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ESTABLISHING A KINETIC ASSESSMENT OF REACTIVE STRENGTH

by

Talin Louder

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Disability Disciplines

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Logan, Utah

2017

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## ABSTRACT

## Establishing a Kinetic Assessment of Reactive Strength

by

Talin Louder, Doctor of Philosophy

Utah State University, 2017

Major Professor: Eadric Bressel, PhD  
Department: Kinesiology and Health Science

The reactive strength index (RSI) is the current “gold standard” assessment of reactive strength. Traditional measures of reactive strength, including the RSI, are not strength-based and are founded using untested theoretical assumptions. The purpose of this study was to develop two versions of a kinetic-based paradigm of reactive strength (New and AdjNew) and compare them against the Coefficient of Reactivity (CoR) and the RSI. Twenty one NCAA Division I basketball players and 59 young adults from the general population performed two reactive strength protocols: Progressive drop jumping and repetitive countermovement jumping. For every jump, the CoR, RSI, New, and AdjNew were computed. Measure agreeability was assessed using the Bland-Altman approach and linear regressions. Analyses of variance (ANOVA) assessed the effect of sport participation, age, and sex on the four measures of reactive strength. Lastly, effects of self-reported physical activity levels were assessed using stepwise linear regressions. The strongest association was observed between AdjNew and the RSI ( $R^2 = 0.636$ ). All

measures of reactive strength were sensitive to effects of sex and sport participation in drop jumping (males > females; NCAA > young adults). The RSI, New, and AdjNew were sensitive to effects of sex and sport participation in repetitive countermovement jumping (males > females; NCAA > young adults). There are theoretical issues with the computation and implementation of the CoR and RSI. For example, the CoR and RSI are non-strength based measures that attempt to measure a strength construct. Further, the CoR, RSI, and New make the theoretical assumption that no biological variability exists in human movement. The AdjNew paradigm addresses and solves the theoretical issues with the CoR, RSI, and New. Therefore it may be argued that the AdjNew paradigm improves the theoretical validity of reactive strength assessment and is preferred over the RSI. The AdjNew is kinetic based, comprised of only measured component variables, and is not founded in assumptions of theory. This dissertation provides objective theoretical evidence to suggest that the AdjNew paradigm is an improvement over the RSI as a model of reactive strength.

(142 pages)

## PUBLIC ABSTRACT

## Establishing a Kinetic Assessment of Reactive Strength

Talin Louder

Three neuromuscular characteristics are identified in Sheppard and Young's model of agility: concentric strength and power, bilateral symmetry, and reactive strength. Measures of reactive strength attempt to model the neuromuscular regulation of tissue stress and strain. The Coefficient of Reactivity (CoR) is the first known assessment of neuromuscular reactivity. The CoR was developed as an assessment of neuromuscular performance in drop jumping. The construct validity of the CoR was placed in question when Warren Young proposed the Reactive Strength Index (RSI). The RSI improved the theoretical validity of reactive strength assessment since it included a component measure (ground contact time) that modelled the interaction of the feet and ground during impact.

There are theoretical issues with the computation and implementation of the CoR and RSI. For example, the CoR and RSI are nonstrength based measures that attempt to measure a strength construct. Further, the CoR and RSI make the theoretical assumption that no biological variability exists in human movement. In the present study, we develop a kinetic (strength)-based paradigm of reactive strength (New and AdjNew) and evaluate it against the CoR and RSI.

Results suggest the AdjNew and RSI attempt to model the same construct. The AdjNew paradigm addresses and solves the theoretical issues with the CoR, RSI, and New. Therefore it may be argued that the AdjNew paradigm improves the theoretical

validity of reactive strength assessment and is preferred over the RSI.

In this document we discuss how wearable technologies may be used to carry out our AdjNew paradigm. It is possible that pairing the AdjNew paradigm with wearable sensors will allow for the assessment of reactive strength through the whole-body center of gravity and through limb segment centers of gravity. Looking forward, a wearable sensor approach to reactive strength assessment could expand the assessment of neuromuscular reactivity in both sport and clinical populations.

## DEDICATION

I dedicate this dissertation to the memories of Steven Lloyd Hodson (December 11, 1954-November 3, 2008), who taught me to be fast but never quick and who lived beyond himself even in the most difficult times.

And to Madeline. You make the world beautiful and I am taken aback by your love, kindness, and sacrifice. Your commitment to social justice touches the lives of many. You are my best friend and the love of my life.



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To my parents (Jeff, Kim, Arden, Barbara, Dennis, and Ellen), thank you for your wisdom, love, and the sacrifices you made to help me reach the end of this journey. To Madeline, thank you for your unconditional love, encouragement, and support. I love you dearly.

Last, I would like to thank all those who live life believing in and advocating for the value that lies in every person. You are my inspiration.

Talin Louder

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## LIST OF ACRONYMS AND ABBREVIATIONS

ACL	Anterior cruciate ligament
Adj.	Adjusted
AdjAmort t	Adjusted amortization time
AdjImp	Adjusted impulse
AdjNew	Kinematically adjusted kinetic-based reactive strength paradigm
Amort t	Amortization time
ANOVA	Analysis of variance
APTA	American Physical Therapy Association
CoR	Coefficient of reactivity
DI	Division one
DayJump	Days per week participating in jumping activities
DayMod	Days per week participating in moderate intensity exercise
DayVig	Days per week participating in vigorous intensity exercise
EWGSOP	European Working Group on Sarcopenia in Older People
Gen	Young adults from general population
Imp	Impulse
NCAA	National Collegiate Athletics Association
New	Kinetic-based reactive strength paradigm
NSCA	National Strength and Conditioning Association
PEDro	Physiotherapy Evidence Database
PlyoExp	Number of months (past 5 year) participating in plyometrics

RCM	Repetitive countermovement
RCM1	1 <sup>st</sup> Repetitive countermovement jump in analysis
RCM2	2 <sup>nd</sup> Repetitive countermovement jump in analysis
RCM3	3 <sup>rd</sup> Repetitive countermovement jump in analysis
RCM4	4 <sup>th</sup> Repetitive countermovement jump in analysis
RSI	Reactive strength index
TimeVig	Minutes spent in a typical session of vigorous intensity exercise

# **CHAPTER I**

## **INTRODUCTION**

There is widespread interest in the identification and assessment of movement constructs in biomechanics research. Balance and agility are examples of movement constructs that cannot be measured directly but can be represented through qualitative and quantitative means. Constructs play a key role in the measurement and evaluation of movement. For example, balance is generally defined as the ability to control one's center of mass over a base of support. Balance is regulated through a complex integration of various physiological systems and is assessed using a variety of tests (Mancini & Horak, 2010). There is merit in discovering ways to improve balance assessment. This is especially true knowing that there are consequences associated with having poor balance. For instance, loss of balance leading to falls in older adults represents a leading cause of fatality and bodily injury. In the U.S., the annual direct cost of treating falls in older adults has been estimated to be over \$30 billion (Burns, Stevens, & Lee, 2016). Measures of balance are tools that researchers and clinicians use to understand factors that increase fall risk and identify ways to minimize the prevalence of falls in older adults.

Agility is defined as “a rapid whole body movement with change of velocity or direction in response to a stimulus” (Sheppard & Young, 2006, p. 4). Perception and decision making, along with change of direction speed, are Sheppard and Young's two main branches of agility. These branches help us understand the various factors that influence how humans move within a spatially and temporally uncertain environment. Within the change of direction speed branch, Sheppard and Young identified the



following key neuromuscular characteristics: Concentric muscle strength and power, bilateral symmetry, and reactive strength (see Appendix A).

Sheppard and Young's (2006) three neuromuscular characteristics are most often considered from the perspective of sport performance yet can be applied to clinical populations as well. For example, Puthoff and Nielson (2007) observed that lower extremity mechanical power predicts performance on the Short Physical Performance Battery, Six-Minute Walk Test, and Late Life Function and Disability Index Functional Limitation Component Score in older adults. In addition, older adults who undergo frequent falling episodes produce less bilateral symmetry in tests of lower extremity mechanical power compared to older adults who do not have a history of frequent falling (Skelton, Kennedy, & Rutherford, 2002). Reactive strength is Sheppard and Young's (2006) neuromuscular quality that is least understood in terms of how it contributes to the performance of agile movement in older adults and has not been investigated in other clinical populations. A primary reason for this is the exclusive nature of high-stress reactive strength testing protocols.

The construct of reactive strength is intended to model the various neuromuscular pathways that contribute to the prevention of injury to the tissues of the body. Traditional reactive strength algorithms use spatial and spatiotemporal ratios (Verkhoshansky, 1968; Young, 1995) that intend to provide a reasonable estimation of a person's ability to produce an "explosive" movement immediately following an impact between the feet and ground. The coefficient of reactivity (CoR; Verkhoshansky, 1968) is the first known assessment of reactive strength (see Appendix B, Equation 1). Computing the CoR

requires the performance of jumping movements that are restricted to non-disabled persons. Further, the construct validity of the CoR was questioned when Young (1995) proposed an alternative assessment of drop jump performance, the Reactive Strength Index (RSI). The RSI was an improvement over the CoR since it included a component measure, ground contact time (s), that modelled the interaction between the feet and ground during short duration impact (see Appendix B, Equation 2).

The RSI modernized the CoR by improving the theoretical validity of reactive strength assessment and is accepted as the ‘gold standard’ reactive strength paradigm in current literature. Researchers have established the RSI as a reliable measure (Ball & Zanetti, 2012; Byrne, Browne, Byrne, & Richardson, 2017; Di Cagno et al., 2013; Flanagan, Ebben, & Jensen, 2008; Markwick, Bird, Tufano, Seitz, & Haff, 2015), found positive associations between the RSI and other measures of explosive performance (Beckham, Suchomel, Bailey, Sole, & Grazer, 2014; Suchomel, Bailey, Sole, Grazer, & Beckham, 2015), evaluated its sensitivity to knee injury rehabilitation progression and sex (Flanagan, Galvin, & Harrison, 2008; Kipp, Kiely, & Geiser, 2016; Laffaye, Choukou, Benguigui, & Padulo, 2016; McMahon, Rei, & Comfort, 2017; Ramirez-Campillo et al., 2016; Suchomel et al., 2015), and have found preliminary results suggesting that the RSI may be predictive of fall risk in older adults (Hoffrén-Mikkola, Ishikawa, Rantalainen, Avela, & Komi, 2015).

Researchers and practitioners have assumed the RSI to be a valid measure of reactive strength. However, there are several theoretical issues related to the computation and implementation of the RSI that need to be addressed. This is of particular importance

given the increased prevalence of research using the RSI to evaluate sport performance, injury prevention and recovery, and physical function in older adults.

A key issue with the RSI is that it is not a direct measure of strength yet is assumed to measure a construct of strength. The technical definition of strength is the ability of a material to withstand mechanical stresses (force/area) applied by an external load (force). The process of computing the RSI does not include force data. Further, the RSI computes to meters per second, which would be typically assumed as a kinematic (non-kinetic, non-strength-based) measure. While one can argue an indirect association between the RSI and reactive strength, it is logical to conclude that replacing the RSI with an algorithm that is sensitive to kinetic, or strength-based data may improve the theoretical validity of reactive strength assessment.

When using the RSI, it is assumed that no biological variability exists in human movement. It is known that there is natural variability in movement, and that a certain degree of variability is considered healthy and advantageous (Stergiou, Kent, & McGrath, 2016). The first theoretical assumption of the RSI is that there is no variability in movement kinematics when a person jumps down from a physical object of known height (e.g., plyometric box). The RSI assumes that the displacement of a person's center of gravity is equal to the height of the physical object. Since a perfectly theoretical drop likely does not occur across persons and within a single person performing multiple drop jumps, it is important to evaluate whether or not assumed drop heights introduce inaccuracies when computing the RSI. Further, it is common to measure the rebound jump height component of the RSI using one half of flight time obtained from a force

platform or contact mat. Using flight time to estimate jump height assumes that limb segment positioning does not differ between jump take-off and landing. This assumption is likely invalid knowing that individuals tend to land from a jump with more flexion of the lower extremity versus take off . Therefore, it is important to evaluate the extent that using assumed rebound jump heights introduces inaccuracies to the computation of the RSI.

Last, both the RSI and CoR are computed from the performance of high-stress jumping movements. A purely kinetic (acceleration, or force-based) paradigm could be implemented using wearable technologies. If a kinetic (strength)-based paradigm of reactive strength is observed to improve the construct validity of reactive strength assessment, it may also facilitate the expansion of reactive strength measurement in sport and clinical populations. It is possible that pairing a kinetic (strength)-based paradigm of reactive strength with wearable sensors will allow for the assessment of reactive strength through the whole-body center of gravity and through limb segment centers of gravity.

### **Purpose**

The purpose of this study was to evaluate the construct validity of a kinetic (strength)-based paradigm of reactive strength against the RSI and CoR. The following research questions were identified.

1. Does kinematic variability in drop jumping introduce inaccuracies to measures of reactive strength?
2. Do differences in limb segment positioning at jump take-off and landing introduce inaccuracies to measures of reactive strength?
3. Does a kinetic (strength)-based paradigm of reactive strength agree with

traditional assessments such as the CoR and RSI?

4. Is a kinetic (strength)-based paradigm of reactive strength sensitive to neuromuscular differences between NCAA Division I basketball players and young adults from the general population?
5. Is a kinetic (strength)-based paradigm of reactive strength sensitive to neuromuscular differences between post-pubescent males and females?
6. Does self-reported level of physical activity predict reactive strength capacity?

In accordance with the research questions, we identified the following potential outcomes.

1. If drop jump kinematics do not differ materially from theoretical expectations, then we can say that movement variability does not influence the computation of reactive strength in drop jumping. Or, if drop jump kinematics vary from theoretical expectations, then we can say that there is a need to adjust for movement variability when computing measures of reactive strength in drop jumping. Since biological variability exists in human movement and is considered healthy to a certain degree, we expected that drop jump kinematics would not follow theoretical expectations.
2. If limb positioning does not differ materially from theoretical expectations, then we can say that movement variability does not influence the computation of reactive strength in repetitive countermovement jumping. Or, if limb positioning varies from theoretical expectations, then we can say that there is a need to adjust for movement variability when computing measures of reactive strength in repetitive countermovement jumping. Since it is known that persons tend to land from a jump with increased flexion of the lower extremity versus take-off, and that biological variability exists in human movement, we expected that limb segment positioning would not follow theoretical expectations.
3. Our kinetic (strength)-based measure of reactive strength does not agree fully with traditional assessments. This outcome would support the argument that a kinetic model of reactive strength is appropriate and needed. Or, our kinetic (strength)-based assessment of reactive strength agrees strongly with traditional assessments. This outcome would support the continued applicability of traditional assessments and provide an alternative kinetic-based measure of reactive strength. Based on prior literature, we expected that kinetic paradigm of reactive strength would agree moderately with the RSI. We also expected that, based on theoretical issues associated with the computation and implementation of the RSI, that the agreement between a

kinetic paradigm and the RSI would not be perfect.

4. Jump-trained NCAA Division I athletes should score better on assessments of reactive strength when compared against young adults from the University and local community. It was expected that NCAA Division I athletes would score higher on all measures of reactive strength. This expectation was based on known differences in performance between athletically trained young adults and young adults from the general population.
5. Males should score better on assessments of reactive strength due to known sex differences in jumping performance. This was expected based on results of prior literature (Kipp et al., 2016; Laffaye et al., 2016; McMahon et al., 2017; Ramirez-Campillo et al., 2015; Suchomel et al., 2015) suggesting that neuromuscular performance in jumping tasks diverges in post-pubescent males and females.
6. If responses to our questionnaire significantly predict reactive strength scores, we can argue in favor of the validity of our questionnaire. If responses to our questionnaire do not significantly predict reactive strength scores, we can assess for improvements to be made to the questionnaire to improve its' sensitivity. We expected weak to moderate positive associations between self-reported measures of physical activity and the various measures of reactive strength used in the present study.

### **Significance**

The CoR is the first known measure of neuromuscular reactivity. It was developed by Verkhoshansky (1968) as an assessment of drop jumping performance. The construct validity of the CoR was brought into question when Young proposed the RSI. The RSI improved the theoretical validity of reactive strength assessment since it included a component measure that modelled the interaction between the feet and ground during short duration impact.

The RSI is the current gold standard assessment of reactive strength since its' construct validity is assumed to be strong. There are several theoretical issues with the RSI that need to be addressed. This is especially important given the increased prevalence

of research on and interest in using the RSI in sport and clinical applications.

First, the RSI is a nonstrength-based measure that is assumed to model the construct of reactive strength. While an indirect association between the RSI and reactive strength can be argued, a kinetic (strength)-based paradigm of reactive strength is arguably more valid from a theoretical perspective. Second, use of the RSI requires the assumption that no biological variability exists in human movement. This assumption likely introduces inaccuracies to the computation of the RSI.

A paradigm of reactive strength that is based on kinetic data (e.g., acceleration, force) and does not include assumptions of mechanical theory may improve the theoretical validity of reactive strength assessment. In addition, a kinetic paradigm could be carried out using newer technologies (e.g., inertial measurement units). Pairing a kinetic paradigm of reactive strength with novel technology could expand the assessment of reactive strength in both sport and clinical populations. Expanding assessment in clinical populations could provide physical therapists and insurance providers an innovative outcome measure to monitor the progress of patients in physical rehabilitation. Current demand for physical therapy services in the United States of America provides approximately 30 billion dollars in annual revenue to the industry (IBISWorld, 2016). The American Physical Therapy Association (APTA, 2016) promotes the use of standardized outcome measures. The APTA believes that valid outcome measures contribute to the evaluation and selection of effective treatments.

Further, it is possible that pairing a kinetic (strength)-based paradigm of reactive strength with wearable sensors could allow for future assessment of reactive strength

through the whole-body center of gravity and through limb segment centers of gravity. This could facilitate the assessment of reactive strength in open-chain movements (e.g., overhand baseball pitching) that are known to produce high levels of stress in body tissues.

### **Limitations**

This study was limited to participants who possessed the physical aptitude necessary for the performance of high-impact jumping movements. Projecting beyond the current investigation, there is opportunity to expand reactive strength assessment into clinical populations. Eventual pairing of our proposed reactive strength algorithm with accommodative hardware (e.g., inertial measurement units) could allow for a complete assessment of Sheppard and Young's (2006) neuromuscular qualities in clinical populations. This development would hold merit knowing that the APTA encourages the use of outcome measures in clinical practice.

### **Assumptions**

The assumptions of this study were as follows.

1. Historically, measures of reactive strength make the assumption that no biological variability exists in human movement. In this study, we evaluate whether variability in drop jump kinematics introduces inaccuracies into the computation of reactive strength. We also evaluate whether differences in limb segment positioning at jump take-off versus landing introduces inaccuracies into the computation of reactive



strength.

2. An original assumption stated that the combination of ground reaction forces and mathematical relations between impulse, momentum, and kinetic energy could effectively model energy dissipation and stress-strain regulation at the tissue level. This turned out to be an invalid assumption. Instead, these relations provided an assessment of measurement error in traditional reactive strength assessments (see Appendix G).

3. A kinetic (strength)-based paradigm of reactive strength effectively models the neuromuscular regulation of tissue stress and strain. This assumption was made in replacement of assumption 2.

### **Definitions of Key Terms**

*Concentric power production:* A neuromuscular quality representing the rate and magnitude of concentric muscle contraction force. Concentric power is produced from the efferent activation of muscle fibers via the alpha motor neuron pathway.

*Bilateral symmetry:* A neuromuscular quality representing structurally balanced movement.

*Reactive strength:* A neuromuscular quality representing the regulation of tissue stress and strain through a coupling of reactive neural mechanisms with concentric activation of muscle. Reactive neural mechanisms include phasic stretch reflex activation and golgi tendon organ suppression.

*Agility:* A population specific construct that describes whole-body movement characterized by ‘rapid movement’ and a change in center of gravity velocity. Agile

movements are performed in a physical environment that contains variable spatial and temporal uncertainties (Sheppard & Young, 2006).

*Functional mobility:* “The manner in which people are able to move around in the environment in order to participate in activities of daily living and, move from place to place” (Forhan & Gill, 2013, p. 2). Functional mobility is a qualitative term intended to describe the ability of a person to successfully perform movements of their choosing.

## **CHAPTER II**

### **LITERATURE REVIEW**

The purpose of this chapter is to provide a theoretical and applied overview of reactive strength literature. This chapter also features extrapolation of the clinical applicability of reactive strength assessment in older adults.

#### **Development of Reactive Strength Theory**

Yuri Verkhoshansky (1968) and Fred Wilt (1975) pioneered the use of jump training for event preparation in Soviet and American track and field athletes. Verkhoshansky is a late Soviet track and field coach and scientist who contributed novel research in the area of jumping movements. Verkhoshansky established the “Shock-method” of training as a way to explore the role of jumping movement specificity in sport. A critical feature of Verkhoshansky’s shock-method research was that it distinguished between jumping movements performed from the ground and those performed immediately succeeding an impact with the ground. Verkhoshansky observed that his athletes produced greater vertical jump heights when they performed a jumping movement immediately after landing from a 0.5 m drop versus no drop. Verkhoshansky believed that “take-offs after a jump for depth” were the “leading method of improving the reactive ability of the nerve-muscle apparatus” (p. 3). His research provided fundamental theory on the application of neuromuscular function to movements that involve reaction to an impact.

Fred Wilt (1975) was a late track and field coach for the U.S. who recognized the

potential of jump training in the preparation of U.S. track athletes. Wilt introduced the idea of “plyometric” training to the U.S. after observing the successes of European track and field athletes who had incorporated jumping movements into their training regimens. Wilt (believed that the utilization of jumping movements by European track and athletes bridged “the gap between sheer strength and the power (rate of work or force x velocity) required in producing the explosive-reactive movements so necessary to excellence in jumping, throwing, and sprinting” (p. 82). Wilt (1975) believed that certain jump training drills provided added stimulation to the neuromuscular system. This belief led him to originate the term “plyometric...from the Greek word plethyein, which means to increase, and isometric.”

Both Verkhoshansky (1968) and Wilt (1975) emphasized the neuromuscular contribution to jumping movements that included an impact with the external environment (ground). Verkhoshansky was the first to provide an assessment. Verkhoshansky introduced the CoR in his foremost experiment. The CoR is defined mathematically as the spatial ratio of rebound jump height to drop height (see Appendix B, Equation 1). Verkhoshansky suggested that the measure effectively modelled the “reactive ability of the nerve-muscle apparatus” (p. 1). A key deficiency of the CoR is that it provides no measure of the interaction between the feet and the ground. Theoretically, one could land from a drop, stand on the ground for an extended period of time, and then jump up and score a high CoR value.

