8-2022

An Investigation into the Use of Biomechanical and Performance Data from Vertical Jump Testing to Monitor Competitive Weightlifters

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A dissertation

presented to

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

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Doctor of Philosophy in Sport Physiology and Performance

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by

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August 2022

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Keywords: Athlete Monitoring, Jump, Weightlifting, Performance, Impulse, Force

ABSTRACT

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This investigation aimed to employ novel analyses to longitudinal jump testing data gathered from competitive weightlifters to identify how certain biomechanical and performance characteristics obtained from the countermovement jump (CMJ) relate to changes in weightlifting performance over time and if they can differentiate higher and lower performers. A linear mixed-effect model was used to assess and compare the ability of countermovement jump height and net-impulse to predict Sinclair weightlifting total. CMJ force-time waveforms were compared in cross-sectional and repeated measures analyses to distinguish the force application patterns of higher-performing weightlifters and if they change over extended periods of training. It was found that both jump height and net impulse were significant predictors of Sinclair weightlifting total; however, likely due to changes in body mass within individuals over time, net impulse was a better predictor. The primary differentiator between higher and lower-performing weightlifters within the countermovement jump was the magnitude of force produced during the propulsive phase. No changes to the athlete's force-time waveforms were observed across three testing sessions separated each by a year. Over the three testing sessions, no significant change in jump height was found; however, net impulse increased over time. The findings of this dissertation demonstrate that countermovement jump net impulse is a beneficial metric to monitor in competitive weightlifters as it demonstrated the capacity to predict changes in

weightlifting performance, differentiated levels of performers, and changes over extended periods of training.

DEDICATION

This dissertation is dedicated to my Wife Abby, my parents, David and Doreen Suarez, and to Mike and Meg Stone. To my wife, Abby, out of all of the amazing things that have happened to me since coming to ETSU meeting you will always be the most important. Thank you, Mom and Dad, for your constant support in everything I have ever done. I remember the first day that I mentioned to you that I was considering moving away and going to school in Tennessee. If it wasn't for your immediate enthusiasm and support of such a big decision, I may not have ever been in this position. Lastly, thank you to Mike and Meg Stone for creating such an amazing program. I came to Tennessee seven years ago simply as a young man who enjoyed lifting weights. Never would I have imagined leaving home and going to Tennessee would set me on the path that it did. If it weren't for what you guys have put together here at ETSU, none of this would have ever been possible for me.

ACKNOWLEDGEMENTS

I would like to acknowledge the following individuals:

Dr. Satoshi Mizuguchi, for everything he has taught me about weightlifting, sport science, and statistics.

Dr. Mike Stone, for his constant support and guidance throughout my time at ETSU.

Dr. Chris Sole, for his own work partially inspiring the idea for the dissertation and for providing key insights into the details of the analyses required.

Dr. Guy Hornsby, for his consistent willingness to be involved in my projects and collaborate.

Also, thank you to the past and present staff and athletes of the ETSU Weightlifting team.

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Chapter 1. Introduction

Vertical jump testing is potentially the most widely used performance assessment in sport (Taylor et al., 2012) and was one of the earliest standardized tests of physical ability (Sargent, 1921). Logically, the most common variable measured during vertical jump tests is jump height (JH); however, the increased use of force plate technology within sport now allows for more in-depth performance insights to be obtained from the ground reaction forces produced during a jump. The collected force-time data can be broken down into different movement phases (unweighing, braking, propulsive, take-off, landing), or the entire curve waveform can be assessed. By analyzing jump phase characteristics and time-series waveforms, recent investigations have discovered distinct differences in jumping biomechanics between higher and lower performers (Floría et al., 2016; Sole et al., 2018), observed changes in the kinetics and kinematics of jumping after a period of training (Cormie et al., 2009; James, Suchomel, et al., 2020), and examined unique movement strategies used by athletes to achieve jumping performances (Guess et al., 2020; Rauch et al., 2020). These analyses may be advantageous to sport science practitioners since jump performance variables like JH and the mechanics underpinning the jump performance can be monitored, allowing for a more comprehensive insight into an athlete's abilities and physical status from a single test. The inclusion of jump measures obtained from these analyses in athlete monitoring programs may be beneficial but are not yet well studied using longitudinal investigations.

