumping. Participants were allowed about 30 seconds of rest time between trials at each height, and about 60 seconds of rest time between trials at different heights as boxes were adjusted. Additional rest time was not necessary since drop jumping did not fatigue participants.

Participants performed 9-16 total depth jumps. This number varied because of criterion involved in determining a successful trial. A trial was deemed unsuccessful if any infrared markers fell off. In this case, the trial was repeated, which happened 0-7 times per athlete. For this project, only data from the first three jumps at each height were used if any jumps were repeated, since infrared marker malfunctions did not influence jump performance or data obtained via force platforms. Following the completion of the final depth jump, all electromyography sensors and infrared markers were removed, at which point the participant was thanked and dismissed.

Instrumentation

Vertical ground reaction force (GRF) data were acquired using a tri-axial force plate system (Advanced Mechanical Technology, Inc., model # OR6-6-2000, Watertown, MA, USA). The force plate system featured two 46 cm by 50.5 cm force plates positioned side-by-side and recessed to be flush with the laboratory floor. Force plates and optical motion camera system were turned on and calibrated at
least one hour prior to each scheduled data collection. Prior to data collection, the z-component (vertical component) of each force plate was zeroed out to ensure accurate sampling of GRF data.

Force plate data were sampled at a commonly used and acceptable sample rate of 1000 Hz, using a distribution of Nexus 3 software (Vicon, Oxford, UK). Data sampling was initiated manually, following the delivery of verbal instructions to the participant. Data sampling was terminated manually immediately following the completion of each jump to minimize data file sizes. GRF data were filtered in Nexus 3 (Vicon, Oxford, UK) using a 4th order, recursive, low-pass Butterworth filter, with a low-pass cutoff frequency of 100 Hz (Bisseling & Hof, 2006). Participants were assigned identifier numbers and all trials were saved using the identifier number to protect identities. Following processing, GRF data were exported as .c3d files to Motion Kinematic and Kinetic Analyzer (Mokka version 0.6.2, Arnaud Barre) and as .csv files to Microsoft Excel 2010 (Microsoft, Redmond, WA, USA) for analysis.

*Data Analysis*

Reactive strength was assessed using the RSI. For each trial, vertical force time-series traces were imported to Mokka in Chart View (Figure 2). From the vertical force time-series data, ground contact time and flight time were calculated by first identifying the following data points: initial ground contact, rebound jump take-off, and rebound jump landing. Contact and take-off time points were confirmed when the time-series data either started or stopped changing by 10 N between data points (rate of force development = 10,000 N/s; Donoghue, Shimojo, & Takagi, 2011).
Using projectile motion equations of constant acceleration, take-off velocity was estimated from rebound jump flight time (Equation 1). Rebound jump height was then estimated from take-off velocities (Equation 2).

\[
\text{Equation 1)} \quad \text{Take-Off Velocity} = \text{Flight Time} \times 9.81 \times 0.5
\]

\[
\text{Equation 2)} \quad \text{Rebound Jump Height} = (\text{Take-Off Velocity})^2 / 19.62
\]

RSI was calculated as the ratio of rebound jump height to contact time (Equation 3).
Equation 3) $RSI = \frac{Rebound\ Jump\ Height}{Contact\ Time}$

From vertical ground reaction force time-series data, maximal concentric strength was identified as the maximal value for vertical ground reaction force across the entirety of the ground contact phase. Average concentric strength was calculated as the average value for vertical ground reaction force across the entirety of the ground contact phase. Strength values were computed bilaterally and unilaterally for both the dominant and non-dominant legs and normalized to participant bodyweight. Bodyweights were assessed for each participant by taking the average of three seconds of vertical ground reaction force data while the participant was standing static on the platform.

External mechanical power time-series data were constructed using the product of vertical ground reaction force and the vertical velocity of the whole body center of mass (Equation 4). For any time period where the feet are in contact with the ground, the change in velocity of the subject’s center of mass due to ground reaction forces is estimated using finite integration (Equation 5).