While researchers and practitioners were prompt in applying the work of Verkhoshansky (1968), interest in neuromuscular reactivity in jumping did not recur until

1995 (Young, 1995). Young introduced the RSI as a temporal ratio of rebound jump flight time (or height) to ground contact time (see Appendix B, Equation 2). The RSI is accepted as the gold standard measure of reactive strength in current literature (Ball & Zanetti, 2012; Beckham et al., 2014; Byrne et al., 2017; Cloak, Nevill, Smith, & Wyon, 2014; Di Cagno et al., 2013; Di Giminiani, Tihanyi, Safor, & Scrimaglio, 2009; Ebben & Petushek, 2010; Feldmann, Weiss, Ferreira, Schilling, & Hammond, 2011; Flanagan & Comyns, 2008; Flanagan, Ebben, & Jensen, 2008; Flanagan, Galvin, & Harrison, 2008; Henry, Dawson, Lay, & Young, 2013; Hoffrén-Mikkola et al., 2015; Kipp et al., 2016; Laffaye et al., 2016; Lloyd, Oliver, Hughes, & Williams, 2009, 2012; Markwick et al., 2015; McClymont, 2005; McMahon et al., 2017; Newton & Dugan, 2002; Ramirez-Campillo et al., 2016; Rössler, Donath, Bizzini, & Faude, 2016; Struzik, Juras, Pietraszewski, & Rokita, 2016; Suchomel et al., 2015; Werstein & Lund, 2012). The RSI (Young, 1995) is similar to the CoR in the belief that it effectively assesses the reactive ability of the neuromuscular system. The RSI improved the construct validity of reactive strength assessment since it contains a component variable (ground contact time) that represents impact between the feet and ground. Temporal components of the RSI can be “cheated” under circumstances where there is participant awareness of the measurement algorithm. For example, the rebound jump time (height) component of the RSI is invalid if a person lands from a rebound jump with exaggerated lower extremity flexion or if there are differences in trunk flexion angle between take-off and landing.

It is recommended to use a force platform for the assessment of reactive strength. However, the cost of a laboratory grade force platform can be prohibitive. Patterson and

Caulfield (2010) proposed an affordable accelerometer-based alternative that features a wearable ankle accelerometer paired with a regression-based RSI algorithm. Patterson and Caulfield (2010) observed a Pearson product correlation ( $r$ ) of 0.98 between traditional RSI (Young, 1995) and their accelerometer-based approach. One benefit of an accelerometer-based approach is that it is cost-effective and largely accessible. Patterson and Caulfield's accelerometer-based algorithm modelled well against the RSI.

The RSI is considered the gold standard assessment of reactive strength and its assumed validity is strong. However, there are several theoretical issues with the computation and implementation of both the CoR and RSI. First, the CoR and the RSI attempt to represent neuromuscular reactivity (reactive strength) through spatial (CoR, see Appendix B, Equation 1) and temporal ratios (RSI, see Appendix B, Equation 2). In other words, the CoR and RSI are nonkinetic (strength) based measures that have been assumed as valid models of a strength construct. It can be argued that the CoR and RSI are indirectly associable to the construct of reactive strength. However, it is also logical to argue that a reactive strength paradigm based on kinetic data could improve the theoretical validity of reactive strength assessment.

Our original approach in developing a kinetic (strength)-based model of reactive strength was to build on the work of Komi and Bosco (1978). Komi and Bosco published an algorithm that modelled utilization of stored elastic energy during depth jumping (see Appendix B, Equation 3). The Komi and Bosco algorithm compared kinetic energy at landing impact with kinetic energy at rebound jump take-off (see Appendix B, Equation 3). It was assumed that we would be able to estimate energy dissipation during contact

with the ground using a force platform. We expected that this approach would model the ability of the neuromuscular system to regulate tissue stress and strain. This approach was not sensitive to tissue stress and strain yet served as a reliable estimate of measurement error in the CoR and the RSI.

Reactive strength is loosely defined as the ability to produce an explosive movement immediately succeeding an impact with the ground. In the present study, our kinetic (strength)-based paradigm of reactive strength is a ratio of net propulsive impulse to amortization time. Both net propulsive impulse and amortization time are measures that correspond to how the body behaves mechanically during an impact between the feet and ground. Net propulsive impulse corresponds to ‘explosiveness’ and is mathematically relatable to the height achieved in a jump. Amortization is a term used to describe a period of time where reactive neural mechanisms, such as the myotatic (stretch) reflex, are active and couple with concentric activation of agonist and antagonist musculature. Short amortization times are believed to represent good neuromuscular reactivity while longer times are often associated with the potentiation of neuroprotective mechanisms, such as the inverse myotatic (golgi tendon) reflex.

The concept of amortization has been explored recently in reactive strength literature. Instead of using a ratio of jump height to ground contact time (RSI), Struzik et al. (2016) split up ground contact time into amortization time and take-off time, or time in propulsion. They then reported two RSI values; one corresponding with amortization time and the other corresponding with the propulsive phase (Struzik et al., 2016). While this approach is more similar to our proposed kinetic-based paradigm than the RSI, it

remains a spatiotemporal ratio that is not kinetic (strength)-based and includes theoretical assumptions in its' computation.

A kinetic (strength)-based paradigm of reactive strength is arguably an improvement over the CoR and RSI from the perspective of construct validity. The RSI is accepted as the current 'gold standard' reactive strength paradigm and is assumed to have strong theoretical validity. However, the RSI is a non-kinetic (strength) based measure that attempts to model the construct of reactive strength. Reactive strength is a construct meant to represent the neuromuscular regulation of tissue stress and strain. Tissue strength is defined as the amount of stress (force/area) that a tissue can withstand before it experiences permanent strain, or injury. Our kinetic (strength)-based paradigm of reactive strength makes the assumption that there is a link between forces placed on the body (e.g., forces between the feet and ground) and the neuromuscular regulation of tissue stress and strain.

The CoR and RSI both assume that there is no biological variability in human movement. The measures assume that the downward displacement of the body's center of gravity during a drop jump is always equal to the height of the object used to perform the drop (e.g., plyometric box). Additionally, the measures assume that limb segment positioning does not differ at the instances of jump take-off and landing. In the present study, we include two versions of our kinetic (strength)-based paradigm. One of these versions (New) uses the same theoretical assumptions as the CoR and RSI in its' computation. Another version (AdjNew) is adjusted to account for biological variability and does not use assumptions of theory in its' computation.



## **Reactive Strength Index Literature**

The purpose of this section of the literature review is to provide an overview of RSI literature. A systematic search of the literature was performed using the Google Scholar and PubMed databases. The search term “reactive strength” was used to execute the search.

### **Reliability of the Reactive Strength Index**

Despite concerns regarding the theoretical validity of the RSI, the measure has been observed to be highly reliable. For instance, Byrne et al. (2017) evaluated the inter-day reliability of the RSI and optimal RSI drop height. These authors observed intraclass correlation coefficients above 0.80 for both the RSI and optimal RSI drop height across two sessions performed 48 hours apart (Byrne et al., 2017).

In twenty two NCAA Division I track and field athletes performing multiple depth jumps from 30 cm, Flanagan, Ebben, and Jensen (2008) observed high Cronbach coefficients ( $\alpha > 0.95$ ). Flanagan, Ebben, and Jensen (2008) suggested that the trial-to-trial reliability of the RSI is acceptable and that the RSI is a valid “indicator of stress on the musculotendinous complex.” In addition, Markwick et al. (2015) observed no trial-to-trial differences in RSI scores across thirteen professional male basketball players performing multiple depth jumps at heights of 20, 40, and 50 cm. Markwick et al. observed low coefficients of variation (2-5%) across repeated depth jump trials.

Results of Flanagan, Ebben, and Jensen (2008) and Markwick et al. (2015) suggest that reactive strength assessment should emphasize the performance of jumps at

multiple drop heights rather than repeated jumps at a single drop height. The performance of jumps at multiple drop heights allows a practitioner to identify jumping conditions that elicit optimal neuromuscular reactivity and minimizes the influence of fatigue from high volumes of jumping.

A majority of published data on the RSI is based on vertically directed jumps. Therefore, Ball and Zanetti (2012) sought to assess the influence of jump direction (vertical / horizontal) on RSI scores. They observed high intraclass correlation coefficients ( $r > 0.881$ ) for RSI scores in a sample of 28 young adults performing vertically and horizontally-directed rebound jumps (drop height = 0.4 m). Participants who scored well on tests of RSI tended to also score well on horizontal tests of RSI. However, longer ground contact times were observed for RSI tests performed in the horizontal direction (Ball & Zanetti, 2012). This result suggests that forward-directed rebound jumps may be neuromechanically specific from vertically directed rebound jumps. It is likely that differences in the performance of vertically and horizontally-directed rebound jumps are due to different neuromuscular activation patterns (e.g., different muscles active; different magnitudes of activation).

Di Cagno et al. (2013) observed mixed findings on the influence of time of day on reactive strength reliability across forty two elite female gymnasts and fifty similarly-aged female controls. However, one of our research questions was whether or not reactive strength assessments are sensitive enough to distinguish between populations of trained athletes and similar age controls. In the same study, Di Cagno et al. did observe that the RSI was sensitive enough to detect better reactive ability in a sample of trained

gymnasts versus untrained controls.

### **Applied Literature**

Evaluating the associativity of the RSI with established measures of athletic performance is a main focus of applied literature. For instance, in a sample of one hundred six NCAA Division I athletes, Beckham et al. (2014) observed moderate to large Pearson correlations ( $r = 0.34-0.54$ ) between the RSI and measures of mid-thigh pull performance. These measures included peak force (N), force at 200 ms (N), rate of force development ( $N*s^{-1}$ ), and impulse ( $N*s$ ) from 0-200 ms. Beckham et al. concluded that the RSI “appears to be a measure of explosive ability.” In one hundred six NCAA Division I athletes, Suchomel et al. (2015) observed moderate to large Pearson correlations ( $r = 0.37-0.78$ ) between the RSI and kinetic measures of jump performance. These measures included peak force (N), peak mechanical power (W), and rate of force development ( $N*s^{-1}$ ).

Injuries to the anterior cruciate ligament (ACL) of the knee are commonly incurred in sport. The effects of a compromised ACL and subsequent rehabilitation programs are commonly studied from a neuromuscular perspective. For instance, Flanagan, Galvin, and Harrison (2008) evaluated the success of anterior cruciate ligament (ACL) reconstruction using a battery of functional measures that included the RSI. These authors observed no difference in RSI scores (partially unloaded depth jumps from 0.3 m) between ten adults with a recent history of ACL reconstruction and an age and activity matched control group. The results of this study suggest that ACL reconstruction and rehabilitation can restore bilateral symmetry between the affected and non-affected knee.

Rates of noncontact ACL injury are much higher in post-pubescent females versus males. Since the RSI is assumed to model the regulation of tissue stress and strain, evaluating the influence of sex on RSI scores has been a focus of recent literature. For instance, Suchomel et al. (2015) observed lower RSI scores in a sample of forty five young female participants compared against a sample of sixty one young male participants. This finding is supported by the work of several researchers observing that young male adults produce between 18% and 85% higher RSI scores versus young female adults (Kipp et al., 2016; Laffaye et al., 2016; McMahon et al., 2017; Ramirez-Campillo et al., 2016).

The influence of sex on the RSI is expressed during the pubescent years. For instance, Laffaye et al. (2016) observed no significant differences in RSI across males and females aged 11 to 16. These same authors observed significantly higher RSI scores in males versus females between the ages of 17 and 20. Researchers are interested in the application of reactive strength testing across the lifespan from children as young as 11 (Rossler et al., 2016) to adults in their seventies (Hoffrén-Mikkola et al., 2015)

Vibration is commonly used to enhance neural function in the human body. Researchers suggest that whole-body vibration may influence reactive strength through potentiation of the stretch reflex (Di Giminiani et al., 2009). For instance, Di Giminiani et al. evaluated the performance of repetitive countermovement jumps in a sample of nine adults prior to and after 8 weeks of optimized whole-body vibration. These authors indirectly observed a significant increase in rebound jump height (+ 4.7 cm) with no significant change in ground contact time. Indirectly, these results suggest that RSI

increased following 8 weeks of optimized whole-body vibration. In addition, Di Giminiani et al. observed no change in rebound jump height or ground contact time in ten adults following 8 weeks of whole-body vibration at a standard frequency of 30 Hz and in a no vibration control group. In support of these findings, Cloak et al. (2014) observed greater RSI scores in twenty five collegiate soccer players following an acute bout of whole-body vibration. Cloak et al. observed no difference in RSI scores in twenty five collegiate soccer players following a 30 s isometric squat and in a no intervention control group.

In summary, the RSI has been shown to be highly reliable. Researchers have provided support for the assumed construct validity of the RSI in studies investigating the associativity of the RSI with other measures of athletic performance and the influence of both sex and age on neuromuscular reactivity.

### **Clinical Inference in Older Adults**

The purpose of this section is to provide an overview of literature describing key physiological changes associated with the aging process and an application of Sheppard and Young's (2006) three neuromuscular qualities in older adults.

Aging is associated with a deterioration of muscle tissue structure and function (Cesari et al., 2006; Goodpaster et al., 2001; Legrand et al., 2014; Manini & Clark, 2012; Mitchell et al., 2015; Srikanthan & Karlamangla, 2014). The loss of muscle mass and contractile performance during aging influences functional mobility (Cesari et al., 2006), risk of falling (Pereira & Goncalves, 2011), hospitalization (Legrand et al., 2014),

mortality (Legrand et al., 2014), and the acquisition of physical disability (Legrand et al., 2014).

Rosenberg (1989) was the first to use the term “sarcopenia” in describing the loss of muscle mass during aging. The European Working Group on Sarcopenia in Older People (EWGSOP; Cruz-Jentoft et al., 2010) advanced the definition of sarcopenia to include classification levels based on the degree of muscle tissue deterioration, muscle weakness, and loss of physical function. The three classification levels are as follows.

1. Presarcopenia: Low muscle mass with normal muscle strength and physical function.
2. Sarcopenia: Low muscle mass coupled with either muscle weakness or impaired physical function.
3. Severe Sarcopenia: Low muscle mass coupled with muscle weakness and impaired physical function.

Sarcopenia has been identified as a ‘geriatric syndrome’ (Cruz-Jentoft et al., 2010) because of its prevalence in older populations, multiple causes, and negative impact on healthy aging. Sarcopenia is influenced by contributing factors from various physiological systems including the metabolic, endocrine, immune, neural, and vascular systems. In comparison with younger adults, older adults express rates of muscle protein breakdown that more frequently exceed rates of muscle protein synthesis (Mitchell et al., 2015). In younger adults, the rate of muscle protein synthesis increases following the ingestion of food or participation in physical activity (Mitchell et al., 2015). Conversely, older adults exhibit a blunted physiological response to food intake and physical activity, in which there is no subsequent increase in muscle protein synthesis (Mitchell et al., 2015).

Aging is associated with a shifting muscle proteome (Mitchell et al., 2015). The body shifts to a preferential expression of slow-twitch myosin heavy chains, or slow-twitch muscle fibers (Mitchell et al., 2015) during aging. Researchers have observed a downregulation of enzymes that contribute to anaerobic metabolism and an upregulation of enzymes that contribute to aerobic metabolism (Mitchell et al., 2015) in older adults. A preferential shift toward upregulating aerobic enzymes supports the idea that fast-twitch muscle fibers are compromised during the aging process.

Hormonal contributions to sarcopenia seem to disproportionately affect older males (Mitchell et al., 2015). Decreased levels of testosterone and other anabolic androgens are believed to contribute to the increased rate of muscle mass loss seen in older males (Mitchell et al., 2015). There is a positive influence of low thyroid activity and high parathyroid activity on levels of sarcopenia in older adults of both sexes (Mitchell et al., 2015). Shifts in thyroid activity result in a reduction of pituitary growth hormone and hepatic insulin-like growth factor 1. Levels of growth hormones are further compromised in older adults with chronic inflammation (Mitchell et al., 2015). The body presents with increased circulation of catabolic cytokines, including interleukin 6 and tumor necrosis factor alpha (Mitchell et al., 2015) when inflammation is present. The age-related increase in levels of catabolic cytokines is associated with reductions in growth hormone levels, functional mobility, mortality, and rates of physical disability (Mitchell et al., 2015).

Deterioration of the neuromotor system is a physiological consequence of aging. Neuromotor impairment is thought to contribute the reduction of muscle mass and loss of

muscle strength (Mitchell et al., 2015) in older adults. Apoptosis is the programmed death of alpha motor neurons. The alpha motor neuron pathway serves as the principal efferent activator of contractile muscle tissue (Mitchell et al., 2015). Deterioration of the neuromotor system during aging is primarily influenced by apoptosis. In addition, a clustering of muscle fiber types has been observed in older adults (Mitchell et al., 2015). It is suggested that muscle fiber clustering represents an attempt by the nervous system to combat alpha motor neuron loss through incomplete reorganization (Mitchell et al., 2015).

Lifestyle modifications such as diet and participation in physical activity can either accelerate or modulate the development of sarcopenia in older adults. For example, reductions in daily protein, calcium, and Vitamin D intake have been shown to negatively impact rates of muscle protein synthesis in older adults (Mitchell et al., 2015). In addition, participation in regular physical activity helps to maintain muscle performance and functional mobility in older adults (Mitchell et al., 2015).

While the EWGSOP provides classification levels based on both muscle tissue structure and function (Cruz-Jentoft et al., 2010), researchers have also argued that sarcopenia should be a term that solely represents the loss of muscle mass during the aging process (Manini & Clark, 2012). Dynapenia has been proposed as an alternative term to describe the age-related loss in muscle strength and functional mobility (Manini & Clark, 2012). Justification for the use of dynapenia was based on recent developments in sarcopenia research that suggest marginal associations between muscle mass loss and reductions in muscle strength among older adults (Manini & Clark, 2012). Reductions in



descending neural drive from the primary motor cortex and corticospinal neurons is thought to be a main contributor to dynapenia and the loss of muscle strength in older adults (Manini & Clark, 2012). Additionally, researchers have proposed that the intrinsic force-generating capacity of muscle fibers is compromised in older adults (Manini & Clark, 2012). It is a preferential shift in muscle fiber types that likely contributes to slower muscle contraction velocity (Manini & Clark, 2012; Mitchell et al., 2015). In addition, impaired excitation-contraction coupling and intramuscular adipose deposits are thought to reduce levels of intrinsic muscle force-generating capacity (Manini & Clark, 2012).

### **Muscle Strength and Mechanical Power**

Aging is associated with the development of muscle weakness and functional decline (Cesari et al., 2006; Goodpaster et al., 2001; Legrand et al., 2014; Pereira & Goncalves, 2011). The loss of muscle mass, reduced neural drive, and impaired intrinsic muscle force-generation capacity as probable causes for the age-related decline in muscle strength (Manini & Clark, 2012; Mitchell et al., 2015).

While the consequences of age-related muscle strength impairments include increased risk of falling (Pereira & Goncalves, 2011), frailty (Cesari et al., 2006), hospitalization (Legrand et al., 2014), and mortality (Legrand et al., 2014), it appears that mechanical power may be a better predictor of physical functioning in older adults (Puthoff & Nielsen, 2007).

For example, Puthoff and Nielsen (2007) explored relationships among lower limb strength and power, functional mobility, and physical disability in a sample of 25

functionally limited older women and 5 functionally limited older men (Age [years]:  $77.3 \pm 7.0$ ). They observed significant relationships between lower limb strength, lower limb power, and functional mobility. For instance, power (W) at 90% of one repetition maximum demonstrated the strongest relationship with measures of balance and walking contained in the Short Physical Performance Battery (partial  $R^2 = 0.39$ ,  $p < 0.001$ ; Puthoff & Nielsen, 2007). In addition, peak power (W) demonstrated the strongest relationship with performance on the 6-Minute Walk Test (partial  $R^2 = 0.48$ ,  $p < 0.001$ ; Puthoff & Nielsen, 2007) and the Late Life Function and Disability Index Functional Limitation Component Score (partial  $R^2 = 0.35$ ,  $p = 0.001$ ; Puthoff & Nielsen, 2007).

Puthoff, Janz, and Nielsen (2008) explored similar relationships between lower limb strength, lower limb power, and measures of walking behavior in a sample of twenty five functionally limited older women and five functionally limited older men. They observed significant relationships between lower limb strength, power, and measures of walking behavior. For instance, peak power (W) demonstrated the strongest relationship with total steps taken over a 6 day time period (partial  $R^2 = 0.16$ ,  $p < 0.05$ ; Puthoff et al., 2008), total walking distance over a 6 day time period (partial  $R^2 = 0.44$ ,  $p < 0.001$ ; Puthoff et al., 2008), and average walking speed over a 6-day time period (partial  $R^2 = 0.50$ ,  $p < 0.001$ ; Puthoff et al., 2008).

Skelton et al. (2002) observed significant deficits in non-dominant lower limb explosive power for twenty independent older women with a recent history of falls ( $< 1$  year). In comparison with an age and strength-matched sample of nonfallers, women with a history of falls produced 24% less mechanical power from their nondominant limb. The

results of this study suggest that lower extremity mechanical power may be predictive of fall risk in older independent women.

Clark et al. (2011) assessed the relationship between voluntary neuromuscular activation, functional mobility, and performance on a leg press task. Clark et al. observed impaired neuromuscular activation (electromyography movement delay and rate electromyography rise) and leg press performance (acceleration and power) in twenty three functionally limited older adults. In comparison with healthy middle-aged and older adults, participants in the functionally limited older adult group produced between 26 and 58% less acceleration and mechanical power during the leg press. The results of this study suggest that leg press performance and assessments of neuromuscular function may be predictive of mobility in functionally limited older adults.

Reid et al. (2012) assessed the role of muscle quality and neuromuscular activation on age-related deficits in power and functional mobility. Reid et al. observed deficits in neuromuscular activation and general muscle quality in a sample of functionally-limited older adults. In comparison with healthy middle-aged and older adults, participants in the functionally limited older adults group produced between 11% and 50% less mechanical power during a leg press task. The results of this study suggest that successful aging and the preservation of lower limb power (Reid & Fielding, 2012) may be influenced by deficits in neuromuscular function and muscle tissue quality (Reid et al., 2014).

Relationships between lower limb power and functional mobility have been observed in other clinical populations. Allen, Sherrington, Canning, and Fung (2010)

assessed the relationship of lower limb power, walking mechanics, and fall risk in a sample of adults with Parkinson's disease. They observed that lower limb power and strength were significantly related to comfortable walking velocity (partial  $R^2 = 0.56$ ,  $p < 0.001$ ; Allen et al., 2010), maximal walking velocity (partial  $R^2 = 0.62-0.66$ ,  $p < 0.001$ ; Allen et al., 2010), and incidence of falls ( $p = 0.04$ ; Allen et al., 2010) in adults with Parkinson's disease.