The definition of the word 'monitoring' includes the mention of "regularly checking the progress of something over time." Therefore, for a test to be deemed an effective athlete monitoring tool, it would need to be investigated longitudinally. Several previous investigations have established that strong cross-sectional relationships exist between weightlifting (WL) performance and measures like JH and peak power (Carlock et al., 2004; Joffe & Tallent, 2020; Travis et al., 2018; Vizcaya et al., 2009); and while the findings support the use of these variables for talent identification purposes (Fry et al., 2006), there is currently a lack of evidence to suggest that they are also valuable monitoring tools since a significant relationship between changes in jump measures and WL performance has not been observed within individual athletes (Joffe & Tallent, 2020). A limitation of using a variable like JH to monitor weightlifters over time is that it is affected by changes in body mass. This is because net impulse (NI) scaled to system mass yields take-off velocity, which is often used to calculate jump height (Kirby et al., 2011), making JH an inherently relative performance variable (i.e., relative net impulse = jump height). Therefore, an athlete who gains body mass over their career will have to generate greater net impulses to achieve the same jump heights, meaning beneficial improvements in their ability to generate force may not exhibit itself as noticeable increases in JH. McMahon et al. (2020) recently presented a convincing rationale for the use of a variable they termed take-off momentum (take-off velocity x body mass), which is mathematically identical to NI (net force x time), to evaluate rugby league athletes whose ability to generate momentum and displace an opponent is potentially more important than their ability to displace themselves. Similarly, in the sport of WL, an athlete must be able to generate a large impulse against another object, the barbell. Therefore, further investigation is necessary to determine if alternative jump measures, like NI, can be beneficial additions to long-term longitudinal monitoring programs among athletes whose sport logically relies more on their ability to generate greater net impulses than being able to displace themselves higher during a jump. This is especially relevant for super-heavyweight athletes who have no upper limit to their weight class and are therefore normally unnecessarily penalized for being heavier when being evaluated with relative performance variables.

A factor often overlooked when evaluating the use of the CMJ as an athlete monitoring tool is that differing jump strategies, such as changes to the velocity and depth of the countermovement, could be unconsciously adopted by athletes over time. Different jump strategies have been shown to greatly influence the performance variables obtained from vertical jump tests (Kirby et al., 2011; Pérez-Castilla et al., 2019; Sánchez-Sixto et al., 2018). Together, changes in factors such as jump strategy alongside changes in body mass over athletic careers could considerably complicate the ability of practitioners to identify any valuable trends from commonly used CMJ performance measures alone. These obstacles could be overcome by identifying and monitoring jump measures that are more closely related to changes in actual sport performance and by evaluating the changes that occur in jump time-series waveforms over time.

Therefore, the purposes of this dissertation are to evaluate the effectiveness of alternative and novel approaches to analyzing vertical jump testing data for monitoring competitive weightlifters and add to the relatively scarce literature that involves long-term longitudinal monitoring programs in trained athletes. To do so, this project will 1) aim to identify if there is a relationship between changes in specific jump measures and WL performance within-individual athletes, 2) examine if differences in biomechanical patterns of force application during a jump can differentiate higher and lower performing weightlifters, and 3) determine if and to what extent jump performance and force application patterns change over extended periods of training.

Operational Definitions

1. Beta coefficients: The degree of change in a variable for every one-unit change in another variable
2. Braking phase: The phase of the countermovement jump after the unweighing which begins when the ground reaction force returns to system mass and continues until the velocity of the center of mass reaches zero.
3. Countermovement jump: A type of vertical jump that begins with a countermovement.
4. Countermovement: A downward movement that precedes an upward movement.
5. Fixed effects: Variables that are constant across individuals
6. Force-time curve: A graphical curve consisting of ground reaction forces on the y-axis and time on the x.
7. Flight time: The amount of time spent in the air during a vertical jump.
8. Ground-reaction force: The force exerted by the ground on an object.
9. Impulse: The produce of force and time or the area under the force time curve.
10. Jump height: Highest vertical elevation of the center of mass achieved during a jumping movement.
11. Jump strategy: The alterations in movement an athlete either consciously or unconsciously selects to achieve a certain jump performance (i.e., higher or lower countermovement depth, faster or slower countermovement, etc.)
12. Linear mixed-effect models: An extension of general linear models that allow for both fixed and random effects.
13. Momentum: The product of force and velocity. A vector quantity of motion.