Equation 4) $Power = Force \times Velocity$

Equation 5) $\Delta Velocity = \frac{\int_0^T Ft\ dt}{Bodyweight \times (9.81^{-1})}$

Instantaneous velocity of the subject’s center of mass is approximated at any time point where the feet were in contact with the ground by subtracting landing
impact velocity from the result obtained via Equation 5. Landing impact velocities were estimated using projectile motion equations of constant acceleration and the known heights of the plyometric boxes used to perform the depth jumps (Equation 6; Table 1). It is important to note that landing impact velocities are negative since the whole body center of mass moves downward as the participant drops from the box.

\[
\text{Equation 6) } \quad \text{Initial Velocity} = \sqrt{\text{Box Height} \times 19.62}
\]

Table 1

Drop Jump Box Heights and Corresponding Initial Velocities of Participants

<table>
<thead>
<tr>
<th>Box Height</th>
<th>Initial Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3810 m</td>
<td>- 2.734 m/s</td>
</tr>
<tr>
<td>0.5334 m</td>
<td>- 3.235 m/s</td>
</tr>
<tr>
<td>0.6858 m</td>
<td>- 3.668 m/s</td>
</tr>
</tbody>
</table>

From the external mechanical power time-series data, bodyweight-adjusted peak power (W/BW) was identified as the maximal value for power across the entirety of the ground contact phase. From this same data series, bodyweight-adjusted average power (W/BW) was estimated by averaging the power data across the entirety of the ground contact phase.
Bilateral symmetry was assessed using percent differences between right and left force plates in peak and average force and peak and average power measurements (Equation 7).

\[
\text{Equation 7) } \% \text{ Difference} = \left| \frac{\text{Right} - \text{Left}}{\text{Combined}} \right| \times 100
\]

Statistical Analysis

To examine the main effect of drop height on dependent measures, a one-way multivariate ANOVA analysis was performed. If main effects were observed, a least squared difference (LSD) post-hoc test provided pairwise comparisons between drop heights. Linear regression was used to analyze statistical relationships between each component of agility, collapsed across drop heights.

All statistical analyses were conducted in SPSS (version 20; IBM, NY, USA). For all hypothesis tests, an alpha (\(\alpha\)) cut-off value of 0.05 was used.
CHAPTER THREE

Results

**One-way Multivariate ANOVA**

The one-way multivariate ANOVA revealed main effects of drop height for peak power, peak force, average power, average force, peak force percent difference, and average power percent difference (Table 2). Main effects of drop height were not observed for RSI, peak power percent difference, average force percent difference, or rebound jump height (Table 2).

LSD post-hoc pairwise comparisons revealed that peak power, peak force, average power, and average force changed by -9.54%, 56.60%, -52.33%, and 6.10% from the 0.38 m drop condition to the 0.53 m drop condition, respectively (Table 3). Peak power, peak force, average power, and average force changed by -10.55%, 21.08%, -35.11%, and 5.75% from the 0.53 m drop condition to the 0.69 m drop condition, respectively (Table 3).

Peak force percent difference and average power percent difference were 38.56% and 36.15% less in the 0.53 m drop condition as compared to the 0.38 m drop condition, respectively (Table 3). There were no significant differences in these dependent measures between the 0.53 m and 0.69 m drop conditions (Table 3).
## Table 2
### ANOVA Main Effects