### **Bilateral Symmetry**

Bilateral symmetry is defined operationally as movement uniformity in contralateral limbs. Bilateral symmetry is identified by Sheppard and Young (2006) as a key neuromuscular characteristic of agility. In addition, bilateral symmetry has been identified as a significant predictor of functional mobility in older adults (Skelton et al., 2002). Skelton et al. observed significantly greater strength and power asymmetry between dominant and nondominant legs in a sample of 20 independent older women with a recent history of falls (< 1 year). A majority of older women in the "faller" group (60%) presented with lower limb power asymmetry above 10%. A much smaller proportion of older women in the "nonfaller" group (13%) presented with lower limb power asymmetry above 10%. The results of this study suggest that strength and power imbalances across dominant and nondominant legs may be predictive of fall risk in older, independent women.

### **Reactive Strength**

The RSI is assumed to be a valid assessment of the reactive ability of the

neuromuscular system. Factors that influence the reactive ability of the neuromuscular system include the storage and recapture of energy in elastic structures (Komi & Bosco, 1978), activation of the central nervous system in anticipation of stress (Enoka, 1996; Fang, Siemionow, Sahgal, Xiong, & Yue, 2001; Grabiner & Owings, 2002), and the coupling of neuroprotective mechanisms with concentric muscle activation (Enoka, 2008).

One limitation reactive strength testing protocols is that they require the performance of high-stress jumping movements that are often contraindicated in older adults. Using repetitive hopping, Hoffrén-Mikkola et al. (2015) were successful in assessing the RSI in a sample of older males (~60 to 80 years old). These authors observed that 11 weeks of hopping training performed by older males was effective at improving RSI scores and decreasing levels of agonist-antagonist muscular coactivation (Hoffrén-Mikkola et al., 2015).

Muscular coactivation is operationally defined as the simultaneous alpha motor neuron activation of agonist and antagonist muscle groups. Muscular coactivation is a neural characteristic that has been observed to negatively influence power production in older women (Pereira & Goncalves, 2011). Muscular coactivation may influence the reactive ability of the neuromuscular system by limiting rate of force development at the onset (0-200 ms) of muscular contraction (Pereira & Goncalves, 2011). Movements that involve a time-sensitive reaction to an impact with the external environment invoke the phasic stretch reflex of muscle (Pereira & Goncalves, 2011). The phasic stretch reflex of muscle increases agonist neural drive and decreases antagonist neural drive (Pereira &

Goncalves, 2011). Granacher, Muehlbauer, and Gruber (2012) suggest that consequences of high levels of coactivation observed in older adults include a reduced ability to respond to balance perturbations. Therefore, jump training in older adults likely decreases agonist-antagonist coactivation which could lead to improved responses to balance perturbations and a reduced risk for falling.

## **CHAPTER III**

### **METHODS**

This chapter describes methods used to address the purposes of the study. This chapter is divided into sections describing the study design, participants, instrumentation, procedures, data analysis, and statistical analysis.

#### **Study Design**

We used a cross-sectional, experimental investigation to address the purposes of the study. To maximize the internal validity and interpretability of results, we referred to the physiotherapy evidence database scale (PEDro; Maher, Sherrington, Herbert, Moseley, & Elkins, 2003) as a guide for implementing the study design. The present study scores a 7 on the PEDro scale (see Appendix C). This is an acceptable score based on prior research observations suggesting that clinical trials score a mean of 5.2 on the PEDro scale (de Morton, 2009).

#### **Participants**

##### **A Priori Power Analysis**

For Bland-Altman agreeability analyses, an increase in  $n$  (sample size) results in increased precision of upper and lower limits of agreement. To estimate the precision of upper and lower limits of agreement, the following equation for standard error was applied to the  $t$  distribution with  $n-1$  degrees of freedom ( $s$  = standard deviation):

$$\text{Standard Error} = \sqrt{\frac{3s^2}{n}}$$

Eighty young adults participated in the present study. Given that the two jumping protocols produced seven values for each of three measures of reactive strength, we obtained a total  $n$  of 560. This  $n$  provided high limits of agreement precision for the planned Bland-Altman agreeability analysis.

To estimate an appropriate sample size for our planned analyses of variance, an a priori power analysis was conducted using the G\*Power software package (Faul, Erdfelder, Land, & Buchner, 2007). Ball and Zanetti (2012) observed a mean RSI score of  $1.39 \pm 0.36$  in sample of 28 active young adults (> 1 year of jump training experience) performing depth jumps at a height of 40 cm. Markwick et al. (2015) observed a mean RSI score of  $2.13 \pm 0.26$  in a sample of 13 athletically trained basketball players performing depth jumps at a height of 40 cm. These two means were matched with our expected unequal sample sizes and inputted to G\*Power to estimate an effect size  $f$ . These means produced an effect size  $f$  of 0.35. An effect size  $f$  (0.35), alpha error probability (0.05), and power (0.8) were entered into G\*Power to estimate the total sample size needed. These values produced an estimated total sample size needed of 70.

### **Participants**

Eighty young adults (male  $n = 41$ ; female  $n = 39$ ) with no recent history of lower extremity injury were asked to volunteer for this study (see Table 1). Fifty-nine young adults were recruited from the community and university student body (male  $n = 31$ ;



Table 1

*Descriptives and Data from a Physical Activity Screen*

Descriptive	NCAA DI basketball players			Young adults		
	Male ( <i>n</i> = 10)	Female ( <i>n</i> = 11)	Total ( <i>n</i> = 21)	Male ( <i>n</i> = 31)	Female ( <i>n</i> = 28)	Total ( <i>n</i> = 59)
Age (years)	20.1 ± 1.3	19.6 ± 0.8	19.9 ± 1.1	23.9 ± 1.7	23.3 ± 1.8	23.6 ± 1.8
Mass (kg)	91.6 ± 11.8	74.4 ± 10.3	82.6 ± 13.9	80.2 ± 12.5	68.0 ± 14.5	74.4 ± 14.7
Height (cm)	196.9 ± 8.0	181.0 ± 8.3	188.6 ± 11.3	177.5 ± 8.4	167.3 ± 8.6	172.7 ± 9.8
DayMod (days)	5.0 ± 0.0	5.0 ± 0.0	5.0 ± 0.0	3.4 ± 1.3	3.8 ± 1.3	3.6 ± 1.3
DayVig (days)	5.0 ± 0.0	5.0 ± 0.0	5.0 ± 0.0	1.8 ± 1.1	2.0 ± 1.3	1.9 ± 1.2
DayJump (days)	1.0 ± 0.0	1.0 ± 0.0	5.0 ± 0.0	1.1 ± 1.2	1.1 ± 1.5	1.1 ± 1.3
TimeVig (hours)	2.0 ± 0.0	2.0 ± 0.0	2.0 ± 0.0	1.1 ± 0.8	1.0 ± 0.4	1.0 ± 0.6
PlyoExp (months)	58.8 ± 3.8	60.0 ± 0.0	59.4 ± 1.7	8.0 ± 14.0	10.4 ± 17.1	9.1 ± 15.5

*Note.* Data are reported as mean ± *SD*.

female *n* = 28). An additional twenty one adults were recruited from NCAA-sponsored athletics. These participants were court sport athletes from the Utah State University men's and women's basketball programs (male *n* = 9; female *n* = 11). Participants were asked to complete a physical activity screen (see Appendix D). While both the NCAA-sponsored court sport athletes and young adult groups were asked to complete the screen, it was primarily used to assess participant uniformity in the young adult group. In addition, it should be mentioned that the physical activity screen did not discriminate specific activities performed. For instance, young adults from the general community could have been actively involved in recreational basketball multiple times per week. Participants were asked to provide responses to the following questions.

1. DayMod: In a typical week, how many days do you participate in moderate intensity exercise?
2. DayVig: In a typical week, how many days do you participate in vigorous

intensity exercise?

3. DayJump: In a typical week, how many days do you participate in activities that include jumping / landing from jumps?
4. TimeVig: On a given day, about how much time do you spend participating in moderate to vigorous intensity exercise?
5. PlyoExp: Within the past 5 years, how much time (e.g., weeks, months, years) have you participated in plyometric / jump training?

### **Exclusion Criteria**

Participants were excluded from participation if:

1. They did not fall between the ages of 18 and 30.
2. They were pregnant or may be pregnant.
3. They had a recent history (within 12 months) of lower extremity injury or neural dysfunction that increased the risk of physical discomfort or harm beyond minimal.
4. Participants from NCAA-sponsored athletics were excluded if they were currently under any restriction from a team physician.

Prior to study involvement, participants were asked to provide consent. Consent was obtained via an informed consent document reviewed and approved by the Utah State University Institutional Review Board.

### **Instrumentation**

A plyometric box with the following dimensions: 20" x 26" x 32" was required to fulfill study procedures. Through the work of prior researchers (de Villarreal, Kellis, Kraemer, & Izquierdo, 2009), these dimensions were identified as optimal for eliciting maximal neuromuscular reactivity.

Kinetic data for all jumping movements were obtained via a tri-axial force platform (Model FP4080, Bertec Corporation, Columbus, OH, USA) recessed to be flush with the laboratory floor. Technical specifications of the force platform included:

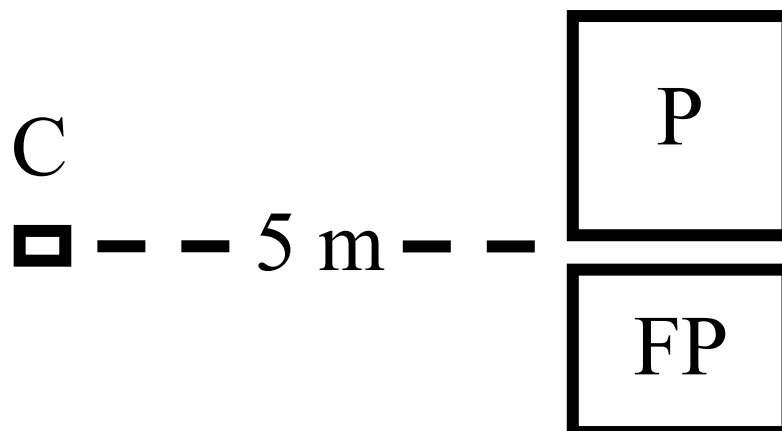
1. Dimensions: Width = 40 cm, Height = 15 cm, Length = 80 cm
2. Mass: 28 kg
3. Max Vertical Load: 10,000 N
4. Max Horizontal Load: 5,000 N
5. Natural Frequency (Vertical): 740 Hz
6. Natural Frequency (Horizontal): 570 Hz
7. Static Resolution:  $\pm 1$  N
8. Resolution: 0.19 N per least significant bit
9. Linearity: 0.2% of full scale output

For all jumping movements, sagittal plane kinematics were obtained via a high-speed camera (Model EX-F1, Casio, Shibuya, Tokyo, Japan) placed at a distance of 5 m from the participant (see Figure 1). The high-speed camera was placed on a level surface 0.67 m above the laboratory floor. Technical specifications for the high-speed camera included:

1. Dimensions: Width = 12.8 cm, Height = 8 cm, Depth = 13 cm
2. Mass: 0.671 kg
3. Effective Pixels: 6.0 megapixels
4. Flash Memory: 31.9 MB
5. Focal Length: 7.3-87.6 mm
6. Optical Zoom: 12X
7. Digital Zoom: 4X
8. Focusing: Contrast Detection Auto Focus
9. Shutter Speed: 1 to 1/2000 second (Auto)

### **Data Sampling**

Kinetic data were sampled at a commonly used and acceptable sample rate of



*Figure 1.* Laboratory set-up for the acquisition of kinetic and kinematic data (P = Plyometric Box, FP = Force Platform, C = High-speed Camera).

1000 Hz. Data acquisition was initiated manually, and occurred immediately following the delivery of verbal cues to the participant. Data acquisition was set for a 20 s time period and was terminated manually once the desired jumping movement had been performed successfully. Kinetic data were filtered using a 4<sup>th</sup> order, recursive, low-pass Butterworth filter, which allowed frequencies at or below 100 Hz to pass through (Bisseling & Hof, 2006).

Although the force platform has been established as a reliable instrument for capturing the kinetics of jumping movements (Cordova & Armstrong, 1996), we obtained an independent estimate of force platform reliability. After auto zeroing the force platform, we placed a 20 kg calibration weight in the center of the platform. We collected static data for 20 seconds and repeated this 10 times. A perfect force platform system would measure the force of a 20 kg calibration weight to be 196 N. Across 10 trials, our force platform set-up recorded a mean force of 194.03 N and a standard deviation of 0.64

N. Dividing the standard deviation by the mean force gave a coefficient of variation of 0.33%. While our force platform measured about 2 N below theoretical, the calibration measurement was highly reliable.

Kinematic data were sampled at a commonly used and acceptable sample rate of 300 Hz. Trunk, thigh, shank, and foot segment angles were measured manually using Kinovea (version 0.8.15, [www.kinovea.org](http://www.kinovea.org)). Segment angles were recorded at the instance of rebound jump take-off and rebound jump landing. Segment angles were obtained for every drop jump trial and for each repetitive countermovement jump.

### **Procedures**

Participants completed a 5-minute familiarization session prior to data collection. Researchers have observed high intraclass correlations for vertical jumps without familiarization (Moir, Button, Glaister, & Stone, 2004). However, allowing for practice exposed participants to the physical requirements of performing high-stress depth jumps and allowed members of the research team to instruct and observe jump technique. Data collection and familiarization were performed on the same day. We followed National Strength and Conditioning Association (NSCA) guidelines for rest and total jump volume (Haff & Triplett, 2015). Twenty minutes of rest was provided in between the completion of familiarization and commencement of data collection. This rest period resulted in a NSCA-recommended work to rest ratio between 1:4 and 1:5. Participants were asked to complete a total of 16 maximal effort jumps. The NSCA recommends no more than 100 foot-to-ground contacts per jump training session. With 16 maximal effort jumps falling

well within recommendations, it is unlikely participants experienced an appreciable amount of fatigue.

Participants attended a single data collection session and were asked to perform five repetitive countermovement jumps and a progressive series of drop jumps from 0.5 m (20 in), 0.66 m (26 in), and 0.81 m (32 in) above the ground. We elected to use these jumping protocols since they are both commonly used in prior RSI literature (Ebben & Petushek, 2010; Flanagan, Ebben, & Jensen, 2008). Participants completed both protocols within an hour-long data collection session. The completion of protocols were randomized across participants.

Participants performed three depth jumps at progressively increasing drop heights (Protocol One; see Appendix E). For depth jumps, participants were instructed to initiate the drop phase by stepping forward with their preferred foot. A member of the research team also demonstrated the drop technique. Participants were instructed to land from the drop with both feet impacting the force platform simultaneously. Participants were instructed to perform a maximal jump upwards following impact with the force platform with an emphasis placed on jumping as high as possible. Since spatial and temporal focused verbal cues have been observed to influence jumping kinetics (Louder, Bressel, & Bressel, 2015), we standardized our instructions across participants. For depth jumps, the following standard verbal instruction was used: “Immediately after impact with the ground, perform an explosive jump upward and focus on jumping as high as you can”

Participants also performed five consecutive countermovement jumps (Protocol Two; see Appendix F). A member of the research team demonstrated the

countermovement technique. While countermovement depth was self-selected, all participants performed jumps that involved a rapid hip flexion, knee flexion, and ankle dorsiflexion immediately prior to propelling the body upward for maximal vertical displacement. Participants were provided the following standardized verbal cue:

“Immediately after impact with the ground, perform an explosive jump upward and focus on jumping as high as you can...you will do this consecutively until five jumps have been performed.”

All jumping movements were monitored visually and in real time by member(s) of the research team. A jump was considered valid if:

1. The participant made simultaneous foot contact when impacting the force platform.
2. The participant did not lose balance or hesitate prior to performing the rebound jump. This was monitored in real time using time-series force data and visually by a member of the research team.
3. A jump was considered invalid if a member of the research team believed that the jump was not performed at maximal effort. This was monitored in real-time using time-series force data.

## **Data Analysis**

### **Protocol One**

Kinetic and kinematic data from three progressively higher depth jumps were used to compute the following dependent measures: CoR, RSI, a kinetic (strength)-based measure of reactive strength (New), and a kinematic-adjusted kinetic (strength)-based measure of reactive strength (AdjNew).

The CoR was computed as the ratio of rebound jump height to drop height (see

Appendix B, Equation 1). Drop height was the height of the plyometric box. Rebound jump height was computed using rebound jump take-off velocity (see Appendix B, Equation 4). Rebound jump take-off velocity was computed using rebound jump flight time obtained from force platform data (see Appendix B, Equation 5).

The RSI was computed as the ratio of rebound jump height to ground contact time (see Appendix B, Equation 2). Rebound jump height used in the computation of RSI was the same as rebound jump height used in the computation of CoR. Ground contact time was obtained directly from force platform data. Foot contact with the force platform was defined by a 10 N change in force over a 0.001 s time period (Donoghue, Shimojo, & Takagi, 2011).

The New was computed as a ratio of net propulsive impulse to amortization time (see Appendix B, Equation 6). Amortization time was computed as the amount of time in propulsion required to offset theoretical impact momentum (see Appendix B, Equation 7). Measured impulse between the feet and force platform less the sum of theoretical impact momentum and a bodyweight integral yielded net propulsive impulse. Measured impulse was obtained through a single integration of the vertical ground reaction force time series. Theoretical impact momentum was computed using the known height of the plyometric box (see Appendix B, Equation 8).

The AdjNew was computed using the same mathematical procedure as the New but factored in a measured value for impact momentum (see Appendix B, Equations 9 and 10). Measured impact momentum was computed using a value for drop time that was identified from sagittal plane video recordings (see Appendix B, Equation 11). The use of



video recordings to identify whole body velocity (momentum) has been used in prior literature and has been shown to be accurate when compared against force platform data (Komi & Bosco, 1978).

### **Protocol Two**

Kinetic and kinematic data from five repetitive countermovement jumps were used to compute the following dependent measures: CoR, RSI, a kinetic (strength)-based measure of reactive strength (New), and a kinematic-adjusted kinetic (strength)-based measure of reactive strength (AdjNew).

The CoR was computed using the same equation as in protocol one (see Appendix B, Equation 1). Flight time for the first jump was used to compute the first drop height, and so on. This method of analysis allowed for the computation of four CoR values across five jumps.

The RSI was computed using modified methods described previously (see Appendix B, Equation 2). This method of analysis allowed for the computation of four RSI values across five jumps.

The New was computed as a ratio of net propulsive impulse to amortization time (see Appendix B, Equation 6). Measured impulse between the feet and force platform less the sum of theoretical impact momentum and a bodyweight integral yielded net propulsive impulse. Measured impulse was obtained through a single integration of the vertical ground reaction force time series. Theoretical impact momentum was computed using one half of total flight time from the prior jump (see Appendix B, Equation 12). Amortization time was computed as the amount of time in propulsion required to offset

theoretical impact momentum (see Appendix B, Equation 8).

The AdjNew was computed using the same mathematical procedure as the New but factored in a measured value for impact momentum (see Appendix B, Equations 9 and 10). Measured impact momentum was computed using a value for drop time that was identified from sagittal plane video recordings (see Appendix B, Equation 13).

### **Validation of a Kinetic-Based Reactive Strength Assessment**

Variability in movement kinematics during drop jumping can introduce inaccuracies into the computation of the CoR, RSI, and New. For instance, if a person jumps upwards off of a plyometric box, they may impact the ground with greater momentum than if they were to step directly off the box. Similarly, if a person lowers their center of gravity prior to leaving the box, they may impact the ground with less momentum than if they were to step directly off of the box. The relationship between center of gravity displacement and impact momentum is quadratic. For example, if a person lowers their center of gravity 5 cm prior to jumping down from a height of 50 cm, they would impact the ground with approximately 5% less momentum than would be expected from a drop of 50 cm. Therefore we used measured drop times obtained from video to compare against theoretical drop times that were based on the height of the plyometric box. We estimated impact velocity using both the measured and theoretical drop times for each depth jump.

Limb segment positioning can influence rebound jump flight times and introduce inaccuracies into the computation of the CoR, RSI, and New. Therefore, we computed

trunk, thigh, shank, and foot segment angles at the instance of rebound jump take-off and rebound jump landing. Segment angles were obtained using Kinovea (version 0.8.15, [www.kinovea.org](http://www.kinovea.org)) by measuring absolute angles referenced to an anterior horizontal line.

### **Statistical Analysis**

All hypothesis tests were conducted at an alpha level of 0.05.

### **Validation Measures**

For the drop jumps, we assessed the statistical relationship between theoretical impact momentum and measured impact momentum by performing a linear regression on drop height (predictor) and measured impact velocity (response). For this regression, the following hypothesis test was conducted:

$H_0$ : There is no linear statistical relationship between drop height and measured impact velocity.

$H_a$ : There is a linear statistical relationship between drop height and measured impact velocity.

This hypothesis test was conducted in relation with research question 1 (see Introduction: Purpose). This test supported an evaluation of the influence of kinematic variability on reactive strength assessments that use the drop jumping protocol. A rejection of the null hypothesis would lead to the conclusion that drop height is linearly related to the “true,” or measured impact velocity. In this case, we would evaluate the strength of the statistical relationship to determine the need for a kinematic adjustment to our kinetic (strength)-based paradigm of reactive strength in depth jumping. Failure to reject the null hypothesis would lead to the conclusion that drop height is not linearly

related to measured impact velocity. In this case, we would argue the need for a kinematic-adjusted kinetic (strength)-based paradigm of reactive strength in drop jumping.

For all jumps, differences in limb segment positioning at jump take-off and landing were assessed using multiple paired  $t$  tests using trunk, thigh, shank, and foot segment angles obtained at rebound jump landing and rebound jump take-off. For these comparisons, the following hypothesis test was conducted:

H<sub>0</sub>: There is no statistical difference in limb segment positioning at the instances of rebound jump take-off and rebound jump landing.

H<sub>a</sub>: There is a statistical difference in limb segment positioning at the instances of rebound jump take-off and rebound jump landing.

This hypothesis test was conducted in relation with research question 2 (see Introduction: Purpose). This test supported an evaluation of the influence of limb segment positioning on reactive strength assessment. A rejection of the null hypothesis would lead to the conclusion that a kinematic-adjusted kinetic (strength)-based paradigm of reactive strength improves the theoretical validity of reactive strength assessment. Failure to reject the null hypothesis would lead to the conclusion that rebound jump kinematics likely do not influence measures of reactive strength.