14. Net-Impulse: The difference between the area under the force-time curve above and below system mass.
15. Normalization: A technique that involves standardizing a measure using a certain reference (i.e., time or body mass) to allow for comparison across multiple samples.
16. Phase durations: The time duration of specific jump phases (i.e., unweighing, braking, propulsive)
17. Power: Product of force and velocity or the rate work is performed.
18. Propulsive phase: The phase of the countermovement jump after the braking phase where the jumper begins propelling themselves upwards. Continues until take-off when the feet leave the floor.
19. Random effects: Variances of parameters (effects) across groups or individuals
20. Relative net-impulse: Net-impulse divided by system mass.
21. Sinclair: Calculation used to scale WL performance to body mass so that weightlifters can be compared across weight classes.
22. Statistical Parametric Mapping: A statistical technique for applying the general linear model framework to continuous data, originally designed for examining differences in brain activity but recently adapted for analyzing biomechanical time-series data.
23. Strength: Ability of a muscle or group of muscles to produce force.
24. System mass: The total mass of the system (body mass + any additional mass or load).
25. Take-off velocity: Vertical velocity of the center of mass at the point of take-off.
26. Take-off: Point of time in the countermovement jump where the jumper is not in contact with the ground.

27. Time normalization: Normalization of continues time-series data that involves re-sampling all data down to the same total number of samples.
28. Time-series Waveform: A graphical curve consisting of a kinetic or kinematic measure on the y-axis and time on the x.
29. Unweighing phase: The phase of the countermovement jump where vertical ground reaction force falls below system mass as the jumper begins moving downward.

Chapter 2. Comprehensive Review of the Literature

History of the Vertical Jump as a Performance Test

The ability to jump high has historically been a widespread and well-accepted measure of general athleticism. Even at very early ages, children are typically impressed by their peers who can jump higher than others to reach random objects such as tree branches. This basic and relatable test of athleticism has advanced to where it is now entirely common to observe specialized equipment and technology used to quantify jump performance for the purposes of assessing and monitoring athlete performance potential at nearly every level of sport. In the past decade, advancements in certain technologies used for jump measurements, such as force plates, have made it easier and more feasible than ever to analyze the kinetics and kinematics of jump performances. However, the use of the vertical jump as a general measure of athletic or physical prowess has been around for centuries. In the late 1800s, French physiologist and Chronotogorapher Etienne-Jules Marey used pressure plates and wired systems to assess the effects of ground reaction forces on movement outcomes. He directly observed Newton's laws of motion in the jumping action by quantifying the amount of force applied into the ground and relating it to the subject's vertical displacement during a jump. In his book "Le Mouvement" he noted that the height of the jump was "not due to the initial energy of the effort, but the amount or quantity of force expended, namely the product of the force and the duration of the effort; in other words, the area of the curve." (Marey, 1894) What Marey was referring to by the area under the curve is Impulse, which, as he stated, is the product of force and time. Interestingly, despite its direct relationship to movement outcomes and observations of its importance going back over one hundred years, Impulse has gotten relatively little attention when it comes to jump performance monitoring within the literature.

While Marey is one of the earliest recorded individuals to quantify vertical jump performance, his primary interests were in understanding movement and motion rather than assessing physical performance. In the early 1900s, physical educator Dudley Allen Seargent wrote critically about using physique measurements and anthropometrics to determine the physical ability and potential power of man (Sargent, 1921) and instead, suggested using what he termed “The New Test,” where an individual bends forward, flexing the trunk, knees, and ankles, and then powerfully jumps upward, attempting to touch a cardboard disc or paper box cover. The highest height at which the individual can touch their head was subtracted from their standing height and recorded. He also noted that the amount of work done by the person can be measured by multiplying their body weight by their JH, and that would be an acceptable measure of “man power.” Despite being developed around a similar time and being a more crude way of measuring jumping than Marey’s setup, the Sargent test was so valuable because it could be conducted by anyone in any setting, requiring no technology or equipment other than some cardboard and measuring tape. The use of jump tests as a general measurement of power became much more feasible and accessible to many with this development.