<table>
<thead>
<tr>
<th>Drop Height</th>
<th>F</th>
<th>p</th>
<th>$\eta_p^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI</td>
<td>0.320</td>
<td>0.727</td>
<td>0.008</td>
</tr>
<tr>
<td>PeakP</td>
<td>8.527</td>
<td>&lt;0.001</td>
<td>0.179</td>
</tr>
<tr>
<td>PeakF</td>
<td>37.084</td>
<td>&lt;0.001</td>
<td>0.487</td>
</tr>
<tr>
<td>AvgP</td>
<td>163.921</td>
<td>&lt;0.001</td>
<td>0.808</td>
</tr>
<tr>
<td>AvgF</td>
<td>10.609</td>
<td>&lt;0.001</td>
<td>0.214</td>
</tr>
<tr>
<td>PP % Diff</td>
<td>0.146</td>
<td>0.865</td>
<td>0.004</td>
</tr>
<tr>
<td>PF % Diff</td>
<td>8.437</td>
<td>&lt;0.001</td>
<td>0.178</td>
</tr>
<tr>
<td>AvgP % Diff</td>
<td>4.050</td>
<td>0.021</td>
<td>0.094</td>
</tr>
<tr>
<td>AvgF % Diff</td>
<td>0.804</td>
<td>0.451</td>
<td>0.020</td>
</tr>
<tr>
<td>JH</td>
<td>0.704</td>
<td>0.498</td>
<td>0.018</td>
</tr>
</tbody>
</table>

*Note.* Main effects for an ANOVA performed on depth jump data. Data are from three depth jumps performed at heights of 0.38 m, 0.53 m, and 0.69 m by a sample of nine young females from an NCAA Division I volleyball team (total jumps = 81). RSI = Reactive Strength Index. PeakP = peak power. PeakF = peak force. AvgP = average power. AvgF = average force. PP % Diff = peak power percent difference between right and left legs. PF % Diff = peak force percent difference between right and left legs. AvgP % Diff = average power percent difference between right and left legs. AvgF % Diff = average force percent difference between right and left legs. JH = rebound jump height.
Table 3  
ANOVA Post-hoc Comparisons

<table>
<thead>
<tr>
<th></th>
<th>15 in (0.38 m) DJ</th>
<th>21 in (0.53 m) DJ</th>
<th>27 in (0.69 m) DJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI</td>
<td>0.64 (0.10)</td>
<td>0.65 (0.07)</td>
<td>0.63 (0.09)</td>
</tr>
<tr>
<td>PeakP</td>
<td>2.83 (0.46)</td>
<td>2.56 (0.48)*</td>
<td>2.29 (0.49)**</td>
</tr>
<tr>
<td>PeakF</td>
<td>2.12 (0.55)</td>
<td>3.32 (0.81)*</td>
<td>4.02 (1.03)**</td>
</tr>
<tr>
<td>AvgP</td>
<td>-0.86 (0.16)</td>
<td>-1.31 (0.18)*</td>
<td>-1.77 (0.21)**</td>
</tr>
<tr>
<td>AvgF</td>
<td>0.82 (0.09)</td>
<td>0.87 (0.08)*</td>
<td>0.92 (0.07)**</td>
</tr>
<tr>
<td>PP % Diff</td>
<td>3.35 (2.55)</td>
<td>3.64 (3.52)</td>
<td>3.81 (3.33)</td>
</tr>
<tr>
<td>PF % Diff</td>
<td>17.87 (13.04)</td>
<td>10.98 (7.37)*</td>
<td>7.90 (5.11)*</td>
</tr>
<tr>
<td>AvgP % Diff</td>
<td>11.59 (9.95)</td>
<td>7.40 (6.10)*</td>
<td>5.96 (5.89)*</td>
</tr>
<tr>
<td>AvgF % Diff</td>
<td>10.93 (10.10)</td>
<td>8.67 (9.24)</td>
<td>7.90 (7.88)</td>
</tr>
<tr>
<td>JH</td>
<td>0.34 (0.03)</td>
<td>0.33 (0.03)</td>
<td>0.34 (0.03)</td>
</tr>
</tbody>
</table>

*Significantly different from the 0.38 m condition (p < 0.05).  †Significantly different from the 0.53 m condition (p < 0.05).  DJ = drop height.  RSI = Reactive Strength Index.  PeakP = peak power.  PeakF = peak force.  AvgP = average power.  AvgF = average force.  PP % Diff = peak power percent difference between right and left legs.  PF % Diff = peak force percent difference between right and left legs.  AvgP % Diff = average power percent difference between right and left legs.  AvgF % Diff = average force percent difference between right and left legs.  JH = rebound jump height.