### **Agreeability Analyses**

Agreeability analyses were conducted in relation with research question 3. These analyses supported an evaluation of the agreeability between a proposed, kinetic (strength)-based reactive strength algorithm (New and AdjNew), the CoR, and the RSI. Using reactive strength data from both protocols (560 total data points), we performed the

following Bland-Altman analyses (Bland & Altman, 2010):

1. CoR versus RSI
2. CoR versus New
3. RSI versus New
4. CoR versus AdjNew
5. RSI versus AdjNew

For all Bland-Altman agreeability analyses, the precision of upper and lower limits of agreement were determined using an equation for standard error (see Introduction: Procdeures). The Bland-Altman approach is favored over correlation, since a correlation analysis does not assess agreeability. Rather, a correlation analysis is sensitive to the interdependence of measures. It is possible for two continuous variables to be highly interdependent yet not agreeable (Bland & Altman, 2010). Therefore, using the Bland-Altman approach provides an analysis of the differences between two continuous variables attempting to measure the same construct. Regressions were performed on Bland-Altman data to assess the statistical relationship between mean score (predictor) and difference score (response).

Using reactive strength data from both protocols, we performed the following linear regression analyses:

1. CoR versus RSI
2. CoR versus New
3. RSI versus New
4. CoR versus AdjNew
5. RSI versus AdjNew

### **Analyses of Variance**

We performed one multivariate general linear model analyses of variance (ANOVA) per jumping protocol. Following the observation of main effects, we assessed

differences using the post-hoc LSD method.

The ANOVA on drop jump data included drop height (20, 26, 32 inches), population (young adult, NCAA Division I basketball player), sex (male, female), and age (years) as factors in the model. Dependent measures included CoR, RSI, New, AdjNew, net propulsive impulse, adjusted net propulsive impulse, amortization time, and adjusted amortization time. In this ANOVA, we used the New and AdjNew as dependent measures yet also broke these down into respective component measures (net propulsive impulse and amortization time). This allowed for a more specific evaluation of performance differences across populations and sexes.

The ANOVA on repetitive countermovement jump data included jump number (RCM1, RCM2, RCM3, and RCM4), population (young adult, NCAA Division I basketball player), sex (male, female), and age (years) as factors in the model. Dependent measures included CoR, RSI, New, AdjNew, net propulsive impulse, adj net propulsive impulse, amortization time, and adjusted amortization time.

For both ANOVA's, the following hypothesis test was performed on the population factor:

H<sub>0</sub>: There is no difference in reactive strength between young adults from the general population and a sample of NCAA Division I basketball players.

H<sub>a</sub>: There is a difference in reactive strength between young adults from the general population and a sample of NCAA Division I basketball players.

This hypothesis test was conducted in relation with research question 4 (see Introduction: Purpose). This test supported an evaluation of the influence of sport participation on dependent measures. A rejection of the null hypothesis would lead to the

conclusion that the measure of reactive strength is sensitive enough to distinguish between young adults from the community and NCAA Division I basketball players. This is the expected scenario given that NCAA Division I basketball players should score better on tests of reactive strength due to training history. Failure to reject the null hypothesis would lead to the conclusion that the measure of reactive strength is not sensitive enough to distinguish between young adults from the community and NCAA Division I basketball players. In this case, we would need to critically evaluate whether or not the measure of reactive strength is valid.

For both ANOVA's, the following hypothesis test was performed on the sex factor:

$H_0$ : There is no difference in reactive strength between males and females.

$H_a$ : There is a difference in reactive strength between males and females.

This hypothesis test was conducted in relation with research question 5 (see Introduction: Purpose). This test supported an evaluation of the influence of sex on dependent measures. A rejection of the null hypothesis would lead to the conclusion that the measure of reactive strength is sensitive enough to distinguish between post-pubescent males and females. Based on prior literature (Kipp et al., 2016; Laffaye et al., 2016; McMahon et al., 2017; Ramirez-Campillo et al., 2016; Suchomel et al., 2015), we expected to reject the null hypothesis. Failure to reject the null hypothesis would lead to the conclusion that the measure of reactive strength is not sensitive enough to distinguish between males and females. In this case, we would need to critically evaluate whether or not the measure of reactive strength is valid.

## Physical Activity Screen

Using data from the physical activity screen, we performed the following stepwise linear regressions on drop jump and repetitive countermovement jump data:

1. Physical Activity (5 Predictors) versus CoR (Response)
2. Physical Activity (5 Predictors) versus RSI (Response)
3. Physical Activity (5 Predictors) versus New (Response)
4. Physical Activity (5 Predictors) versus AdjNew (Response)

This analysis was conducted in relation with research question 6 (see Introduction: Purpose). This analysis supported an evaluation of the influence of levels of self-reported physical activity on reactive strength assessments. Variable inclusion probability was set at  $p = 0.05$ . Variable exclusion probability was set at  $p = 0.10$ . Using this approach, the following variables were tested for inclusion in the model:

1. Number of days per week participants engage in moderate intensity physical activity.
2. Number of days per week participants engage in vigorous intensity physical activity.
3. Number of days per week participants engage in activity that requires extensive jumping.
4. Amount of time participants engage in a single session of vigorous intensity physical activity.
5. Number of months within the last 5 years that participants have engaged in plyometric-type training activities.



## CHAPTER IV

### RESULTS

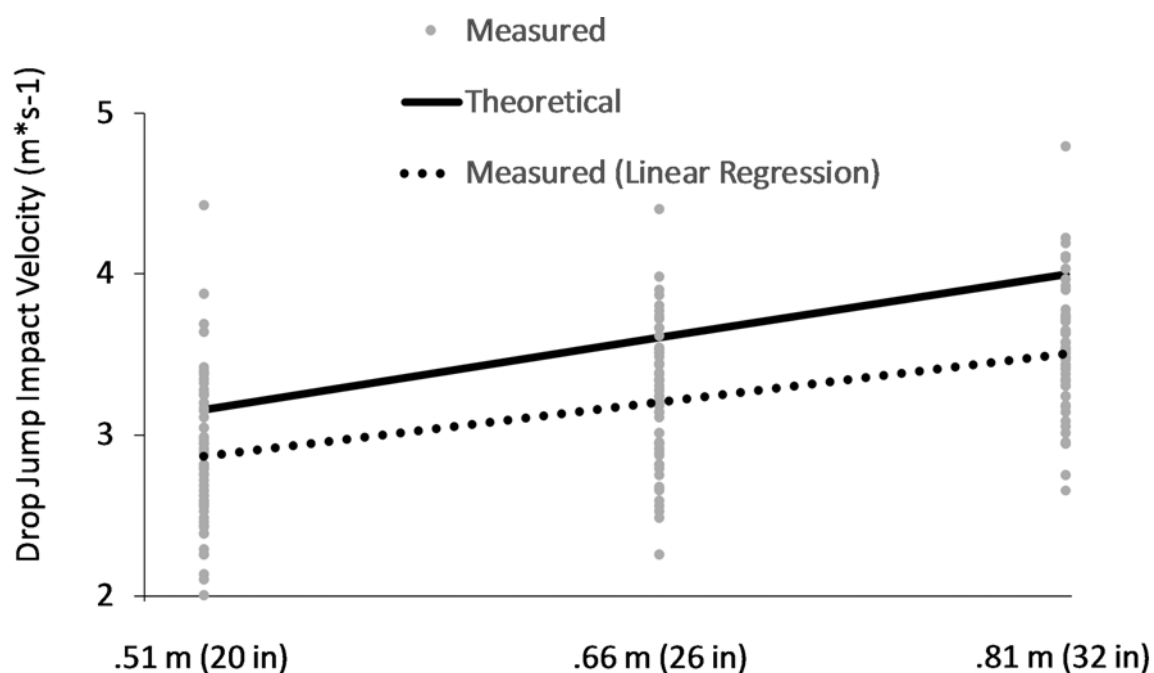
This purpose of this chapter is to present the results of the study within the context of research questions 1 through 6. The chapter begins by addressing the influence of drop kinematics and limb segment kinematics on measures of reactive strength. The second section of this chapter addresses the agreeability between our new kinetic (strength)-based measure of reactive strength, a kinematic-adjusted kinetic (strength)-based measure, the RSI, and the CoR. We then address and compare the population and sex sensitivity of the four assessments of reactive strength. Lastly, we assess the statistical relationship between self-reported measures of physical activity and the four assessments of reactive strength.

#### **Influence of Drop and Limb Segment Kinematics on Reactive Strength**

The following regression model ( $r = .552$ ,  $R^2 = .302$ ,  $F = 92.189$ ,  $p = 0.000$ ; see Figure 2) was obtained using simple linear regression:

$$\text{Measured Impact Velocity} = 0.761(\text{Drop Height}) + 0.465$$

Drop height did significantly predict measured impact velocity ( $p < 0.000$ ). However, measured impact velocity was less than the expected theoretical impact velocity at every drop jump height. Also, results of the regression suggest that measured drop jump impact velocity can be expected to increase at a rate of 76.1% for every 100% increase in drop height.



*Figure 2.* Scatter plot and linear regression between drop height (x-axis) and measured drop jump impact velocities (y-axis). Theoretical is a perfect linear line representing expected drop jump impact velocities based on drop jump box height. Data were collected on a sample of young males and females from NCAA Division I basketball teams and from the community.

Subjects had significantly greater trunk flexion, hip flexion, and knee flexion at RCM landing versus take-off (see Table 2). There was no difference in foot segment angle between RCM jumping take-off and landing. Differences between segment angles at take-off and landing result in asymmetrical projectile motion of the body center of gravity.

### **Agreeability Analyses**

Central tendency and dispersion data for the CoR, RSI, New, and AdjNew are presented in Table 3.

Table 2

*Segment Angle Data Corresponding with the Instances of Jump Take-Off and Jump Landing*

Segment	Take-off angle (°)	Landing angle (°)	<i>p</i>
Trunk	81.6 ± 5.2	80.5 ± 7.2	0.018
Thigh	92.2 ± 4.1	105.0 ± 5.8	0.000
Shank	90.2 ± 4.4	79.6 ± 5.4	0.000
Foot	113.0 ± 5.5	113.1 ± 6.1	0.470

*Note.* Data are reported as mean ± *SD*. *p* values were obtained from simple paired *t* tests ( $\alpha = 0.05$ ). Data were averaged across four countermovement jumps and three drop jumps (0.51 m, 0.66 m, and 0.81 m) performed by a sample of young males and females from NCAA Division I basketball teams and from the community.

Table 3

*Central Tendency and Variability for All Measures of Reactive Strength*

Condition	CoR	RSI (m*s-1)	New (kN)	AdjNew (kN)
0.51 m (20 in) DJ	0.73 ± 0.22	0.96 ± 0.36	0.92 ± 0.35	1.13 ± 0.51
0.66 m (26 in) DJ	0.56 ± 0.16	0.97 ± 0.36	0.89 ± 0.37	1.16 ± 0.52
0.81 m (32 in) DJ	0.48 ± 0.15	0.94 ± 0.38	0.83 ± 0.35	1.16 ± 0.49
RCM 1	1.02 ± 0.11	0.69 ± 0.36	0.85 ± 0.46	0.84 ± 0.47
RCM 2	1.02 ± 0.10	0.73 ± 0.43	0.88 ± 0.49	0.87 ± 0.52
RCM 3	0.98 ± 0.14	0.72 ± 0.42	0.90 ± 0.51	0.89 ± 0.52
RCM 4	1.00 ± 0.13	0.72 ± 0.40	0.89 ± 0.46	0.88 ± 0.46

*Note.* Data were reported as mean ± *SD*. Data were obtained from a sample of young males and females from NCAA Division I basketball teams and from the community. These data are pooled from three drop jumps (DJ) and four repetitive countermovement jumps (RCM) performed by each participant (total jumps = 560). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength.

All comparisons produced at least 91% agreement (see Table 4) The lowest percentage of agreement was found in the comparisons of New versus RSI and AdjNew versus RSI (see Table 4). In addition, we observed minimal measurement bias across all comparisons. The largest amount of bias was found in the comparisons of AdjNew versus CoR and AdjNew versus RSI. Bias is not a critical component of these Bland-Altman analyses given that the CoR, RSI, New, and AdjNew are represented by different units.

Evaluating whether or not agreeability trends exist in the Bland-Altman data is important to understanding the stability of measurement differences across a range of reactive strength scores. Regressions (see Table 5) suggest the presence of trends in expected difference scores (see Figure 3) in all Bland-Altman comparisons ( $R^2 = .142 - .342$ ) except for New versus RSI ( $R^2 = .008$ ).

These trends do not support measure agreeability. For example, in the CoR versus New Bland-Altman plot (see Figure 3), we observe a negative trend in the data. In comparison with New, this trend suggests that the CoR detects greater reactive strength

Table 4

*Bland-Altman Agreeability Data*

Comparison	Bias	Upper limit (95% CI)	Lower limit (95% CI)	% agreement
CoR versus RSI	-.01	.90 to 1.04	-.92 to -1.06	97.68
New versus CoR	-.05	.85 to .93	-.96 to -1.04	96.79
New versus RSI	-.06	.43 to .57	-.55 to -.69	91.61
AdjNew versus CoR	-.16	1.00 to 1.09	-1.32 to -1.42	96.96
AdjNew versus RSI	-.17	.36 to .54	-.70 to -.88	92.32

*Note.* Bland-Altman comparisons were made using pooled data from three drop jumps (0.51 m, 0.66 m, and 0.81 m) and four repetitive countermovement jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 560). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength.

Table 5

*Linear Regressions Performed on Bland-Altman Data*

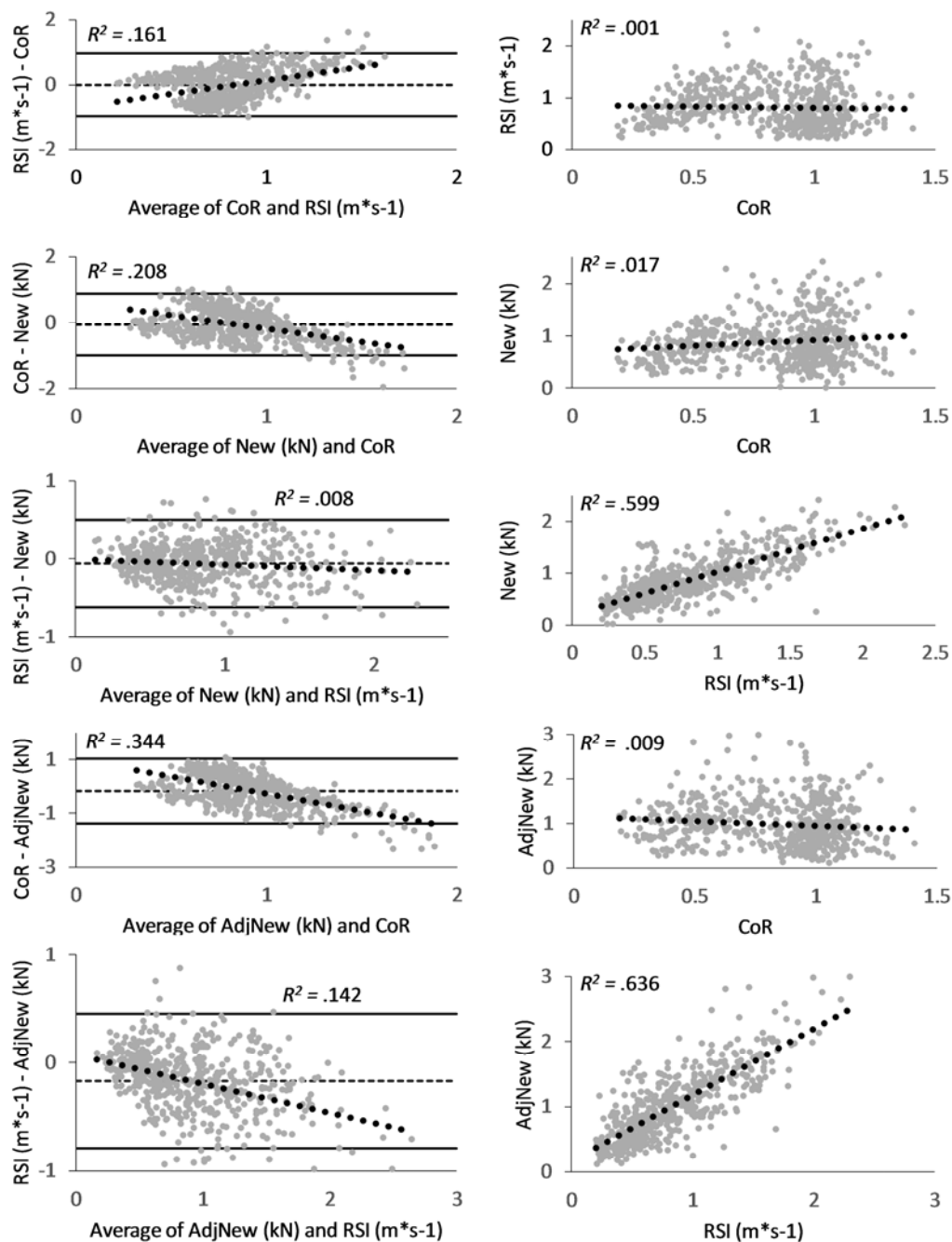
Comparison	$r$	$R^2$	$F$	$p$	Constant	$p$	$\beta$	$p$
CoR versus RSI	.403	.161	108.257	0.000	-.691	0.000	.828	0.000
New versus CoR	-.458	.208	147.971	0.000	.640	0.000	-.810	0.000
New versus RSI	-.099	.008	5.563	0.019	-.001	0.966	-.071	0.019
AdjNew versus CoR	-.588	.344	294.499	0.000	1.000	0.000	-1.279	0.000
AdjNew versus RSI	-.378	.142	93.154	0.000	.072	0.011	-.270	0.000

*Note.* Significance ( $p < 0.05$ ) indicates a linear relationship in expected difference scores. Regressions were performed on Bland-Altman comparisons made using data pooled across three drop jumps (0.51 m, 0.66 m, and 0.81 m) and four repetitive countermovement jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 560). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength.

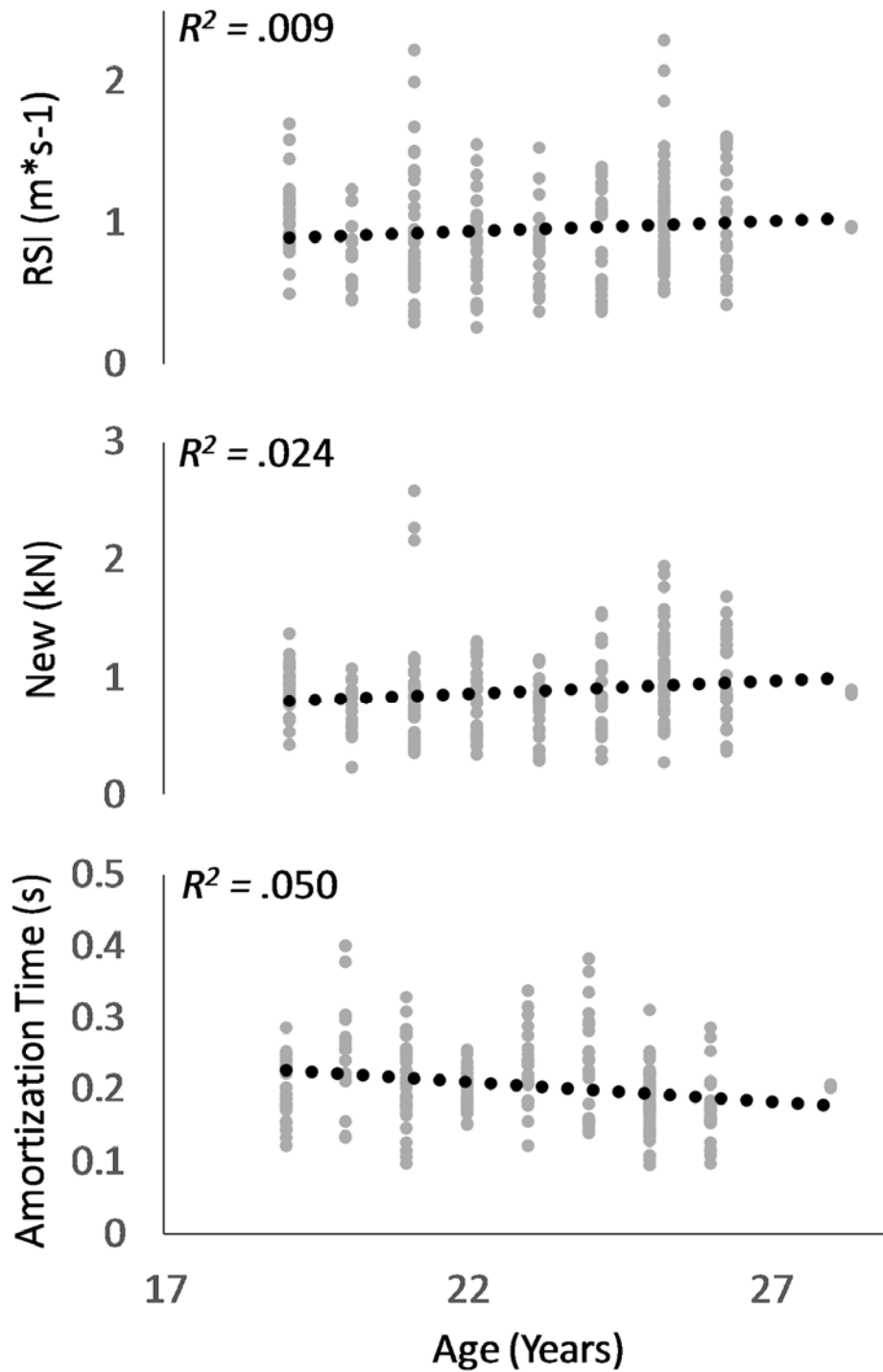
scores when reactive strength is low yet detects lower reactive strength scores when reactive strength is high. Negative trends were also observed for comparisons made between New versus RSI, CoR versus AdjNew, and RSI versus AdjNew (see Figure 3). A positive trend in measurement differences was observed for the comparison of RSI versus CoR.

Regressions (see Figures 3 and 4 and Table 6) on reactive strength data suggest poor agreeability for all comparisons ( $R^2 = .001 - .017$ ) except for New versus RSI ( $R^2 = .599$ ) and AdjNew versus RSI ( $R^2 = .636$ ).

Regressions suggest that our kinematic-adjusted and unadjusted kinetic (strength)-based algorithms of reactive strength are most similar to the RSI. With a high proportion of variance explained in these regressions, it is likely that the RSI, New, and AdjNew attempt to assess the same performance variable.



*Figure 3.* Plots of measure agreeability. Bland-Altman plots are on the left, scatter plots are on the right. Trendlines are based on linear regression results. Bland-Altman plots were created using pooled data from three drop jumps and four repetitive countermovement jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 560). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength.



*Figure 4.* Scatter plots that represent the influence of age on select dependent measures. Data are from three drop jumps performed at heights of 0.51 m, 0.66 m, and 0.81 m by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 240). RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength.

Table 6

*Regression Data on Comparisons Made Between Various Measures of Reactive Strength*

Comparison	<i>r</i>	<i>R</i> <sup>2</sup>	<i>F</i>	<i>P</i>	Constant	<i>p</i>	$\beta$	<i>p</i>
CoR vs. RSI	-.029	.001	.486	0.486	.856	0.000	-.045	.486
New vs. CoR	.136	.017	10.572	0.001	.696	0.000	.223	0.001
New vs. RSI	.775	.599	837.149	0.000	.205	0.000	.825	0.000
AdjNew vs. CoR	-.103	.009	6.038	0.014	1.158	0.000	-.202	0.014
AdjNew vs. RSI	.798	.636	977.189	0.000	.157	0.000	1.018	0.000

*Note.* Regressions were performed using pooled data from three drop jumps and four repetitive countermovement jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 560). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength.

### ANOVA Analyses

#### Drop Jumps

Sex was observed as a significant main effect for all variables (see Table 7).

Condition (drop height) was observed as a significant main effect for the CoR only (see Table 7). Population was observed as a significant main effect for the CoR, RSI, New, AdjNew, net propulsive impulse, and adjusted net propulsive impulse (see Table 7).

Age was observed as a significant main effect for RSI ( $F = 9.471$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.040$ ), New ( $F = 12.338$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.052$ ), and amortization time ( $F = 5.790$ ,  $p = 0.017$ ,  $\eta_p^2 = 0.025$ ). These effects were minimal (see Figure 4).

Condition (drop height) data are presented in Table 8. Drop height did not significantly affect the majority of measures. However, the CoR did decrease as drop height increased ( $p < 0.05$ ).

Sport participation data are presented in Table 9. All four measures of reactive strength were greater in our sample of NCAA Division I basketball players ( $p < 0.05$ ). No



Table 7

*Main Effects for an ANOVA Performed on Drop Jump Data*

Variable	Sex			Condition			Sport participation		
	<i>F</i>	<i>p</i>	$\eta_p^2$	<i>F</i>	<i>p</i>	$\eta_p^2$	<i>F</i>	<i>p</i>	$\eta_p^2$
CoR	85.756	0.000	0.274	49.018	0.000	0.302	8.655	0.004	0.037
RSI (m*s-1)	25.540	0.000	0.101	0.095	0.909	0.001	15.314	0.000	0.063
New (kN)	34.548	0.000	0.132	1.496	0.226	0.013	13.391	0.000	0.056
AdjNew (kN)	31.090	0.000	0.120	0.209	0.812	0.002	8.134	0.005	0.035
Imp (Ns)	201.365	0.000	0.470	0.782	0.459	0.007	29.025	0.000	0.113
AdjImp (Ns)	130.403	0.000	0.365	0.358	0.699	0.003	16.675	0.000	0.068
Amort t (s)	8.167	0.005	0.035	0.655	0.521	0.006	0.019	0.890	0.000
AdjAmort t (s)	6.135	0.014	0.026	0.128	0.860	0.001	0.019	0.891	0.000

*Note.* Data are from three drop jumps performed at heights of 0.51 m, 0.66 m, and 0.81 m by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 240). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

Table 8

*ANOVA Effects of Condition: Drop Jumping*

Variable	20 in (0.51 m) DJ	26 in (0.66 m) DJ	32 in (0.81 m) DJ
CoR	0.75 ± 0.22	0.58 ± 0.16*	0.48 ± 0.15**†
RSI (m*s-1)	1.01 ± 0.36	1.02 ± 0.36	0.99 ± 0.38
New (kN)	0.96 ± 0.35	0.94 ± 0.37	0.87 ± 0.35
AdjNew (kN)	1.17 ± 0.51	1.21 ± 0.52	1.21 ± 0.49
Imp (Ns)	179.68 ± 48.14	177.01 ± 50.30	172.01 ± 50.81
AdjImp (Ns)	199.64 ± 62.19	202.42 ± 60.59	206.89 ± 64.56
Amort t (s)	0.20 ± 0.06	0.20 ± 0.06	0.21 ± 0.05
AdjAmort t (s)	0.19 ± 0.05	0.19 ± 0.06	0.19 ± 0.05

*Note.* Data were collected from drop jumps (DJ) performed by a sample of young males and females from NCAA Division I basketball teams and from the community. CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

\*Significantly different from the 0.51 m condition ( $p < 0.05$ ).

†Significantly different from the 0.66 m condition ( $p < 0.05$ ).

Table 9

*ANOVA Effects of Sport Participation: Drop Jumping*

Variable	NCAA	Young adults	Cohen's <i>d ES</i>
CoR	0.65 ± 0.20	0.56 ± 0.21*	0.30
RSI (m*s-1)	1.14 ± 0.35	0.87 ± 0.37*	0.50
New (kN)	1.05 ± 0.39	0.80 ± 0.35*	0.44
AdjNew (kN)	1.34 ± 0.47	1.06 ± 0.51*	0.39
Imp (Ns)	196.12 ± 48.91	156.35 ± 48.22*	0.54
AdjImp (Ns)	223.94 ± 55.81	182.03 ± 61.55*	0.48
Amort t (s)	0.21 ± 0.07	0.21 ± 0.05	0.00
AdjAmort t (s)	0.19 ± 0.06	0.19 ± 0.05	0.00

*Note.* Data were collected from three drop jumps performed at heights of 0.51 m, 0.66 m, and 0.81 m by a sample of young males and females from NCAA Division I basketball teams (NCAA) and from the community (Young Adults). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

\*Significantly different from NCAA Division I athletes ( $p < 0.05$ ).

population differences in amortization times were observed across our samples of NCAA athletes and young adults. However, NCAA basketball players did produce greater net propulsive impulses, which correspond with greater jump heights.

Sex data are presented in Table 10. All dependent measures were significantly influenced by participant sex ( $p < 0.005$ ). All four measures of reactive strength and both net propulsive impulse measures were greater in males versus females. In addition, both measures of amortization time were greater in males versus females. Our kinetic (strength)-based measure of reactive strength is directly related to net propulsive impulse and inversely related to amortization time. Greater net propulsive impulse values observed in males outweighed the influence of shorter amortization times in females, resulting in greater reactive strength scores in males versus females.

Table 10

*ANOVA Effects of Sex: Drop Jumping*

Variable	Males	Females	Cohen's <i>d ES</i>
CoR	0.71 ± 0.20 <sup>†</sup>	0.50 ± 0.17	0.74
RSI (m*s-1)	1.13 ± 0.36 <sup>†</sup>	0.88 ± 0.30	0.49
New (kN)	1.06 ± 0.37 <sup>†</sup>	0.79 ± 0.26	0.54
AdjNew (kN)	1.39 ± 0.52 <sup>†</sup>	1.00 ± 0.38	0.55
Imp (Ns)	212.68 ± 42.25 <sup>†</sup>	133.56 ± 30.50	1.38
AdjImp (Ns)	243.76 ± 56.04 <sup>†</sup>	162.21 ± 45.27	1.04
Amort t (s)	0.22 ± 0.06 <sup>†</sup>	0.20 ± 0.05	0.24
AdjAmort t (s)	0.20 ± 0.06 <sup>†</sup>	0.18 ± 0.05	0.24

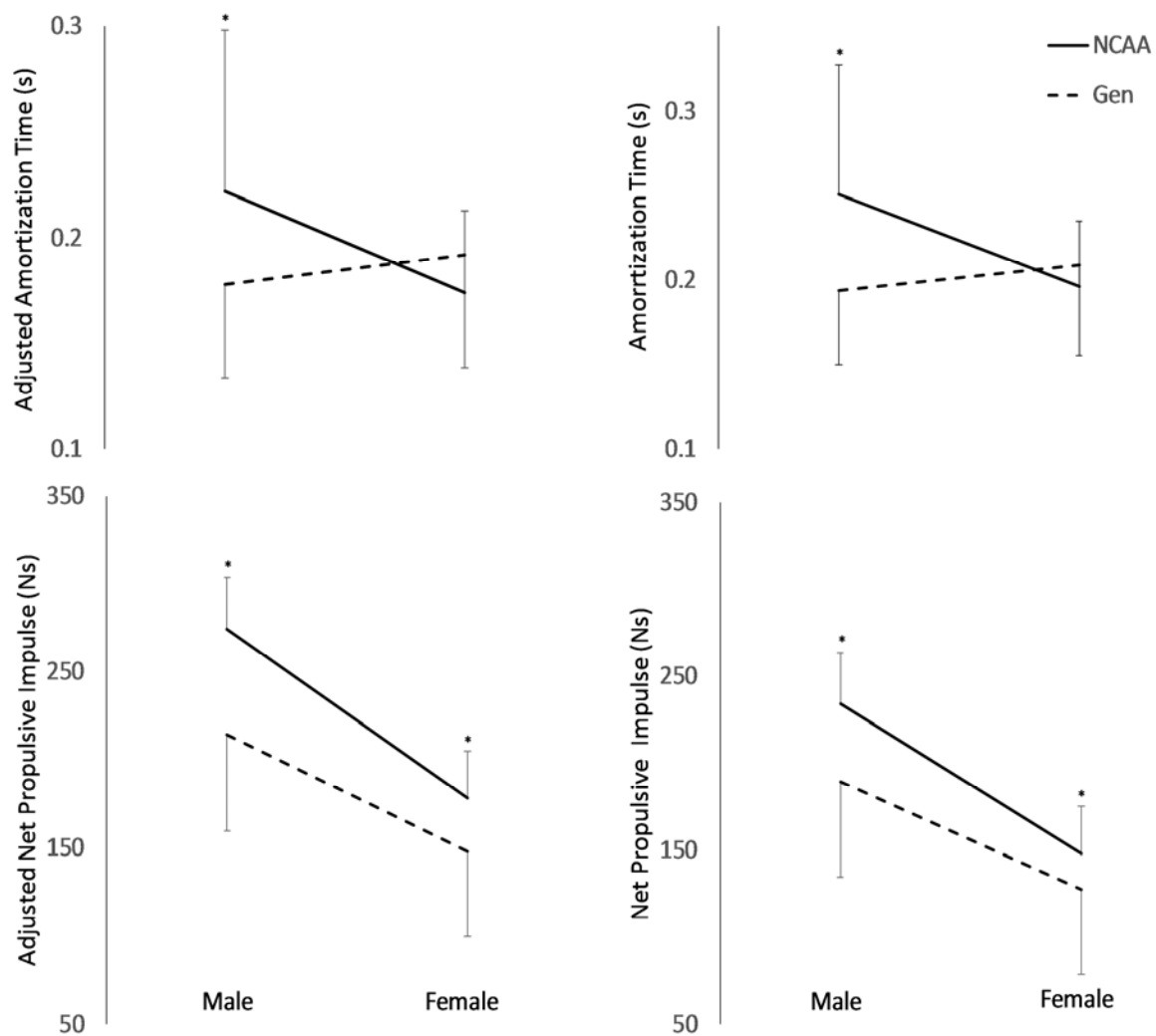
*Note.* Data were collected from three drop jumps performed at heights of 0.51 m, 0.66 m, and 0.81 m by a sample of young males and females from NCAA Division I basketball teams and from the community. CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

<sup>†</sup>Significantly different from females ( $p < 0.05$ ).

Population and sex interactions were observed for net propulsive impulse, adjusted net propulsive impulse, amortization time, and adjusted amortization time (see Figure 5). In our sample of young adults, females produced greater values for amortization time. In our sample of NCAA Division I basketball players, the opposite was observed. There was a greater influence of sex on net propulsive impulse values in our sample of NCAA Division I basketball players versus young adults from the general population.

### **Repetitive Countermovement Jumps**

Sex was observed as a significant main effect for RSI, New, AdjNew, net propulsive impulse, and adjusted net propulsive impulse (see Table 11). Condition was not observed as a significant main effect (see Table 11). Population was observed as a



\*Significantly different from Gen ( $p < 0.05$ ).

*Figure 5.* Significant sex-sport participation interactions identified from an ANOVA performed on drop jump data. NCAA = NCAA Division I basketball players. Gen = Young adults from the community.

Table 11

*Main Effects for an ANOVA Performed On Repetitive Countermovement (RCM) Jumping Data*

Variable	Sex			Condition			Sport participation		
	<i>F</i>	<i>p</i>	$\eta_p^2$	<i>F</i>	<i>p</i>	$\eta_p^2$	<i>F</i>	<i>p</i>	$\eta_p^2$
CoR	0.551	0.459	0.02	0.486	0.692	0.005	2.056	0.153	0.007
RSI (m*s-1)	4.648	0.032	0.015	0.041	0.989	0.000	8.058	0.005	0.026
New (kN)	2.805	0.095	0.009	0.035	0.991	0.000	8.043	0.005	0.026
AdjNew (kN)	3.718	0.055	0.012	0.088	0.967	0.001	20.666	0.000	0.064
Imp (Ns)	3.516	0.062	0.012	0.126	0.945	0.001	36.022	0.000	0.107
AdjImp (Ns)	3.351	0.068	0.011	0.241	0.868	0.002	54.538	0.000	0.153
Amort t (s)	1.823	0.178	0.006	0.023	0.995	0.000	0.954	0.329	0.003
AdjAmort t (s)	1.515	0.219	0.005	0.076	0.973	0.001	2.973	0.086	0.010

*Note.* Data are from four RCM jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 320). ). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

significant main effect for RSI, New, AdjNew, net propulsive impulse, and adjusted net propulsive impulse (see Table 11).

Age was observed as a significant main effect for RSI ( $F = 4.648$ ,  $p = 0.032$ ,  $\eta_p^2 = 0.015$ ). This effect was minimal (see Figure 6).

Condition (jump number) data are presented in Table 12. Dependent measures did not change across the four repetitive countermovement jumps.

Sport participation data are presented in Table 13. RSI, New, and AdjNew were greater in our sample of NCAA Division I basketball players ( $p < 0.05$ ). There was no difference in CoR between our samples of NCAA Division I basketball players and young adults. No population differences in amortization times were observed. However,

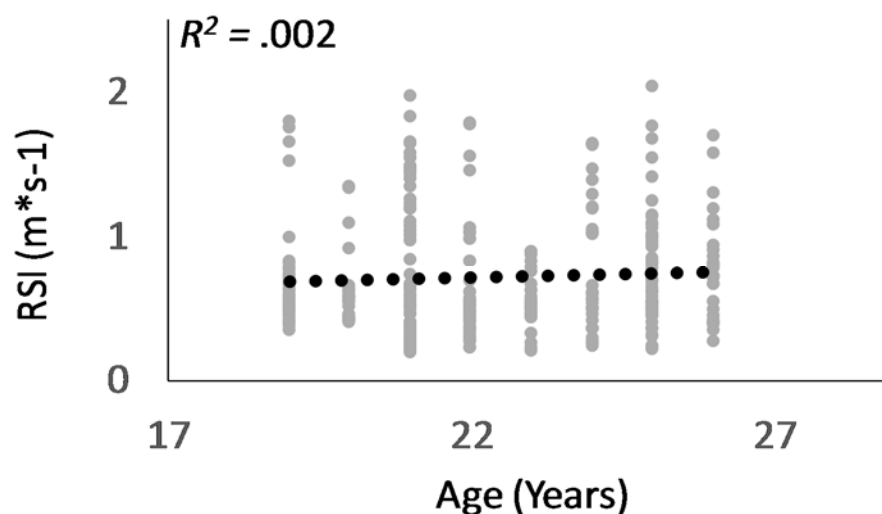


Figure 6. Scatter plot that represents the influence of age on the RSI. Data are from four RCM jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community (total jumps = 320). RSI = Reactive Strength Index.

Table 12

*ANOVA Effects of Condition: RCM Jumping*

Variable	RCM1	RCM2	RCM3	RCM4
CoR	1.01 ± 0.11	1.00 ± 0.10	0.99 ± 0.14	1.00 ± 0.13
RSI (m*s-1)	0.75 ± 0.36	0.77 ± 0.43	0.77 ± 0.42	0.75 ± 0.39
New (kN)	0.93 ± 0.46	0.93 ± 0.49	0.95 ± 0.51	0.94 ± 0.46
AdjNew (kN)	0.95 ± 0.47	0.95 ± 0.52	0.98 ± 0.52	0.98 ± 0.46
Imp (Ns)	194.72 ± 55.49	190.92 ± 51.80	189.96 ± 54.25	192.74 ± 51.02
AdjImp (Ns)	196.00 ± 56.40	191.36 ± 58.45	189.94 ± 56.82	195.37 ± 55.73
Amort t (s)	0.25 ± 0.18	0.25 ± 0.14	0.25 ± 0.13	0.25 ± 0.12
AdjAmort t (s)	0.25 ± 0.16	0.25 ± 0.14	0.25 ± 0.13	0.24 ± 0.12

*Note.* Data were collected from five repetitive countermovement (RCM) jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community. Five jumps performed gave reactive strength values for four RCM jumps. No significant differences were observed. CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

Table 13

*ANOVA Effects of Sport Participation: RCM Jumping*

Variable	NCAA	Young Adults	Cohen's <i>d</i> Effect Size
CoR	0.98 ± 0.09	1.02 ± 0.13	0.26
RSI (m*s-1)	0.86 ± 0.41	0.66 ± 0.39*	0.33
New (kN)	1.06 ± 0.45	0.82 ± 0.48*	0.35
AdjNew (kN)	1.16 ± 0.46	0.77 ± 0.49*	0.55
Imp (Ns)	217.30 ± 51.17	166.86 ± 50.11*	0.66
AdjImp (Ns)	224.92 ± 53.01	161.41 ± 51.81*	0.80
Amort t (s)	0.24 ± 0.12	0.26 ± 0.15	0.10
AdjAmort t (s)	0.23 ± 0.16	0.27 ± 0.14	0.17

\*Significantly different from NCAA Division I athletes ( $p < 0.05$ ).

*Note.* Data were collected from four RCM jumps performed by a sample of young males and females from NCAA Division I basketball teams (NCAA) and from the community (Young Adults). CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

NCAA basketball players did produce greater net propulsive impulse values ( $p < 0.05$ ), which correspond with greater jump heights.

Sex data are presented in Table 14. RSI, New, AdjNew, net propulsive impulse, and adjusted net propulsive impulse were significantly influenced by participant sex ( $p < 0.005$ ). RSI, New, AdjNew, and both net propulsive impulse measures were greater in males versus females. Measures of amortization time were not different in males versus females.

Population and sex interactions were observed for RSI, New, AdjNew, net propulsive impulse, adjusted net propulsive impulse, and amortization time (see Figure 7). There was a greater influence of sex on the RSI, New, and AdjNew. NCAA males

Table 14

*ANOVA Effects of Sex: RCM Jumping*

Variable	Males	Females	Cohen's <i>d ES</i>
CoR	1.00 ± 0.11	1.00 ± 0.12	0.00
RSI (m*s-1)	0.86 ± 0.42 <sup>†</sup>	0.66 ± 0.39	0.33
New (kN)	1.06 ± 0.45 <sup>†</sup>	0.81 ± 0.48	0.36
AdjNew (kN)	1.08 ± 0.54 <sup>†</sup>	0.85 ± 0.43	0.30
Imp (Ns)	211.51 ± 55.53 <sup>†</sup>	172.65 ± 48.08	0.49
AdjImp (Ns)	212.29 ± 63.39 <sup>†</sup>	174.04 ± 47.31	0.44
Amort t (s)	0.25 ± 0.16	0.25 ± 0.12	0.00
AdjAmort t (s)	0.25 ± 0.16	0.24 ± 0.11	0.05

*Note.* Data were collected from four repetitive countermovement jumps performed by a sample of young males and females from NCAA Division I basketball teams and from the community. CoR = Coefficient of Reactivity. RSI = Reactive Strength Index. New = kinetic (strength)-based paradigm of reactive strength. AdjNew = kinematic-adjusted kinetic (strength)-based paradigm of reactive strength. Imp = net propulsive impulse. AdjImp = adjusted net propulsive impulse. Amort t = amortization time. AdjAmort t = adjusted amortization time.

<sup>†</sup>Significantly different from females ( $p < 0.05$ ).

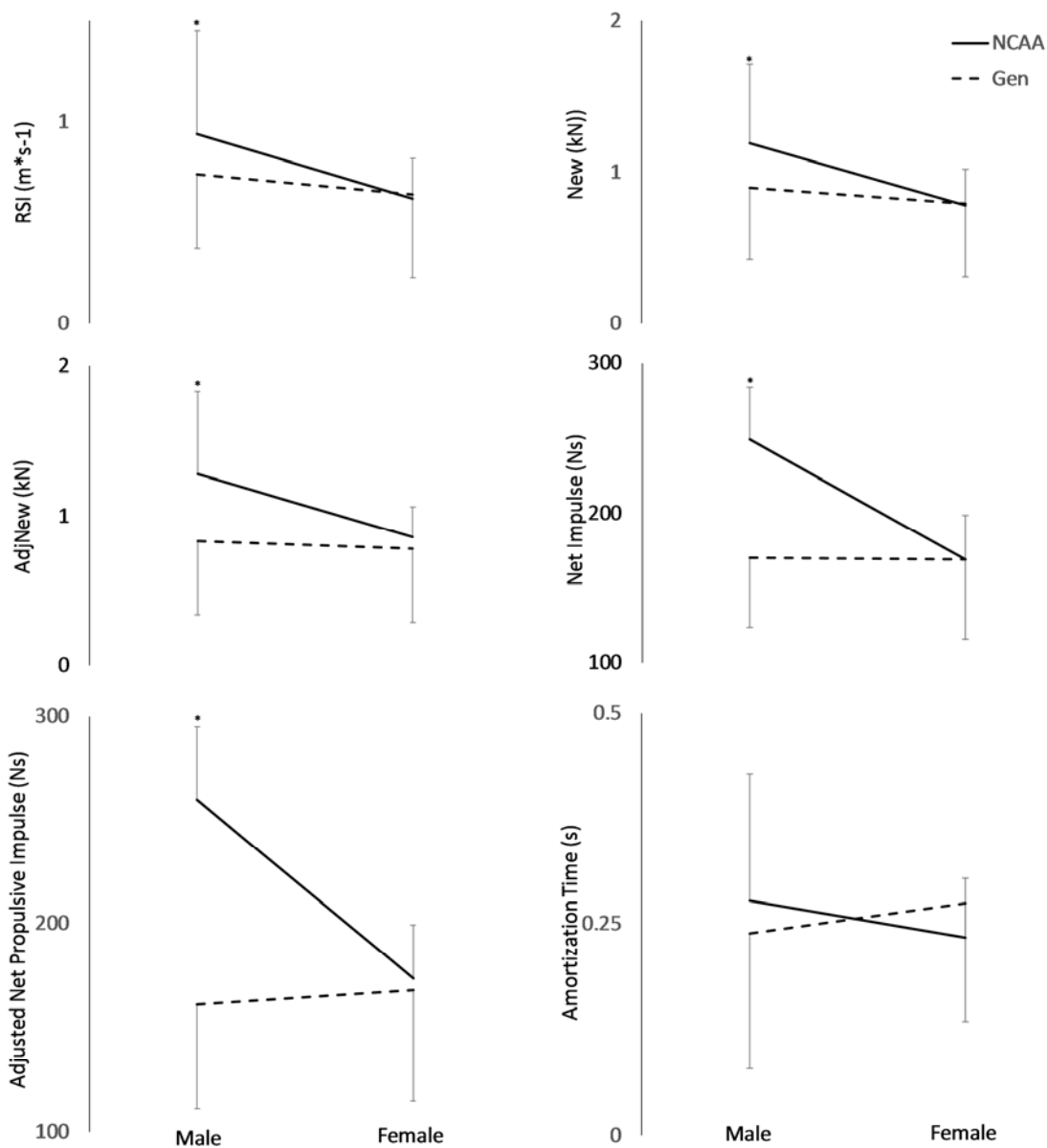
scored higher than NCAA females on these assessments. In young adults, there was little separation in these assessments. In addition, similar interactions were observed for net propulsive impulse and adjusted net propulsive impulse. Amortization time was greater in NCAA male basketball players versus NCAA female basketball players. In our sample of young adults, amortization time was greater in females versus males.