Note. ANOVA effects of condition. Data were collected from depth jumps (DJ) performed by a sample of nine young females from an NCAA Division I volleyball team.  *significantly different from the 0.38 m condition (p < 0.05).  †significantly different from the 0.53 m condition (p < 0.05).  DJ = drop height.  RSI = Reactive Strength Index.  PeakP = peak power.  PeakF = peak force.  AvgP = average power.  AvgF = average force.  PP % Diff = peak power percent difference between right and left legs.  PF % Diff = peak force percent difference between right and left legs.  AvgP % Diff = average power percent difference between right and left legs.  AvgF % Diff = average force percent difference between right and left legs.  JH = rebound jump height.
**Linear Regression**

*Reactive Strength vs Concentric Strength and Power*

Significant linear associations were observed for RSI vs. peak power and RSI vs. average force (Table 4). No significant associations were observed for RSI vs. average power and RSI vs. peak force (Table 4).

*Concentric Strength and Power vs Bilateral Symmetry*

Significant linear associations were observed for peak power vs. peak power percent difference, peak force vs. peak force percent difference, and average power vs. average power percent difference (Table 5). No significant associations were observed for average force vs. average force percent difference (Table 5).

*Reactive Strength vs Bilateral Symmetry*

Significant linear associations were observed for RSI vs. average force percent difference (Table 6). No significant linear associations were observed for RSI vs. peak power percent difference, RSI vs. peak force percent difference, or RSI vs. average power percent difference (Table 6).

*Neuromuscular Characteristics of Agility vs Rebound Jump Height*

Significant linear associations were observed for rebound jump height vs. RSI and rebound jump height vs. average force (Table 7). No significant linear associations were observed for rebound jump height vs. average power, rebound jump height vs. average power percent difference, or rebound jump height vs. average force percent difference (Table 7).
Table 4
Regression Data on Reactive Strength and Concentric Strength and Power

<table>
<thead>
<tr>
<th></th>
<th>$r$</th>
<th>$R^2$</th>
<th>$F$</th>
<th>$p$</th>
<th>Constant</th>
<th>$p$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI – PP</td>
<td>0.40</td>
<td>0.16</td>
<td>14.73</td>
<td>&lt;0.001</td>
<td>1.04</td>
<td>0.01</td>
<td>2.40</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>RSI – AP</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.99</td>
<td>-1.31</td>
<td>&lt;0.001</td>
<td>-0.01</td>
<td>0.99</td>
</tr>
<tr>
<td>RSI – PF</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.92</td>
<td>3.24</td>
<td>&lt;0.001</td>
<td>-0.14</td>
<td>0.92</td>
</tr>
<tr>
<td>RSI – AF</td>
<td>0.59</td>
<td>0.34</td>
<td>41.28</td>
<td>&lt;0.001</td>
<td>0.479</td>
<td>&lt;0.001</td>
<td>0.619</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Note. Regression data on comparisons made between reactive strength and concentric strength and power. Regressions were performed using pooled data from three depth jumps performed by a sample of young females from an NCAA Division I volleyball team (total jumps = 81). RSI = Reactive Strength Index. PP = peak power. PF = peak force. AP = average power. AF = average force. PP%D = peak power percent difference between right and left legs. PF%D = peak force percent difference between right and left legs. AP%D = average power percent difference between right and left legs. AF%D = average force percent difference between right and left legs. JH = rebound jump height.
Figure 3. Significant associations between reactive strength and concentric strength and power measurements.
Table 5
Regression Data on Concentric Strength and Power and Bilateral Symmetry