### Physical Activity Screen

#### Drop Jumps

A stepwise regression performed on CoR (response) and self-reported measures of physical activity (multiple predictors) produced the model shown on page 67.





\*Significantly different from Gen ( $p < 0.05$ ).

*Figure 7.* Significant sex-sport participation interactions identified from an ANOVA performed on RCM jump data. NCAA = NCAA Division I basketball players. Gen = Young adults from the community

$$\text{CoR} = 0.031(\text{DayJump}) - 0.026(\text{DayMod}) + 0.622$$

$$\begin{aligned} r &= 0.242 \\ R^2 &= 0.058 \\ F &= 7.350 \\ p &= 0.001 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p = 0.034$ ), and a constant ( $p < 0.000$ ) were included in the stepwise regression model as significant predictors of CoR response. DayVig, TimeVig, and PlyoExp did not achieve a sufficient probability level for inclusion in the model. A low R squared value suggests that the influence of self-reported physical activity is minimal.

A stepwise regression performed on RSI (response) and self-reported measures of physical activity (multiple predictors) produced the following model:

$$\text{RSI} = 0.086(\text{DayJump}) - 0.059(\text{DayMod}) - 0.112(\text{TimeVig}) + 1.151$$

$$\begin{aligned} r &= 0.315 \\ R^2 &= 0.099 \\ F &= 8.674 \\ p &< 0.001 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p = 0.005$ ), TimeVig ( $p = 0.004$ ), and a constant ( $p < 0.000$ ) were included in the stepwise regression model as significant predictors of RSI response. DayVig and PlyoExp did not achieve a sufficient probability level for inclusion in the model. A low R squared value suggests that the influence of self-reported physical activity is minimal.

A stepwise regression performed on New (response) and self-reported measures of physical activity produced the following model:

$$\text{New} = 0.050(\text{DayJump}) - 0.088(\text{DayMod}) + 1.121$$

$$\begin{aligned} r &= 0.275 \\ R^2 &= 0.076 \\ F &= 9.723 \\ p &= 0.014 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p < 0.000$ ), and a constant were included in the stepwise regression model as significant predictors of New response. DayVig, TimeVig, and PlyoExp did not achieve a sufficient probability level for inclusion in the model. A low R squared value suggests that the influence of self-reported physical activity is minimal.

A stepwise regression performed on AdjNew (response) and self-reported measures of physical activity (multiple predictors) failed to identify a statistically significant model. DayJump, DayMod, DayVig, TimeVig, and PlyoExp did not achieve a sufficient probability level for inclusion in the model.

### **Repetitive Countermovement Jumps**

A stepwise regression performed on AdjNew (response) and self-reported measures of physical activity (multiple predictors) failed to identify a statistically significant model. DayJump, DayMod, DayVig, TimeVig, and PlyoExp did not achieve a sufficient probability level for inclusion in the model.

A stepwise regression performed on RSI (response) and self-reported measures of physical activity produced the following model:

$$\text{RSI} = 0.173(\text{DayJump}) - 0.066(\text{DayMod}) - 0.009(\text{PlyoExp}) + 0.816$$

$$\begin{aligned} r &= 0.432 \\ R^2 &= 0.186 \\ F &= 24.131 \\ p &< 0.001 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p < 0.000$ ), PlyoExp ( $p < 0.000$ ), and a constant ( $p < 0.000$ ) were included in the stepwise regression model as significant predictors of RSI response. DayVig and TimeVig did not achieve a sufficient probability level for

inclusion in the model. The R square value ( $R^2 = 0.186$ ) for this regression was approximately twice as large in comparison with the RSI model in drop jumping ( $R^2 = 0.186$ ). However, self-reported measures of physical activity had contrasting effects (+ = DayJump; - = DayMod and PlyoExp).

A stepwise regression performed on New (response) and self-reported measures of physical activity produced the following model:

$$\text{New} = 0.148(\text{DayJump}) - 0.099(\text{DayMod}) - 0.011(\text{PlyoExp}) + 0.082(\text{DayVig}) + 0.981$$

$$\begin{aligned} r &= 0.420 \\ R^2 &= 0.177 \\ F &= 16.898 \\ p &< 0.001 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p < 0.000$ ), PlyoExp ( $p < 0.000$ ), DayVig ( $p = 0.011$ ), and a constant ( $p < 0.000$ ) were included in the stepwise regression as significant predictors of New response. TimeVig did not achieve a sufficient probability level for inclusion in the model. The R square value ( $R^2 = 0.177$ ) for this regression was more than twice as large in comparison with the New model in drop jumping ( $R^2 = 0.076$ ). However, self-reported measures of physical activity had contrasting effects (+ = DayJump and DayVig; - = DayMod and PlyoExp).

A stepwise regression performed on AdjNew (response) and self-reported measures of physical activity produced the following model:

$$\text{AdjNew} = 0.130(\text{DayJump}) - 0.099(\text{DayMod}) - 0.009(\text{PlyoExp}) + 0.111(\text{DayVig}) + .892$$

$$\begin{aligned} r &= 0.437 \\ R^2 &= 0.191 \\ F &= 18.595 \\ p &< 0.001 \end{aligned}$$

DayJump ( $p < 0.000$ ), DayMod ( $p < 0.000$ ), PlyoExp ( $p < 0.000$ ), DayVig ( $p <$

0.000), and a constant ( $p < 0.000$ ) were included in the stepwise regression model as significant predictors of AdjNew response. TimeVig did not achieve a sufficient probability level for inclusion in the model. While this regression produced the greatest amount of explained variance ( $R^2 = 0.191$ ), it didn't not explain a large amount of variance. Self-reported measures of physical activity had mixed effects in the model (+ = DayJump and DayVig; - = DayMod and PlyoExp).

## CHAPTER V

### DISCUSSION

The purpose of this chapter is to provide an interpretation of the results of the study within the context of research questions 1 through 6. The chapter is organized by subsections that correspond with research questions 1 through 6. The chapter begins with a brief review of theoretical concerns relating to the construct validity of reactive strength measures. This is immediately followed by a discussion of research questions 1 and 2. These questions address the theoretical concerns relating to the construct validity of reactive strength measures. Specifically, research questions 1 and 2 address the extent that theoretical assumptions introduce inaccuracies into the computation of the CoR, RSI, and New. The chapter continues with a discussion of research question 3. It addresses the agreeability between our kinetic (strength)-based algorithms of reactive strength, the CoR, and the RSI. A discussion of research questions 4 and 5 follow next. These questions address the sensitivity of all measures of reactive strength to sex and sport participation. Then, a brief discussion of research question 6 addresses the influence of self-reported levels of physical activity on reactive strength assessment. The chapter finishes with an applied discussion that addresses the limitations of our kinetic (strength)-based approach to reactive strength assessment, the implications of the present study, and suggestions for future application of reactive strength theory.

#### **Research Question #1**

*“Does kinematic variability in drop jumping introduce inaccuracies to measures*

*of reactive strength?”*

Historically, the CoR and RSI have been used to assess the reactive capacity of lower extremity musculature in jumping tasks. The CoR was proposed by Yuri Verkhoshansky in 1968. The CoR is a ratio of rebound jump height to drop height (see Equation 1). A theoretical issue with the CoR is that it attempts to model the neuromuscular reactivity of the lower extremity when the feet are in short duration impact with the ground yet it does not contain a component measure that models this impact. The RSI was introduced by Warren Young in 1995. The RSI improved the construct validity of the CoR since it replaced the drop height variable with ground contact time (see Equation 2).

The assumed validity of the RSI is strong and it is widely recognized as the ‘gold standard’ assessment of reactive strength. However, there are theoretical issues with the computation and implementation of the RSI that need to be addressed. First, the RSI is a non-kinetic (strength)-based measure that attempts to model the construct of reactive strength. While it is arguable that an association between the RSI and reactive strength exists, it is also logical to suggest that a kinetic (strength)-based paradigm of reactive strength would improve the theoretical validity of reactive strength assessment. Therefore, we developed a kinetic (strength)-based paradigm of reactive strength (New; see Equation 6).

The CoR, RSI, and New paradigms are founded in assumptions of mechanical theory. Specifically, these measures assume that no biological variability exists in human movement. In drop jumping, these measures assume that the downward displacement of

the body's center of gravity always equals the height of the box used to perform the drop. For example, our New paradigm makes the assumption that drop height can be used to estimate a value for theoretical impact momentum. Biological variability in movement makes it difficult to assume that impact momentum will follow theoretical expectations.

The present study evaluated whether kinematic variability in drop jumping introduces inaccuracies to the CoR, RSI, and New paradigms. Measured drop times were obtained using video recordings. Measured drop times were used to compute measured drop jump landing impact velocities. Since body mass is unchanged, landing impact velocities are a good representation of measured drop jump impact momentum. At each of three drop heights, measured impact velocities were compared against theoretical impact velocities using the regression statistical procedure (see Figure 2). We expected that biological variability in drop kinematics would result in measured impact velocities that differ materially from theoretical.

The regression procedure revealed a linear statistical relationship between drop height and measured impact velocities ( $R^2 = .302$ ). However, approximately 70% of the variability in measured impact velocities was not explained by drop height. Coefficients of variation on measured impact velocities were 0.15, 0.12, and 0.10 for the 0.51 m, 0.66 m, and 0.81 m drop conditions, respectively. Results suggest that kinematics in drop jumping are variable across individuals and diverge substantially from theoretical expectations. There were instances where drop kinematics produced measured impact velocities exceeding and below theoretical expectations (see Figure 2). At each drop height, measured impact velocities were collectively lower than theoretical expectations



(see Figure 2). Additionally, measured impact velocities increased at a rate of 76% versus theoretical as drop height increased. This suggests that participants anticipated higher drop heights by utilizing drop kinematics intended to reduce the amount of landing impact momentum.

We are able to estimate the downward displacement of the body's center of gravity using measured impact velocities since they are mathematically relatable. For instance, we observed measured drop velocities that correspond with center of gravity displacements (measured drop heights) of 0.46 m, 0.59 m, and 0.71 for the 0.51 m, 0.66 m, and 0.81 m conditions, respectively.

Additionally, measured impact velocities have a positive linear relationship with measured impact momentums. Based on this relationship, participants used drop kinematics in the 0.51 m condition that reduced impact momentum by 9.3%, drop kinematics in the 0.66 m condition that reduced impact momentum by 10.7%, and drop kinematics in the 0.81 m condition that reduced impact momentum by 12.4%.

We observed variability in measured impact velocities across participants and across jumps performed by the same participant at progressively higher drop heights. Participants used drop kinematics that produced measured impact velocities exceeding and below theoretical expectations. For instance, in the 0.51 m drop condition, one participant landed with a measured impact velocity of  $3.8 \text{ m}\cdot\text{s}^{-1}$  while another landed with a measured impact velocity of  $2.0 \text{ m}\cdot\text{s}^{-1}$ . These values correspond with a range of measured drop heights of 0.73 m and 0.20 m in the 0.51 m drop conditions.

Such a large amount of variability in drop jump kinematics cannot be ignored.

This variability influences computation accuracy and interpretation of the CoR and New paradigms. Further, these values influence the interpretability of the RSI. Results suggest that RSI scores obtained from two different people performing drop jumps from the same height may not be comparable. Based on this, we conclude that drop jump kinematics cannot be assumed to follow theoretical assumptions and that using an assumption that no biological variability exists in drop kinematics is flawed and suggests that there are construct validity issues in reactive strength assessments made using the CoR, RSI, and New paradigms. The AdjNew paradigm, which uses measured values for impact momentum, is likely a more appropriate model of reactive strength from the perspective of theoretical validity.

### **Research Question #2**

*“Do differences in limb segment positioning at jump take-off and landing introduce inaccuracies to measures of reactive strength?”*

There are theoretical concerns with the computation and implementation of reactive strength assessments that span across jumping protocols. Drop kinematics are not relevant in reactive strength tests using RCM jumps. However, both the drop jumping and RCM jumping protocols require the performance of an explosive rebound jump. In these protocols, it is assumed that participants take-off and land from a rebound jump with no differences in limb segment positioning.

Differences in limb segment positioning at the instances of jump take-off and landing result in asymmetrical projectile behavior through the whole-body center of

mass. Computation of the CoR, RSI, and New paradigms include an assumption that the body center of mass behaves symmetrically during the flight phase of the rebound jump. These paradigms use rebound jump heights (drop jumping and RCM jumping) and theoretical impact momentums (RCM jumping) that are based on one half of total flight time. However, if there are differences in limb segment positioning at the instances of jump take-off and landing, the apex of jump height will not correspond with one half of total flight time. This means that jump take-off to apex of flight and apex of flight to jump landing are not completed over the same amount of time.

To screen for differences in limb segment positioning, the present study contrasted major segment angles measured at jump take-off and landing. These data were obtained for every rebound jump in the drop jumping protocol. For RCM jumping, segment angle data were obtained for each of the five jumps performed. Significant differences in segment angles were observed (see Table 2). Participants landed from jumps with 1.3% more trunk flexion, 13.9% more thigh flexion, and 11.8% more shank flexion versus take-off. To confirm the influence of limb segment positioning on projectile motion of the whole-body center of gravity, we conducted a follow-up analysis.

Using videography from participants' sagittal perspective, we measured ascent and descent times for every rebound jump and RCM jump performed. A post-hoc paired  $t$  test ( $\alpha = 0.05$ ) revealed that descent times ( $0.25 \pm 0.04$  s) were significantly longer than ascent times ( $0.24 \pm 0.05$  s). This confirms that greater segment flexion at jump landing versus take-off resulted in asymmetrical projectile motion through the whole-body center of gravity.

Longer descent times influences the computation accuracy of the CoR, RSI, and New paradigms. Based on this, we conclude that rebound jump heights and theoretical impact momentums in RCM jumping should not be computed using the theoretical assumption of one half of total flight time. The AdjNew paradigm, which is kinematic adjusted to account for asymmetrical projectile motion of the body's center of gravity, is likely a more appropriate model of reactive strength from the perspective of theoretical validity. It should be noted that kinematic adjustments appear to be more critical when reactive strength tests are carried out using the drop jump protocol versus the RCM jumping protocol (see Table 3).

### **Research Question #3**

*“Does a kinetic (strength)-based paradigm of reactive strength agree with traditional assessments such as the CoR and RSI?”*

Sheppard and Young (2006) identify concentric strength and power, bilateral symmetry, and reactive strength as three neuromuscular characteristics that contribute to agility. These characteristics play important roles in sport performance and in the performance of mobility tasks in clinical populations (e.g., aging). In addition, there is an increasing prevalence of research investigating the sport and clinical application of reactive strength assessment (Ball & Zanetti, 2012; Beckham et al., 2014; Byrne et al., 2017; Cloak et al., 2014; Di Cagno et al., 2013; Di Giminiani et al., 2009; Ebben & Petushek, 2010; Feldmann et al., 2011; Flanagan & Comyns, 2008; Flanagan, Ebben, & Jensen, 2008; Flanagan, Galvin, & Harrison, 2008; Henry et al., 2013; Hoffrén-Mikkola

et al., 2015; Kipp et al., 2016; Laffaye et al., 2016; Lloyd et al., 2012; Lloyd et al., 2009; Markwick et al., 2015; McClymont, 2005; McMahon et al., 2017; Newton & Dugan, 2002; Ramirez-Campillo et al., 2015; Rossler et al., 2015; Struzik et al., 2016; Suchomel et al., 2015; Werstein & Lund, 2012). In the present study, we sought to improve upon traditional measures of reactive strength by proposing a kinetic (strength)-based paradigm. In research questions 1 and 2 we discussed the CoR, RSI, and New paradigms from the perspective of theoretical validity. Results suggested that the AdjNew paradigm, which is kinematic adjusted to account for the invalidity of assuming that no biological variability exists in human movement. Results from research questions 1 and 2 suggest that there is room to improve the construct validity of reactive strength assessment. It is logical to argue that the AdjNew paradigm improves the construct validity of reactive strength. However, it is important to support this argument by evaluating the agreeability of the AdjNew against the RSI. This is because the RSI is the most widely accepted measure of reactive strength and its' assumed validity is strong among researchers and practitioners.

Central tendency and variability data for all reactive strength measures are presented in Table 3. These data are comparable to prior literature. Struzik et al. (2016) observed mean RSI values between 0.85 and 1.04 in a sample of young males performing drop jumps from heights ranging from 0.15 m to 0.60 m. Hoffrén-Mikkola et al. (2015) observed mean RSI values between 0.60 and 1.20 in a sample of elderly men performing maximal effort hopping. In children and young adults, including collegiate athletes, researchers have reported mean RSI values ranging between 0.75 and 2.22 (Kipp et al.,

2016; Laffaye et al., 2016; Rossler et al., 2016). RSI values for the present study fit well within the range of previously reported data.

Central tendency data suggests that kinematic adjustments influence reactive strength scores to a greater extent in drop jumping versus RCM jumping. For example, AdjNew was between 23% and 40% greater than New for drop jumps and approximately 1% lower than New for repetitive countermovement jumps (see Table 3).

The CoR versus RSI regression (see Table 6) failed to detect statistical association. Further, regressions on CoR, New, and AdjNew detected poor statistical associations ( $R^2 = 0.009-0.017$ ). Lastly, regressions on Bland-Altman data detected the strongest trends in expected difference score for comparisons made using CoR (see Table 5). In comparison with the other measures, the CoR did detect similar effects of sex and sport participation on reactive strength in drop jumping (see Tables 9 and 10). However, the CoR was the only reactive strength measure that failed to detect significant effects of sex and sport participation in RCM jumping (see Table 12).

The CoR and RSI are nonkinetic (strength)-based measures that attempt to model a strength construct. An additional deficiency of the CoR is that it does not contain a component variable that models the interaction between the feet and ground during short duration impact. This is an significant theoretical flaw and is not surprising that the CoR did not model well against the RSI. It is assumed that the RSI improved the construct validity of reactive strength assessment when it replaced the CoR. From the results of the present study, it is arguable that the CoR is the least valid assessment of reactive strength from a theoretical perspective.

Since the assumed validity of the RSI is strong, comparisons made between New, AdjNew, and the RSI are the most relevant. New and AdjNew modelled well against the RSI. Regressions detected the strongest statistical associations between our kinetic (strength)-based paradigms (New and AdjNew) and the RSI ( $R^2 = 0.599-0.636$ ; see Table 6). In addition, regressions on Bland-Altman data detected the greatest stability in expected difference score when the RSI was compared against New and AdjNew ( $R^2 = 0.008-0.142$ ; see Table 5).

Results from research questions 1 and 2 suggest that theoretical assumptions made in the computation and interpretation of the CoR, RSI, and New paradigms are invalid. The AdjNew paradigm is arguably the strongest from the perspective of theoretical validity since it is kinetic (strength)-based and is adjusted to account for assumptions of mechanical theory. Regression performed on the AdjNew and RSI produced the strongest statistical association ( $R^2 = 0.636$ ; see Table 6). The amount of variance explained in this regression is large enough to suggest that both the RSI and AdjNew attempt to measure reactive strength. However, the amount of variance explained is not large enough to say that both measures are equally valid and effective assessments. This regression revealed that 36.4% of the variance in the AdjNew is not explained by the RSI. A considerable amount of unexplained variance is a preface to comparing the validity of the RSI and AdjNew paradigms.

The AdjNew paradigm of reactive strength is arguably an improvement over the RSI from the perspective of theoretical and construct validity. The AdjNew paradigm is kinetic-based and does not require the use of theoretical assumptions in its' computation.

In addition, the AdjNew paradigm improves inference to the key neuromuscular pathways associated with the construct of reactive strength.

Reactive strength is a construct used to describe the neuromuscular pathways involved in the regulation of tissue stress and strain. The net propulsive impulse component of AdjNew (numerator) models the magnitude of concentric activation of muscle. Concentric activation of muscle occurs via the alpha motor neuron efferent pathway (Enoka, 2008). Concentric muscle action is the primary mechanism responsible for the performance of an “explosive” movement. Reactive strength is a construct that attempts to model the performance of an explosive movement occurring immediately following a large impact. In the AdjNew paradigm, an increased in net propulsive impulse corresponds with a more explosive rebound movement and an increased reactive capacity.

The amortization time component of AdjNew (denominator) is the time period in which the body is absorbing the momentum of an impact (stress). During this time, spinal reflexes are active participants in the regulation of tissue stress and strain (Chmielewski, Myer, Kauffman, & Tillman, 2006). These reflexes include the neuroenhancing stretch (myotatic) reflex and the neuroprotective golgi tendon (inverse myotatic) reflex. Short to moderate amortization times are often associated with potentiation of the stretch reflex. The stretch reflex is believed to potentiate force in the agonist muscle within 80 ms of receiving a stimuli (Chmielewski et al., 2006). Activation of the stretch reflex can augment muscle activity during amortization and in the propulsive phase of jumping (Chmielewski et al., 2006). When coupled with maximal muscle activation (isometric),



long amortization times are often associated with potentiation of neuroprotective mechanisms like the golgi tendon reflex (Chmielewski et al, 2006). In the AdjNew model, short amortization times increase reactive strength capacity while long amortization times decrease reactive strength capacity.

#### **Research Question #4**

*“Is a kinetic (strength)-based paradigm of reactive strength sensitive to neuromuscular differences between NCAA Division I basketball players and young adults from the general population?”*

All four measures of reactive strength were sensitive to differences between NCAA athletes and young adults from the general community (see Table 9) in drop jumping. The CoR detected 16% greater reactive strength capacity in NCAA athletes. The remaining measures detected between 26% and 31% greater reactive strength capacity in NCAA athletes versus young adults from the general community. Both net propulsive impulse values were greater in NCAA athletes versus young adults from the general community (see Table 9). Amortization times were not different between NCAA athletes and young adults from the general community (see Table 9).

All measures of reactive strength, except for the CoR, were sensitive to differences between NCAA athletes and young adults from the general community (see Table 13). The CoR detected 4% greater CoR reactive strength capacity in young adults from the general community. The RSI, New, and AdjNew detected greater reactive strength capacity in NCAA athletes versus young adults from the general community.

AdjNew detected 51% greater reactive strength capacity in NCAA athletes. The RSI and New detected 30% and 29% greater reactive strength capacity in NCAA athletes, respectively. Both net propulsive impulse values were greater in NCAA athletes versus young adults from the general community (see Table 12). Amortization times were not different between NCAA athletes and young adults from the general community (see Table 13).

Basketball performance is dependent on both anaerobic and aerobic metabolism (Gomes de Araujo, Mancado-Gobatto, Papoti, Camargo, & Gobatto, 2014). Basketball is a sport that requires short-burst, or anaerobic, movements for success. For example, driving in for a lay-up, jumping for a rebound, and transitioning between defense and offense are highly anaerobic movements (Gomes de Araujo et al., 2014). Vertical jump tests are used to predict lower extremity anaerobic power in basketball players (Hoffman, Epstein, Einbinder, & Weinstein, 2000). For example, Hoffman et al. observed Kendall's tau correlation coefficients of 0.59 and 0.76 between countermovement jump height and peak and mean power outputs obtained via the Wingate test, respectively.

It is assumed that athletes participating in NCAA Division I basketball are superior in jumping ability versus similarly aged recreationally active young adults. Therefore, it is expected that a sample of NCAA Division I athletes would have greater reactive strength capacity versus young adults from the general community. Results of the present study confirmed that all measures of reactive strength detected greater reactive strength capacity in the sample of NCAA Division I basketball players versus young adults from the general population. NCAA Division I athletes achieved greater net

propulsive impulse values and similar amortization time values versus young adults from the general community (see Tables 9 and 13). NCAA Division I athletes displayed an ability to produce more force over similar ground contact times, which resulted in a more explosive movement.

Results of the present study support the construct validity of the CoR (drop jumping only), RSI, New, and AdjNew. The influence of sport participation on these measures gave effect sizes ranging from 0.30 to 0.50 in drop jumping and 0.26 to 0.55 in RCM jumping (see Tables 9 and 13). The AdjNew paradigm detected the largest effect size (0.55) in RCM jumping while the RSI detected the largest effect size (0.50) in drop jumping. The AdjNew paradigm detected similar effects of sport participation on reactive strength capacity versus the RSI. The AdjNew is arguably a more theoretically valid paradigm of reactive strength since it is kinetic (strength)-based, does not use assumptions of theory, and detected similar effects of sport participation versus the RSI.

### **Research Question #5**

*“Is a kinetic (strength)-based paradigm of reactive strength sensitive to neuromuscular differences between post-pubescent males and females?”*

All four measures of reactive strength were sensitive to differences between post-pubescent males and females (see Table 10) in drop jumping. Measures of reactive detected between 28% and 42% greater reactive strength capacity in males versus females. Both net propulsive impulse values and amortization time values were greater in males versus females. Amortization times in males were longer in duration yet not long

enough to offset the greater magnitudes of net propulsive impulse in males. Amortization times in males were not long enough to reflect a high degree of potentiation of neuroprotective spinal reflexes.

All measures of reactive strength, except for the CoR were sensitive to differences between post-pubescent males and females (see Table 14). Measures of reactive strength detected between 27% and 31% greater reactive strength capacity in post-pubescent males versus females. Since amortization times were not different between sexes, the effect of sex on reactive strength was due to greater net propulsive impulses. Males displayed an ability to produce more force over similar ground contact times, which resulted in a more 'explosive' movement. This result is supported by prior literature revealing amortization rates and mechanical power outputs to be between 36% and 85% greater in males versus females (Louder, Bressel, Nardoni, & Dolny, in press).

It is important that measures of reactive strength are sensitive to differences across sexes. The construct of reactive strength attempts to model the neural activation of lower extremity musculature under stress from an impact between the feet and ground. Lower extremity neuromuscular function has been observed to diverge between post-pubescentt males and females (Laffaye et al., 2016).

Differences in physical performance across sexes are minimal during the pre-pubescent stages of life (Quatman, Ford, Myer, & Hewett, 2006). Males and females undergo a physiological divergence during maturation that lead to measurable differences in movement (Quatman et al., 2006). It has been observed that males present with increased power, strength, and improved body control following puberty (Quatman et al.,

2006). These neuromuscular adaptations have not been observed on the same scale in females following puberty (Quatman et al., 2006).

Quatman et al. (2006) conducted a longitudinal study of jumping performance in thirty four adolescents. They observed that male adolescents jumped higher and landed from jumps with less impact following puberty (Quatman et al., 2006). Vertical jump height and landing impact were unchanged in female adolescents following puberty (Quatman et al., 2006). When normalized for body weight, the sample of female adolescents jumped with lower take-off forces following puberty (Quatman et al., 2006).

Acute or chronic instances where reactive strength capacity is poor may result in an injury from muscle stress overload or a transfer of stress to the supportive structures of the body (e.g., ACL). Noncontact injury risk in females following puberty is greater than in males, whereas prior to maturation there are no sex differences (Quatman et al., 2006). Anterior cruciate ligament sprain is more common in post-pubescent females versus males (Quatman et al., 2006). This type of sprain occurs in non-contact situations where the feet impact the ground.

The construct of reactive strength attempts to model the regulation of tissue stress and strain in lower extremity musculature. It was expected that post-pubescent females would have lower reactive strength capacity scores. Results of the present study confirmed this, as females had lower reactive strength capacity scores versus males. Results support the construct validity of the CoR (drop jumping only), RSI, New, and AdjNew. The influence of sex on these measures gave effect sizes ranging from 0.49 to 0.74 in drop jumping and 0.00 to 0.36 in RCM jumping (see Tables 10 and 14). The New

paradigm detected the largest effect size (0.36) in drop jumping while the CoR detected the largest effect size (0.74) in RCM jumping. The AdjNew paradigm detected similar effects of sex on reactive strength capacity versus the RSI. The AdjNew is arguably a more theoretically valid paradigm of reactive strength since it is kinetic (strength)-based, does not use assumptions of theory, and detected similar effects of sport participation and sex versus the RSI.

### **Research Question #6**

*“Does self-reported level of physical activity predict reactive strength capacity?”*

In the present study, we included a physical activity questionnaire that was intended to assess the uniformity of our sample of young adults. Central tendency and variability data for the questionnaire are presented in Table 1. Our sample of NCAA Division I basketball players reported greater levels of physical activity across all questions.

We also sought to evaluate the influence of self-reported levels of physical activity on measures of reactive strength. Results from stepwise regressions performed on drop jump and RCM data suggest minimal influence ( $R^2 = 0.058-0.191$ ). The stepwise models were stronger when performed on RCM data ( $R^2 = 0.177-0.191$ ) in comparison with drop jump data ( $R^2 = 0.058-0.099$ ). This result makes sense when one considers the principle of training specificity.

Training specificity is a principle used to describe the importance of training for a specific outcome (Coburn & Malek, 2012). For example, an athlete who competes in the

100 m sprint race would not necessarily benefit from participating in long distance aerobic training. Likewise, an older adult who is at risk for falling should engage in specific exercises intended to improve balance. In the present study, we asked participants to provide a report of participation in activities that include jumping and in organized plyometric training. It is plausible that participation in these activities did not include the performance of drop jumps. In the present study, we observed greater association between physical activity and RCM jumping. Our questionnaire did not distinguish between types of jumping activities performed. It is likely that when participants engaged in physical activity, the type of jumping performed was more specific to RCM jumping than drop jumping. Further research is needed to determine the relationship between the specificity of training and performance on tests of reactive strength.

## CHAPTER VI

### SUMMARY AND CONCLUSIONS

The construct of reactive strength attempts to model the neuromuscular regulation of tissue stress and strain. The Coefficient of Reactivity (CoR; Verkhoshansky, 1968) is the first known assessment of lower extremity neuromuscular reactivity in jumping tasks. The Reactive Strength Index (RSI; Young, 1995) was proposed in 1995, by Warren Young. The RSI was accepted as an improvement over the CoR from the perspective of theoretical validity. In addition, it is the current gold standard assessment of reactive strength used by researchers and human movement practitioners. The theoretical and construct validity of the RSI is assumed to be strong. However, there are several theoretical concerns in the computation and interpretation of the RSI.

First, the RSI is a nonkinetic (strength)-based measure that is used to model the construct of reactive strength. An indirect association between the RSI and reactive strength is defensible. However, it is logical to argue that a measure computed from kinetic (strength) data improves the construct validity of reactive strength assessment. Therefore we proposed two versions of a kinetic (strength)-based paradigm of reactive strength (New and AdjNew).

The RSI and New paradigms make the assumption that biological variability does not exist in human movement. These paradigms assume that when a person performs a drop jump, the displacement of the whole-body center of gravity will always be equal to the height of the object used to drop from (e.g., plyometric box). These paradigms also assume that limb segment positioning is not different between the instances of jump take-



off and landing. We hypothesized that these assumptions are not valid and that they introduce inaccuracies to the computation of reactive strength. We supposed that the AdjNew paradigm, which is kinematic adjusted to account for these assumptions, would improve the theoretical and construct validity of reactive strength testing when compared against the CoR, RSI, and New paradigms.

Fifty nine young adults from the general community and twenty one NCAA Division I basketball players completed a series of three drop jumps (0.51 m, 0.66 m, 0.81 m) and five repetitive countermovement (RCM) jumps. Kinetic and kinematic data were used to compute the following measures of reactive strength: The CoR, RSI, New, and AdjNew. We evaluated the extent that drop jump kinematic variability introduces inaccuracies to the computation of reactive strength. We also evaluated the extent that differences in limb segment positioning at the instances of jump take-off and landing introduce inaccuracies to the computation of reactive strength. We evaluated the agreeability of the CoR, RSI, New, and AdjNew paradigms their sensitivity to sport participation, sex, and self-reported levels of physical activity.

Approximately 70% of the variability in measured drop jump landing impact velocities was not explained by drop height (see Figure 2). This is reflective of kinematic variability in drop jumping and suggests that it is invalid to assume that biological variability does not influence the computation and interpretation of the CoR, RSI, and New paradigms.

The trunk, thigh, and shank were in significantly greater flexion (1.3-13.9%) at the instance of jump landing versus take-off (see Table 2). This result invalidates the

assumption that limb segment positioning are not different at the instances of jump landing and take-off. This assumption is made in the CoR, RSI, and New paradigms.

A linear regression detected a strong relationship between the RSI and AdjNew constructs ( $R^2 = 0.636$ ; see Table 6). While a large proportion of the variance was explained, approximately 36% of the variance in AdjNew was not explained by the RSI. This suggests that although the RSI and AdjNew paradigm attempt to model the same physiological characteristic, they may not be equally valid. Both the RSI and AdjNew paradigms were sensitive to sport participation and differences between post-pubescent males and females.

Results of the present study favor the adoption of the AdjNew paradigm of reactive strength in favor of the RSI. However, there are a few limitations with respect to clinical applicability and accessibility of the AdjNew paradigm.

### **Clinical Applicability**

Perceptual and decision making factors and change of direction speed are the two main branches of Sheppard and Young's (2006) model of agility. Agility is a population specific construct that is assessable in healthy, athletic, and clinical populations.

Concentric strength and power, bilateral symmetry, and reactive strength are the three neuromuscular characteristics identified in Sheppard and Young's model.

Concentric strength and power are two variables that have been linked to healthy aging. Low levels of concentric strength and power output have been linked to increased risk of falling, frailty, hospitalization, and mortality in older adults (Cesari et al., 2006;

Legrand et al., 2014; Pereira & Goncalves, 2011; Puthoff & Nielsen, 2007). In addition, bilateral symmetry has been observed to significantly predict fall risk in older adults (Skelton et al., 2002).

Reactive strength capacity is typically not tested in clinical populations due to the high-stress nature of testing protocols. Current measures of reactive strength require the performance of high intensity jumping. To the best of our knowledge, there has been only one clinical investigation of reactive strength. Using repetitive hopping, Hoffrén-Mikkola et al. (2015) were successful in assessing the RSI in a sample of older males (~60 to 80 years old). These authors observed that 11 weeks of hopping training performed by older males was effective at improving RSI scores and decreasing levels of agonist-antagonist muscular coactivation (Hoffrén-Mikkola et al., 2015). Pairing the AdjNew paradigm with accommodative hardware (sensor embedded), such as the sledge device may be a prolific direction for future research. Kramer, Ritzmann, Gollhofer, Gehring, and Gruber (2010) have proposed a sledge apparatus design that nearly approximates the kinetics of unrestricted land jumping.

### **Wearable Sensors**

Wearable sensors may also factor into future investigations of reactive strength capacity. Since the AdjNew paradigm is based on acceleration, or force, data, there is an opportunity to develop the AdjNew paradigm for application in wearable sensor technology. A wearable sensor approach to reactive strength assessment may be favorable for several reasons. First, there are affordability and accessibility concerns with

the AdjNew paradigm, as implemented in the present study. In order to carry out the AdjNew paradigm, one must have access to a highly specific force platform dynamometer, a high-speed camera, and software for processing two dimensional kinematics. In addition, data processing times using these technologies can be lengthy and prohibit the use of the AdjNew paradigm in both sport and clinical applications.

Recent developments in the use of wearable technologies may provide a solution to this problem. Wearable systems consisting of multiple inertial measurement units could be used to approximate the mechanical behavior of the body's center of gravity. If mass is known, and acceleration data from a wearable system provides an accurate representation of the mechanical behavior of the body's center of gravity, then wearable technology could be used to carry out the AdjNew paradigm through the whole-body center of gravity and through limb segment centers of gravity. This could facilitate the assessment of reactive strength in open-chain movements (e.g., overhand baseball pitching) that are known to produce high levels of stress in body tissues.

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APPENDICES

## Appendix A

The Sheppard and Young (2006) Model of Agility

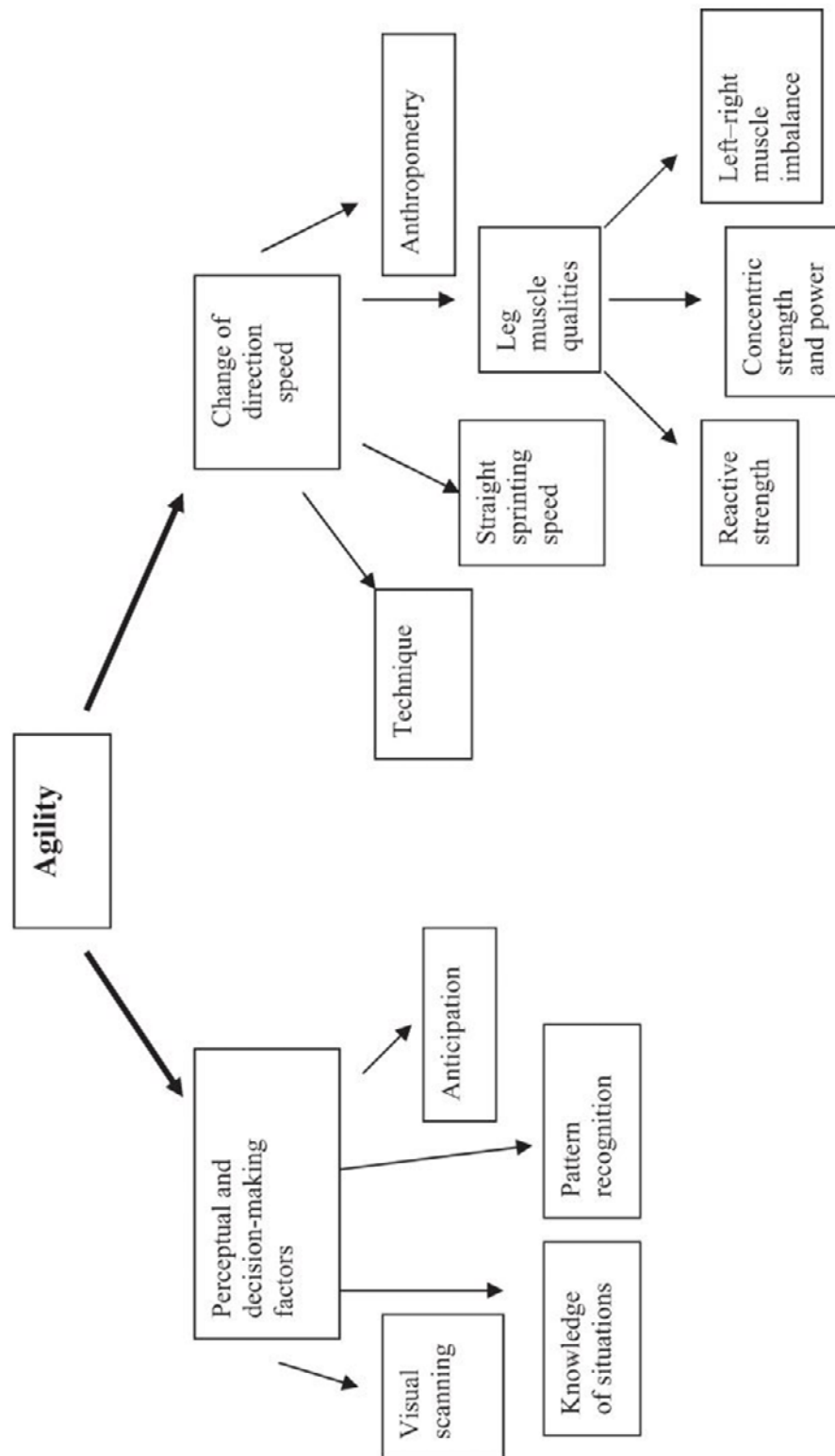


Figure A1. The Sheppard and Young (2006) model of agility.

Appendix B

Equations

Equation 1. Coefficient of Reactivity (*CoR*; Verkhoshansky, 1968).

$$CoR = \frac{\text{rebound jump height}}{\text{drop height}}$$

Equation 2. Reactive Strength Index (*RSI*; Young, 1995).

$$RSI = \frac{\text{rebound jump height}}{\text{force platform contact time}}$$

Equation 3. Utilization of Energy (*U*, *KE* = kinetic energy; Komi and Bosco, 1978)

$$U = KE_{\text{take-off}} - KE_{\text{impact}}$$

Equation 4. Rebound Jump Height (*h*).

$$h = \left| \frac{v_{rj}^2}{19.62} \right|$$

Equation 5. Rebound Jump Take-off Velocity ( $v_{rj}$ ). ( $t$  = reb. jump time in the air)

$$v_{rj} = |4.905(t)|$$

Equation 6. Kinetic-based Reactive Strength Assessment (*New*).

$$New (kN) = \frac{\int Ft - (|mv_{\text{theoretical impact}}| + \int BW(t))}{\text{Amortization Time}} = \frac{\text{Net Impulse}}{\text{Amortization Time}}$$

Equation 7. Amortization Time (*AT*) for *New* using Theoretical Momentum

$$\int_0^{AT} Ft - mv_{\text{theoretical impact}} = 0$$



Equation 8. Theoretical Momentum at Impact ( $mv_{theor.}$ ). ( $d = \text{drop height}$ )

$$mv_{theor.} = |m * (\sqrt{19.62(d)})|$$

Equation 9. Kinematic-adjusted Kinetic-based Reactive Strength Assessment ( $AdjNew$ ).

$$AdjNew = \frac{\int Ft - (|mv_{measured\ impact}| + \int BW(t))}{Amortization\ Time} = \frac{Net\ Impulse}{Amortization\ Time}$$

Equation 10. Amortization Time ( $AT$ ) for  $AdjNew$  using Measured Momentum.

$$\int_0^{AT} Ft - mv_{measured\ impact} = 0$$

Equation 11. Measured Momentum at Impact ( $mv_{meas.}$ )

$$mv_{meas.} = |m * (-9.81(t))|$$

Equation 12. Theoretical Momentum at Impact ( $mv_{meas.}$ )

$$mv_{meas.} = |m * (-4.905(t))|$$

Equation 13. Theoretical Momentum at Impact ( $mv_{meas.}$ )

$$mv_{meas.} = |m * (-4.905(t))|$$

Appendix C

PEDro Scale Assessment

1. Eligibility criteria were specified: YES

*Eligibility criteria are contained in the 'Exclusion Criteria' subsection of the Methods section.*

2. Random allocation of treatments: YES

*While each participant completes each jumping protocol, the order of completion will be randomized. This information is located in the Procedures subsection of the Methods section.*

3. Allocation was concealed: YES

*Yes, participants were not informed that they were allocated to a general population group or NCAA athletics group. Additionally, participants were not made aware that a purpose of the study was to assess group differences.*

4. Groups were similar at baseline: NO

*One of the study purposes is to evaluate the sensitivity of a novel force-based assessment of reactive strength. Specifically, we plan to evaluate two groups of different background ability in performing high-stress jumping movements.*

5. There was blinding of all participants: NO

*There is no way to blind participants in the present study. All participants will be aware that they are performing jumping movements.*

6. There was blinding of all therapists: NO

*There will be no clinicians involved in this study.*

7. There was blinding of all assessors: NO

*There is no way to blind assessors in the present study. All assessors will be aware of the jumping movements performed.*

8. Measures of at least one key outcome were obtained from more than 85% of enrolled participants: YES

*We expect to assess reactive strength using three different measures and expect that we will obtain these values from at least 85% of enrolled participants.*

9. All participants for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analyzed by “intention to treat”: YES

*We expect to satisfy this criterion.*

10. Results of between-group statistical comparisons are reported for at least one key outcome: YES

*We will conduct a statistical analysis comparing reactive strength across athletically trained young adults and young adults from the general population. We will obtain a statistical comparison of reactive strength across groups.*

11. Study provides point measures and measures of variability: YES

*We will assess reactive strength variability across repetitive countermovement jumps.*

*We will report means and standard deviations where appropriate.*

Appendix D  
Physical Activity Screen

## Physical Activity Screen

Participant Number: \_\_\_\_\_

Participant Group: \_\_\_\_\_

In a typical week, how many days do you participate in moderate intensity exercise?

In a typical week, how many days do you participate in vigorous intensity exercise?