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>$R^2$</th>
<th>$F$</th>
<th>$p$</th>
<th>Constant</th>
<th>$p$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP – PP%D</td>
<td>0.36</td>
<td>0.13</td>
<td>11.43</td>
<td>0.001</td>
<td>9.08</td>
<td>&lt;0.001</td>
<td>-2.14</td>
<td>0.001</td>
</tr>
<tr>
<td>PF – PF%D</td>
<td>0.34</td>
<td>0.12</td>
<td>10.34</td>
<td>0.002</td>
<td>21.67</td>
<td>&lt;0.001</td>
<td>-2.99</td>
<td>0.002</td>
</tr>
<tr>
<td>AP – AP%D</td>
<td>0.26</td>
<td>0.07</td>
<td>5.49</td>
<td>0.02</td>
<td>14.63</td>
<td>&lt;0.001</td>
<td>4.82</td>
<td>0.02</td>
</tr>
<tr>
<td>AF – AF%D</td>
<td>0.02</td>
<td>0.00</td>
<td>0.04</td>
<td>0.85</td>
<td>7.28</td>
<td>0.464</td>
<td>2.17</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Note. Regression data on comparisons made between concentric strength and power and bilateral symmetry. Regressions were performed using pooled data from three depth jumps performed by a sample of young females from an NCAA Division I volleyball team (total jumps = 81). RSI = Reactive Strength Index. PP = peak power. PF = peak force. AP = average power. AF = average force. PP%D = peak power percent difference between right and left legs. PF%D = peak force percent difference between right and left legs. AP%D = average power percent difference between right and left legs. AF%D = average force percent difference between right and left legs. JH = rebound jump height.
Figure 4. Significant associations between concentric strength and power and bilateral symmetry measurements.
Table 6
Regression Data on Reactive Strength and Bilateral Symmetry

<table>
<thead>
<tr>
<th></th>
<th>r</th>
<th>$R^2$</th>
<th>F</th>
<th>p</th>
<th>Constant</th>
<th>p</th>
<th>β</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI – PP%D</td>
<td>0.08</td>
<td>0.01</td>
<td>0.44</td>
<td>0.51</td>
<td>1.87</td>
<td>0.48</td>
<td>2.72</td>
<td>0.51</td>
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<tr>
<td>RSI – PF%D</td>
<td>0.16</td>
<td>0.03</td>
<td>2.02</td>
<td>0.16</td>
<td>0.62</td>
<td>0.94</td>
<td>18.34</td>
<td>0.16</td>
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<tr>
<td>RSI – AP%D</td>
<td>0.19</td>
<td>0.04</td>
<td>2.95</td>
<td>0.09</td>
<td>-2.67</td>
<td>0.68</td>
<td>17.32</td>
<td>0.09</td>
</tr>
<tr>
<td>RSI – AF%D</td>
<td>0.23</td>
<td>0.05</td>
<td>4.20</td>
<td>0.04</td>
<td>-5.97</td>
<td>0.43</td>
<td>23.87</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Note. Regression data on comparisons made between reactive strength and bilateral symmetry. Regressions were performed using pooled data from three depth jumps performed by a sample of young females from an NCAA Division I volleyball team (total jumps = 81). RSI = Reactive Strength Index. PP = peak power. PF = peak force. AP = average power. AF = average force. PP%D = peak power percent difference between right and left legs. PF%D = peak force percent difference between right and left legs. AP%D = average power percent difference between right and left legs. AF%D = average force percent difference between right and left legs. JH = rebound jump height.

Figure 5. Significant associations between reactive strength and bilateral symmetry measurements.
Table 7
Regression Data on Neuromuscular Characteristics of Agility and Rebound Jump Height