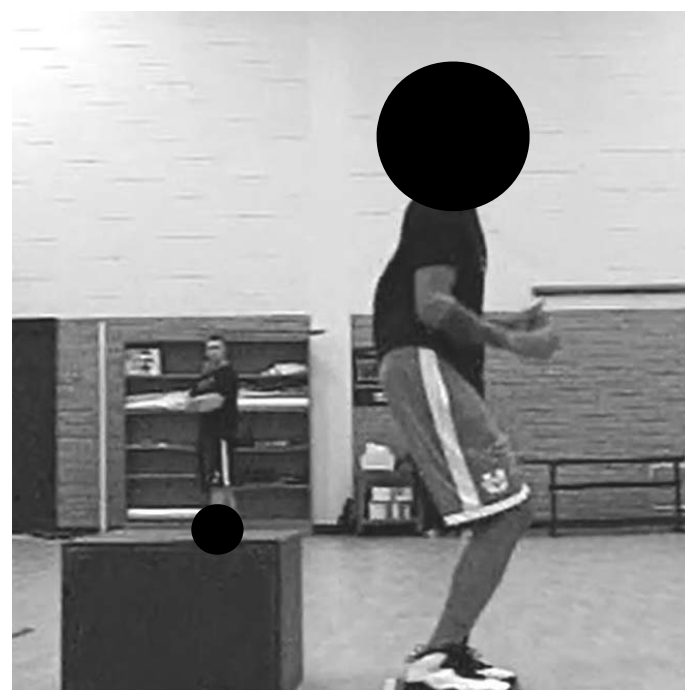
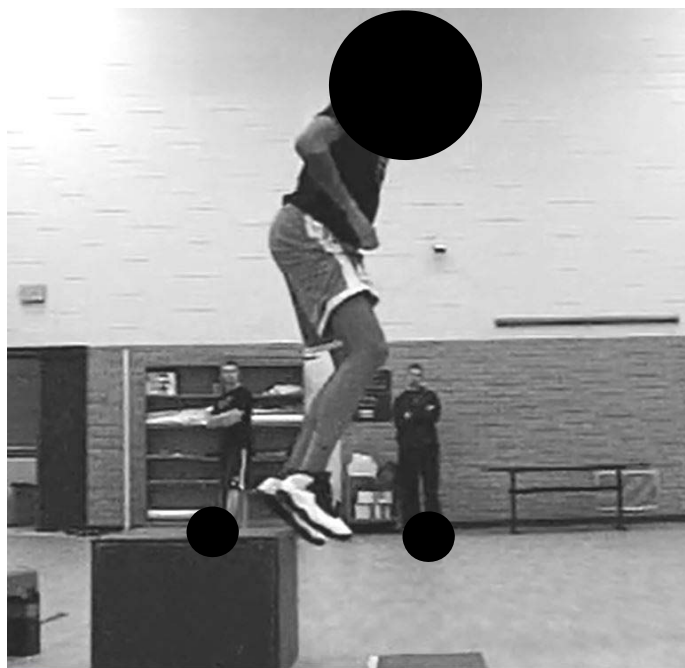
In a typical week, how many days do you participate in activities that include jumping / landing from jumps?

On a given day, about how much time do you spend participating in moderate to vigorous intensity exercise?

Within the past 5 years, how much time (e.g., weeks, months, years) have you participated in plyometric / jump training?

Appendix E

Depth Jump Technique







Appendix F

Countermovement Jump Technique





Appendix G  
Original Approach

### Original Approach

In this section we address our original approach to developing a kinetic-based model of reactive strength. Our original approach was based on prior literature by ... We made the assumption that pairing our algorithm with force platform data would be sensitive to energy dissipation. We believed that an assessment of energy dissipation would then be directly relatable to the ability of the neuromuscular system to regulate tissue stress and strain.

Our original algorithm related a net impulse value to energy dissipation using the following equation:

Net Impulse ( $I_{net}$ ). ( $F = force, t = time$ )

$$I_{net} = \int Ft - (|mv_{impact}| + |mv_{take-off}|)$$

An error in this algorithm is the lack of a body weight integral. The addition of a body weight integral produces the following revised model:

Net Impulse ( $I_{net}$ ). ( $F = force, t = time$ )

$$I_{net} = \int Ft - (|mv_{impact}| + |mv_{take-off}| + \int \mathbf{BW}t)$$

This revised model is sensitive to measurement errors that arise from the use of assumptions of theory. Assumptions of theory are included in the CoR, RSI, and New reactive strength paradigms. The revised model computes to zero if a drop jump or countermovement jump is performed with perfect theoretical technique. Observations of

the present study suggest that data from drop jumps and countermovement jumps are variable and deviate from theoretical expectations. Therefore, it makes sense that this revised model detected measurement error percentages of 5.7% across all drop jumps and 3.8% across all repetitive countermovement jumps.

## CURRICULUM VITA

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#### Current Employment

<b>Presidential Doctoral Research Fellow</b>	Department of Kinesiology and Health Science Utah State University, Logan, UT.
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#### Education

<b>PhD</b>	2017	Disability Disciplines	Utah State University, Logan, UT
<b>MS</b>	2013	Biomechanics	Utah State University, Logan, UT
<b>BS</b>	2010	Exercise Science	Utah Valley University, Orem, UT
<b>AS</b>	2008	General Studies	Southern Utah University, Cedar City, UT

#### Distinctions and Honors

2016	<b>Lawson Fellowship</b>	Utah State University, Logan, UT
2015	<b>Lawson Fellowship</b>	Utah State University, Logan, UT
2014	<b>Fellowship</b>	National Swimming Pool Foundation
2013	<b>Outstanding Grad Res. Assist.</b>	KHS Department, Utah State University, Logan, UT
2011	<b>Outstanding Student Award</b>	Utah Valley University, Orem, UT
2010	<b>Summa Cum Laude</b>	Utah Valley University, Orem, UT
2010	<b>Continuing Student Scholars.</b>	Utah Valley University, Orem, UT
2010	<b>Dean's List (F, Sp, Sum)</b>	Utah Valley University, Orem, UT
2009	<b>Dean's List (F)</b>	Utah Valley University, Orem, UT
2009	<b>Outstanding Merit Scholarship</b>	Utah Valley University, Orem, UT
2008	<b>Employee of the Month</b>	BWay Corp., Cedar City, UT
2007	<b>Continuing Student Scholars.</b>	Southern Utah University, Cedar City, UT
2005	<b>Dean's List (F)</b>	Southern Utah University, Cedar City, UT
2005	<b>Presidential Scholarship</b>	Southern Utah University, Cedar City, UT
2005	<b>Salutatorian</b>	Canyon View High School, Cedar City, UT
2005	<b>Academic All-State Basketball</b>	<i>UHSAA</i> , Canyon View High School, Cedar City, UT

#### Employment History

2016	<b>Consultant (Unpaid)</b> Utah State University Athletics: Strength and Conditioning
------	--



2015-2016	<b>Researcher (Summer Months)</b> Department of Kinesiology and Health Science, Utah State University, Logan, UT  <b>Collaborators:</b> Hydroworx and Manchester United Soccer Club
2014-2015	<b>Fellow</b> National Swimming Pool Foundation, Colorado Springs, CO
2013-2014	<b>Graduate Assistant</b> Department of Kinesiology and Health Science, Utah State University, Logan, UT
2013	<b>Manufacturing Engineer II</b> RMS, Tucson, AZ
2011-2013	<b>Graduate Research Assistant</b> Department of Kinesiology and Health Science, Utah State University, Logan, UT
2011-2013	<b>Graduate Teaching Assistant</b> Department of Kinesiology and Health Science, Utah State University, Logan, UT
2010-2011	<b>Undergraduate Researcher – Unpaid</b> Biomechanics Laboratory, Utah Valley University, Orem, UT
2005-2009	<b>Production Lead: Plastics Manufacturing</b> NAMPAAC, a division of B-Way Corporation, Cedar City, UT

### Teaching Experience

Spring 2016	PEP 4200: <b>Biomechanics</b> , Utah State University, Logan, UT
Fall 2015	PEP 4200: <b>Biomechanics</b> , Utah State University, Logan, UT
Spring 2015	PEP 3250: <b>Anatomical Kinesiology</b> , Utah State University, Logan, UT
Fall 2014	PEP 3250: <b>Anatomical Kinesiology</b> , Utah State University, Logan, UT
2011-2013	PEP 4200: <b>Biomechanics Laboratory</b> , Utah State University, Logan, UT

### Research Proficiencies

#### *Current:*

Wearable Technology: Inertial Measurement Units (e.g. Opals by APDM, Inc.)  
Tri-Axial Force Platform Assessment  
2 Dimensional Videography / Kinematics (e.g. LoggerPro Video Analysis, Kinovea Video Analysis)  
3 Dimensional Videography / Kinematics (e.g. Motion Capture by Vicon Motion Systems, Ltd.)  
Quantitative Computing in Microsoft Excel  
Statistical Analysis in SPSS, R, Python, and RPy

#### *Past:*

Electromyography (e.g. Delsys)  
Balance and Mobility Testing (e.g. Neurocom, Inc.)  
Anthropometry  
Writing Scripts for Data Processing in Python  
Temporospatial Gait Analysis (e.g. GAITrite)

## Publications

### Articles:

- Louder, T.**, Dolny, D., and Bressel, E. (2017). Biomechanical Comparison of Countermovement Jumps Performed on Land and in Water: Age Effects. *Journal of Sport Rehabilitation*, **In Press**
- Louder, T.**, Bressel, E., Nardoni, C., and Dolny, D. (2017). Biomechanical Comparison of Countermovement Jumps Performed on Land and in Water. *The Journal of Strength and Conditioning Research*, **In Press**
- Bressel, E., **Louder, T.**, Hoover, J., Roberts, L., and Dolny, D. (2016). Acute and Chronic Effects of Aquatic Treadmill Training on Land Treadmill Running Kinematics: A Cross-over and Single-subject Approach. *Journal of Sport Sciences*, **In Press**.
- Louder, T.**, Searle, C., and Bressel, E. (2016). Aquatic Plyometric Jumping: Mechanical Parameters and Flight Phase Characteristics. *Sports Biomechanics*, **15**, 342-356.
- Bressel, E., **Louder, T.**, and Dolny, D. (2016). Age-Related Changes in Postural Sway are not Consistent between Land and Aquatic Environments. *Journal of Geriatric Physical Therapy*, E-pub ahead of Print.
- Louder, T.**, Bressel, M., and Bressel, E. (2015). The Kinetic Specificity of Plyometric Training: Verbal Cues Revisited. *Journal of Human Kinetics*, **49**, 201-208.
- Schaefer, S. Y., **Louder, T.**, Foster, S., and Bressel, E. (2015). Effect of Water Immersion on Dual-task Performance: Implications for Aquatic Therapy. *Physiotherapy Research International*, E-pub ahead of Print.
- Horlbeck, W., **Louder, T.**, and Bressel, E. (2015). Association between Pelvic Motion and Hand Velocity in College-Aged Baseball Pitchers. *The Baseball Research Journal*, **44**, 58-61.
- Louder, T.**, Bressel, E., Baldwin, M., Dolny, D., Gordin, R., and Miller, A. (2014). Effect of Water Immersion on Static Balance. *International Journal of Aquatic Research and Education*, **8**, 53-65.

### Articles in Review:

- Searle, C., **Louder, T.**, and Bressel, E. (2017). Plyometric Landings on Land and in Waist-deep Water: Comparison between Young and Middle-aged Adults. *Under Review*
- Louder, T.**, Dolny, D., Thompson, B., and Bressel, E. (2017). Working toward a Kinetic (Strength)-Based Model of Reactive Strength. *Under Review*
- Bressel, E., **Louder, T.**, Raikes, A., Alphonsa, S., and Kyvelidou, A. (2017). Water Immersion Affects Episodic Memory and Postural Control in Healthy Older Adults. *Under Review*

### Articles in Preparation / Planning:

- Louder, T.**, Dolny, D., and Bressel, E. A Case for Increased Social Awareness in Clinical Biomechanics Research: Obesity, Cumulative Inequality, and Postural Stability.

Nielson, S., **Louder, T.**, and Bressel, E. Mechanics of Jump Landings on Land and in Water Using Unloaded and Loaded Countermovement Jumping.

**Louder, T.** The Influence of Sex on Reactive Strength in Young Adults and NCAA Division I Basketball Players.

**Louder, T.** Alternate Forms Reliability of Kinetics Using the Drop Jump and Countermovement Jump in a Sample of NCAA Division I Basketball Players.

**Louder, T.** ROC Sensitivity of Jump Kinetics to Sex and Participation in NCAA Division I Basketball.

**Louder, T.** Analyzing Jumping Movement Performance: A Methodological Review.

**Louder, T.**, Dolny, D., and Bressel, E. Using Wearable Sensors to Assess the Validity of Force Platform Posturography in Water.

**Louder, T.**, Bressel, E., and Dolny, D. Using Wearable Sensors to Assess the Validity of Force Platform Assessment of Jumping in Water.

**Louder, T.** Force Platform and Wearable Sensor Comparison of Reactive Strength Measurement Validity and Inter-Trial Reliability.

**Louder, T.** Wearable Technology and the Aquatic Environment Permit the Assessment of Reactive Strength in Clinical Populations.

**Louder, T.** The Assessment of Reactive Strength on Land and in Water: Age Effects.

*Abstracts:*

**Louder, T.**, Clark, N., Bressel, E., and Dolny, D. (2016). The Relative Effect of an Aquatic Environment on Jumping Kinetics between Older and Younger Adults. *Medicine and Science in Sports and Exercise*, **48**

Dolny, D., **Louder, T.**, Roberts, L., Hoover, J., Clark, N., and Bressel, E. (2016). Aquatic Treadmill Running does not Alter Select Land Treadmill Running Kinematics after Six Weeks of Training. *Medicine and Science in Sports and Exercise*, **48**

Patterson, D., **Louder, T.**, Nardoni, C., Clark, N., Bressel, E., and Dolny, D. (2016). Comparison of Propulsive Power during Loaded Countermovement Jumps Performed in Water Versus Land in Males. *Medicine and Science in Sports and Exercise*, **48**

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**Louder, T.**, Searle, C., and Bressel, E. (2015). Aquatic Plyometric Jumping: Mechanical Parameters and Flight Phase Characteristics. *Medicine and Science in Sports and Exercise*, **47**, 356-356.

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*Abstracts in Review:*

**Louder, T.**, Bressel, E., and Dolny, D. Biomechanical Comparison of Loaded Countermovement Jumps on Land and in Water. *Under Review at Medicine and Science in Sports and Exercise*.

Dolny, D., Bressel, E., and **Louder, T.** Biomechanical Comparison of Countermovement Jumps on Land and in Water: Age Effects. *Under Review at Medicine and Science in Sports and Exercise*.

Patterson, D., **Louder, T.**, Bressel, E., and Dolny, D. Landing Kinetics and Time to Stabilization for Loaded Countermovement Jumps Performed on Land and in Water. *Under Review at Medicine and Science in Sports and Exercise*.

**Presentations**

*Conference Presentations:*

**Louder, T.** Mechanical Specificity of Aquatic-based Jumping Movements. SWACSM Annual Chapter Meeting, October 2016, Costa Mesa, CA.

**Louder, T.**, Clark, N., Bressel, E., and Dolny, D. The Relative Effect of an Aquatic Environment on Jumping Kinetics between Older and Younger Adults. ACSM National Meeting, June 2016, Boston, MA.

Dolny, D., **Louder, T.**, Roberts, L., Hoover, J., Clark, N., and Bressel, E. Aquatic Treadmill Running does not Alter Select Land Treadmill Running Kinematics after Six Weeks of Training. ACSM National Meeting, June 2016, Boston, MA.

Patterson, D., **Louder, T.**, Nardoni, C., Clark, N., Bressel, E., and Dolny, D. Comparison of Propulsive Power during Loaded Countermovement Jumps Performed in Water Versus Land in Males. ACSM National Meeting, June 2016, Boston, MA.

Searle, C., **Louder, T.**, Dolny, D., and Bressel, E. Jump Landings on Land and in Waist-Deep Water: Comparison between Young and Middle-Age Adults. ACSM National Meeting, June 2016, Boston, MA.

Bressel, E., **Louder, T.**, Dolny, D., Foster, S. Effect of Water Immersion on Dual Task Performance in Older Adults. ACSM National Meeting, June 2016, Boston, MA.

**Louder, T.**, Searle, C., Bressel, E. Aquatic Plyometric Training: Mechanical Parameters and Flight Phase Characteristics. ACSM National Meeting, May 2015, San Diego, CA.

**Louder, T.** Aquatic Plyometric Training. Student Research Symposium, April 2015, Logan, UT.

**Louder, T.**, Searle, C., Bressel, E. Aquatic Plyometric Training: Mechanical Parameters and Flight Phase Characteristics. Annual World Aquatic Health Conference, Oct 2014, Portland, OR.

- Louder, T.**, Hoover, J., Bressel, E. Differences in Strike Index Between Land and Aquatic Treadmill Running in Experienced Distance Runners. Annual World Aquatic Health Conference, Oct 2014, Portland, OR.
- Louder, T.**, Popoca, T., Bressel, E. Functional Strength in the Context of Plyometric Training: Verbal Cues Revisited. NSCA National Meeting, July 2014, Las Vegas, NV.
- Popoca, T., **Louder, T.**, Bressel, E. Effect of Verbal Instruction on Depth Jump Performance. Undergraduate Research Symposium, Apr. 2014, Logan, UT.
- Louder, T.**, Popoca, T., Bressel, E. Functional Strength in the Context of Plyometric Training: Impulse-Momentum Revisited. Intermountain Graduate Research Symposium, Apr. 2014, Logan, UT.
- Horlbeck, W., **Louder, T.**, Bressel, E. Association between Pelvic Motion and Hand Velocity in College-Aged Pitchers. Intermountain Graduate Research Symposium, Apr. 2014, Logan, UT.
- Hoover, J., **Louder, T.**, Schaefer, S., Bressel, E. Differences in Strike Index between Land and Aquatic Treadmill Running in Experienced Distance Runners. Intermountain Graduate Research Symposium, Apr. 2014, Logan, UT.
- Bressel, E., Baldwin, M., **Louder, T.** Effect of Water Immersion and Jet Resistance on Balance. Annual World Aquatic Health Conference, Oct 2013, Indianapolis, IN.
- Baldwin, M., **Louder, T.**, Bressel, E. Effect of Water Immersion and Jet Resistance on Balance. ACSM National Meeting, May 2013, Indianapolis, IN.
- Louder, T.**, Baldwin, M., Bressel, E. Effect of Fluid Mechanics on Static Balance. Intermountain Graduate Research Symposium, Apr. 2013, Logan, UT.
- Baldwin, M., **Louder, T.**, Bressel, E. Effect of Water Immersion and Jet Resistance on Balance. Intermountain Graduate Research Symposium, Apr. 2013, Logan, UT.
- Bressel, E., **Louder, T.**, Spindzor, A., Dolny, D., Effect of Water Immersion on Postural Sway Characteristics. 9th Annual World Aquatic Health Conference, Oct. 2012, Norfolk, VA.
- Louder, T.**, Flynn, D., Garner, R. Effect of Acute Static Stretching of Agonists v. Antagonists on Vertical Jump Performance. Intermountain Graduate Research Symposium, Apr. 2012, Logan, UT.
- Bohne, M., Drum, S., **Louder, T.**, Mohlman S., Abendroth, J. Effect of Unstable Walking Shoes on Lower Extremity Kinematics Including Rear-Foot Angle. ACSM National Meeting, May 2011, Denver, CO.
- Louder, T.**, Bohne, M., Mohlman, S. Effect of Unstable Walking Shoes on Specific Gait Kinematics. NCUR, Mar. 2011, Ithaca, NY.
- Louder, T.**, Bohne, M., Mohlman, S. Effect of Unstable Walking Shoes on Specific Gait Kinematics. UCUR, Feb. 2011, Ogden, UT.

*Invited Lecture / Seminar Presentation:*

- Louder, T.** Sheppard and Young's Model of Agility. On Campus Interview: Teaching Sample (Dr. Brett Comstock), University of South Dakota, Spring Semester 2017.

- Louder, T.** The Mechanics of Agility, PEP 4200: Biomechanics (Dr. Eadric Bressel), Utah State University, Fall Semester 2016
- Louder, T.** The Physics of Strength, USU 1010: University Connections (Daphne Hartzheim), Utah State University, August 2014.
- Louder, T.** Functional Strength: Impulse-Momentum, PEP 4200: Biomechanics (Dr. Eadric Bressel), Utah State University, Spring Semester 2014.
- Louder, T.** Verbal Cues and the Neuromuscular Specificity of Jumping Movements, Free Motion Master Coach Training, Feb. 2013.
- Louder, T.** New Graduate Student Orientation, PEP 6300: Graduate Seminar (Dr. Sydney Schaefer), Utah State University, Fall Semester 2013.
- Louder, T.** Water Immersion and Postural Sway, PEP 6300: Graduate Seminar (Dr. Dennis Dolny), Utah State University, Fall Semester 2012.

### **Research Proposals and Grant Activity**

- Louder, T.** (In Prep.) “Modelling Reactive Strength using Inertial Measurement Units”, NIH R41
- Louder, T.** (2014) Fellowship, National Swimming Pool Foundation, *Proposed: \$2000, Funded: \$2000*
- Louder, T.** (2014 / 2012) Force and Motion Academic Research Scholarship, AMTI, *Proposed: \$10000, Funded: Not Funded*
- Louder, T.** (2013) GSS Research and Projects Grant, Utah State University, *Proposed: \$1000, Funded: \$1000.*
- Louder, T.** (2013) GSS Graduate Enhancement Award, Utah State University, *Proposed: \$4000, Funded: Not Funded.*
- Louder, T.** (2010) Scholarly Activities Committee, Undergraduate Research Award, Utah Valley University, *Proposed: \$1000, Funded: \$1200.*

### **Mentorship**

- Devin Patterson** (2017) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project*
- Sam Nielsen** (2017) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project*
- Bryan Beachem** (2016) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project*
- Kristin Gallofon** (2016) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through submission for publication*

- Beri Dwyer** (2016) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through preparation for publication*
- Ryan Moreau** (2016) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported the completion of Plan B thesis project*
- Cade Searle** (2015) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through submission for publication*
- Luke Roberts** (2015) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through accepted publication*
- Christie Brunnel** (2015) Undergraduate, Utah State University, Logan, UT  
*Served as faculty mentor for undergraduate honor's contract*
- Clint Nardoni** (2015) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through submission for publication*
- Tony Popoca** (2014) BS Health and Human Movement, Utah State University, Logan, UT  
*Supported an undergraduate research experience capped with a poster presentation*
- James Hoover** (2014) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through accepted publication*
- Will Horlbeck** (2014) MS Health and Human Movement, Utah State University, Logan, UT  
*Supported Plan B thesis project from conceptualization through accepted publication*

### Professional Organizations

2016-2017	<b>Student Rep.</b>	<i>American College of Sports Medicine: Southwest Chapter</i>
2010-Present	<b>Member</b>	<i>American College of Sports Medicine</i>

### Service

2012-Present	<b>Student Mentor</b>	<i>Utah State University</i>	<i>Logan, UT</i>
2010	<b>Volunteer</b>	<i>Habitat for Humanity</i>	<i>Orem, UT</i>
2010	<b>Volunteer</b>	<i>Special Olympics of Utah</i>	<i>Orem, UT</i>
2010	<b>Volunteer</b>	<i>Central Utah Clinic</i>	<i>Orem, UT</i>