<table>
<thead>
<tr>
<th></th>
<th>$r$</th>
<th>$R^2$</th>
<th>$F$</th>
<th>$p$</th>
<th>Constant</th>
<th>$p$</th>
<th>$\beta$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSI – JH</td>
<td>0.84</td>
<td>0.70</td>
<td>187.00</td>
<td>&lt;0.001</td>
<td>0.15</td>
<td>&lt;0.001</td>
<td>0.30</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>AP – JH</td>
<td>0.08</td>
<td>0.01</td>
<td>0.45</td>
<td>0.51</td>
<td>0.33</td>
<td>&lt;0.001</td>
<td>-0.01</td>
<td>0.51</td>
</tr>
<tr>
<td>AF – JH</td>
<td>0.33</td>
<td>0.11</td>
<td>9.50</td>
<td>0.003</td>
<td>0.24</td>
<td>&lt;0.001</td>
<td>0.11</td>
<td>0.003</td>
</tr>
<tr>
<td>AP%D – JH</td>
<td>0.10</td>
<td>0.01</td>
<td>0.82</td>
<td>0.37</td>
<td>0.33</td>
<td>&lt;0.001</td>
<td>0.00</td>
<td>0.37</td>
</tr>
<tr>
<td>AF%D – JH</td>
<td>0.21</td>
<td>0.05</td>
<td>3.76</td>
<td>0.06</td>
<td>0.33</td>
<td>&lt;0.001</td>
<td>0.00</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Note. Regression data on comparisons made between various neuromuscular characteristics of agility and rebound jump height. Regressions were performed using pooled data from three depth jumps performed by a sample of young females from an NCAA Division I volleyball team (total jumps = 81). RSI = Reactive Strength Index. PP = peak power. PF = peak force. AP = average power. AF = average force. PP%D = peak power percent difference between right and left legs. PF%D = peak force percent difference between right and left legs. AP%D = average power percent difference between right and left legs. AF%D = average force percent difference between right and left legs. JH = rebound jump height.
Figure 6. Significant associations between various neuromuscular characteristics of agility and rebound jump height.
CHAPTER FOUR
Discussion

The purpose of this study was to evaluate the influence of drop height on and the statistical associations between Sheppard and Young’s (2006) neuromuscular characteristics of agility. Participants performed depth jumps from multiple drop heights, with performance assessed using measures of reactive strength, concentric strength and power, and bilateral symmetry.

Influence of Drop Height on Dependent Variables

Dependent measures of peak power, peak force, average power, average force, peak force percent difference, and average power percent difference were significantly different across depth jump drop heights (Table 3). Peak power and average power decreased, while peak force and average force increased at greater drop heights (Table 3). Negative average power values reflected that rebound jump height was lower than drop height. Peak and average power decreased (increased in magnitude) with drop height, indicating that athletes likely landed with increased impact velocity and force. Peak and average force increases were also likely due to the increased drop height, which is associated with larger impact velocities and likely higher landing forces.

Interestingly, as drop height increased, peak force increased by 56.60% and 21.08%, while average force increased just 6.10% and 5.75% (Table 3). This difference may have occurred because participants were required to absorb greater amounts of energy upon landing from higher drops, but may have been unable to maximize the transfer of energy into their jump phase. Peak force percent
difference and average power percent difference both decreased with drop height increases, indicating a decrease in asymmetry present with higher impact velocities (Table 3). With increasing drop height demands, there may have been a need to balance larger impacts across both limbs as muscles were taxed closer to maximum (Schmidt & Lee, 2014). Each bilateral symmetry measurement was characterized by large standard deviations (Table 3), reflecting either a high amount of variance between individuals or that participants were inconsistent across drop jump height conditions.

Dependent measures of RSI, peak power percent difference, average force percent difference, and rebound jump height were not significantly different across depth jump drop heights (Table 3). A previous study testing drop jumps from 0.30 m found average RSI scores of 0.872 (0.185), 0.781 (0.159), and 0.727 (0.145) for NCAA DI, DII and DIII women’s volleyball players respectively (Barnes et al., 2007). The population and procedure are highly similar, yet RSI scores in the present study were lower by about 25% (Table 3). However, the drop heights used in the present study were 0.08 m, 0.23 m, and 0.39 m higher than the 0.30 m height used in Barnes et al.’s (2007) study. It is possible that the box heights chosen in the present study produced impacts that were near, or exceeded participants’ maximum reactive capabilities. A lack of change in RSI scores across drop heights suggests that drop heights chosen may have elicited maximal neuromuscular reactivity from participants. Low RSI scores suggest that this sample of women’s volleyball players possess below average reactive strength.
Association between Neuromuscular Characteristics of Agility

It was hypothesized that the strongest associations would be between peak power, RSI, and rebound jump height. It was also expected that concentric strength and power would associate moderately with corresponding measurements of bilateral symmetry. Lastly, it was expected that the weakest associations would be between bilateral symmetry, RSI, and rebound jump height.

Reactive Strength vs. Concentric Strength and Power

Linear regressions revealed weak associations between RSI and peak power (Table 4). However, RSI was modestly associated with average force. Regressions revealed that 34% of the variance in RSI explained the variance in average force (Table 4), while just 16% of the variance in RSI explained the variance in peak power (Table 4). Linear regressions revealed no statistical associations between RSI and both measures of average power and peak force.

A possible explanation for the lack of association between peak force and RSI is that peak force is a single data point reflecting the maximal force applied to the lower extremity kinetic chain during the landing phase of depth jumping, and likely does not contribute much to either rebound jump height or ground contact time. Although not observed in the present study, it would be reasonable to expect that very large impact forces may act to lengthen ground contact time by increasing the potentiation of the Golgi Tendon Organ reflex.

In the present study, average power was computed across the entire GRF time-series, meaning that negative power during the landing phase and positive power from the take-off phase both influenced the average power variable. While
average power was not associated with RSI in the present study, it would not be surprising to observe significant associations between average power during the take-off phase of jumping and RSI. However, this assumption would need to be evaluated in a follow-up investigation.

Peak power was associated linearly with RSI, perhaps because it is a point measure of power that occurs during the jump phase and not the landing phase. Average force may have associated most highly with RSI of all concentric strength and power measures because it took into account the entire process leading to takeoff, therefore including measurements from the time in ground contact and the creation of forces that led to jump height.

Concentric Strength and Power vs. Bilateral Symmetry

It was hypothesized that strength and power measurements would associate strongly with their respective bilateral symmetry measurements. Additionally, it was hypothesized that strength and power variables would be positively associated with bilateral symmetry (lower percent differences). In the present study, all measures of strength and power, except average force, were either positively or negatively associated with corresponding measures of bilateral symmetry.

Peak power and peak force were negatively associated with corresponding measures of peak power percent difference and peak force percent difference (Table 5). It is plausible that a more symmetrical, stable stance would contribute to an increased ability to absorb and exert external force and power.

In contrast, average power was positively associated with average power percent difference (Table 5). It may be possible that since average power contains
data from the entire time period where the feet are in contact with the ground, average power measurements are more sensitive to bilateral asymmetries.

*Reactive Strength vs. Bilateral Symmetry*

It was hypothesized that RSI and measures of bilateral symmetry would be moderately associated. However, in the present study, RSI was found to be associated with only average force percent difference, and association was weak (Table 6). Regressions suggested that for every one-unit increase in RSI, average force percent difference would be expected to increase 23.87% (Table 6). This may seem like a large increase, however, RSI values had a mean of 0.64, so increases in RSI are more likely to be on the scale of tenths of units (Table 3). Therefore, a one-tenth unit increase in RSI would predict a 2.387% increase in average force percent difference. Additionally, the proportion of variance in RSI that explained the variance in average force percent difference was just 5% (Table 6). A negative association between RSI and average force percent difference is logical when considering that RSI was most strongly associated with average force out of all concentric strength and power measures (Table 4). There were no significant associations between RSI and peak power percent difference, peak force percent difference, or average power percent difference (Table 6).

*Neuromuscular Characteristics vs. Rebound Jump Height*

A final group of linear regressions evaluated the associations between Sheppard and Young’s (2006) neuromuscular characteristics of agility and rebound jump height, which was selected as a dependent measure of athletic performance. Average values for power and force as well as average power and force percent
differences were chosen, as they best represent the entirety of the jump phase. It was hypothesized that RSI would be strongly associated with jump height, which was supported by the results. Regressions revealed that 70% of the variance in RSI explained the variance in jump height (Table 7). This was the strongest relationship between any two dependent variables observed in the present study. For every one-unit increase in RSI, jump height increased by 0.30 m (Table 7). A more applicable and relevant interpretation would be that for every one-tenth unit increase in RSI, jump height increased by 0.03 m, or 3 cm. An association between RSI and jump height supports the validity of the RSI for evaluating explosiveness, since the drop jump is a quick and powerful movement with rebound jump height as the measurable movement outcome.

Average force was also significantly associated with rebound jump height (Table 7). Since average force significantly associated with RSI, this result was not surprising (Tables 6, 7). Regressions revealed that 11% of the variance in average force explained the variance in rebound jump height (Table 7). Additionally, regressions suggested that for every meter of increased rebound jump height, average force would be expected to increase by 0.11 BW. In other words, average force increased by an average of 0.001 BW for every additional centimeter of rebound jump height attained (Table 7).

Impact on Training

Results of the present study suggest that in order to improve explosiveness, strength and conditioning coaches may consider prioritizing training to improve average force. Average force was most strongly associated with both RSI and jump
height (Tables 4, 7). Additionally, peak power may also be an important variable to consider for monitoring performance in training programs aimed at improving agility. After average force, peak power was most strongly associated with RSI and jump height (Tables 4, 7). These associations support the idea that strength is a more fundamental capability than power. In other words, power production may not be effectively maximized, or trained, without first developing a base level of strength. In strength and conditioning periodization models, such as the Triphasic System, strength cycles are believed to maximize athletic performance enhancement when they precede power cycles (Dietz & Peterson, 2012).

Results of the present study did not support the notion that bilateral symmetry influences the performance of explosive movements. For instance, RSI was not significantly associated with percent differences in peak power, peak force, or average power (Table 4). Additionally, neither average force percent difference nor average power percent difference were significantly associated with rebound jump height (Table 7).

Bilateral symmetry has previously been shown to influence injury rates and contribute significantly to injury prevention (Paterno et al., 2017). Although we did not collect data on injury rates in the present study, a large degree of between-subject variability suggests that some participants may have bilateral deficits due to previous injury, training history, demands of sport, or intrinsic physical irregularity (Table 3).
Study Limitations and Further Research

The biggest change to consider in future studies would be to decrease box heights, or employ a wider range of box heights in comparison with those used in the present study. For example, previous studies used box heights of 0.30 m to assess neuromuscular reactivity in collegiate female volleyball players (Barnes et al., 2007); 0.30 m for various male athletes (Young et al., 2002); 0.15, 0.30, 0.45, and 0.60 m for male basketball players (Struzik, Juras, Pietraszewski, & Rokita, 2016); 0.60 m for various male athletes (Kollias, Panoutsakopoulos, & Papaiaikovou, 2004); and 0.50, 0.66, and 0.81 m for young, college-aged adults and collegiate basketball players (Louder, 2017). Although our box heights of 0.38, 0.53 and 0.69 m are within the range presented by these studies, they are towards the higher end and exceed the height of 0.30 m used in the most similar previous study (Barnes et al., 2007). Neuromuscular characteristics tended to change less between 0.53 m and 0.69 m than between 0.38 m and 0.53 m, possibly indicating that the highest drop height conditions elicited maximal, or near maximal neuromuscular reactivity (Table 3). Protective neuromuscular functions may have activated and lowered force production. Lower box heights would allow a more effective examination of participants’ full capabilities.

It would also be interesting to collect data on previously injured athletes, or athletes rehabilitating from injury by conducting follow-up examinations to determine the impact of bilateral symmetry on injury and rehabilitation. It may be the case that asymmetry across limbs would reflect previous injury or may predict future injury.
Lastly, in the present study, statistical assessments were made using a convenience sample of nine collegiate volleyball players. Repeating this study with more participants, and thus a greater sample size, would provide greater statistical power for detecting significance.
REFERENCES