Similar to the Sargent test, Russian scientist Vitaly Abalakov developed a practical method of measuring vertical jump height with arm movement using a tape measure attached to the waist of the subject and the ground in the 1930s (Bosco et al., 1983). A few decades later, the accuracy of measuring jump performance was significantly improved with the use of force plates and strain gauges 1972; Davies & Rennie, 1968). Since the vertical velocity of the center of gravity of the subject is determined by the impulse divided by the subject’s mass, the center of gravity's displacement could be estimated by measuring the force applied during the movement (Bosco et al., 1983). The calculation of JH through this impulse-momentum relationship became the gold standard; however, especially at the time, most practitioners working with athletes did not have access to this specialized equipment. In the 1970s, Asmussen and Bonde-Petersen (1974) introduced the estimation of vertical JH based on the subject's flight time. The flight time is the time between take-off and landing during the jump and is much easier to measure and doesn't require as specialized equipment. Using this new, more practical estimate of JH Carmelo Bosco was pivotal in introducing a series of jump tests to assess lower-body mechanics and power in athletes. The use of contact mats to measure flight time also began to increase in popularity for measuring jump performance outside of the lab. Additionally, Bosco suggested removing the arm swing that was a part of previous tests like the Sargent and Abalakov tests in order to isolate the performance of the lower body (Bosco et al., 1983). Additional jump test variations such as squat jumps, loaded jumps, drop jumps, and repeated jumps were also used by Bosco to assess various strength and power qualities in athletes. (Bosco et al., 1983).

While many of the tests and technology used by Bosco in the 1980s is still commonly used, force plates, which are the gold standard for measuring jump performance, have become more accessible and are now a common component of weight rooms in collegiate and pro sport settings. With greater and easier access to the vast amount of information obtained with force plates, it is more important than ever for sport performance practitioners to establish the most effective methods for measuring and monitoring jump performance in their specific athlete populations. While measures such as JH and estimates of power have historically been the most practical to measure, they may not always be the most relevant.

Common Jump Testing Protocols

As mentioned previously, many different types of vertical jump tests exist. The original and most common jump test is known as the countermovement jump (CMJ). The CMJ consists of the subject dipping down by flexing at their hips, knees, and ankles before rapidly and explosively extending those joints to project themselves vertically. The CMJ can be conducted with arms, which produces higher jump heights (Bobbert et al., 1996), or by placing the hands-on-hips or holding a dowel to isolate the performance to the lower body. While the CMJ with arms may be more sport-specific in many scenarios, the CMJ without arms has shown to be more reliable (Heishman et al., 2020) and, therefore, more effective for longitudinal monitoring of physical performance potential.

The second most common type of jump testing protocol is the squat or static jump (SJ). The SJ removes the countermovement portion of the jump and is initiated in a static squatting position. The SJ helps to remove some movement variability in the jumping motion and isolate the performance to lower body concentric force production ability. For these reasons, the SJ has shown strong correlations to sport performances that depend highly on concentric actions such as weightlifting (Travis et al., 2018; Vizcaya et al., 2009) and sprint starts (Sleivert & Taingahue, 2004).

Additional common jump tests include repeated hop tests to measure reactive and stretch-shortening cycle abilities (Harper et al., 2011). Single leg jump tests to determine differences between limbs (Lee et al., 2021). Approach jumps that include one or multiple steps before performing a jump and are more specific to game like jumping actions in sports such as basketball (Pleša et al., 2022). Jump and reach tests that include the coordination of the upper body limbs (Menzel et al., 2010). And horizontal/broad jumps and lateral jumps that tests an athlete’s ability to project themselves forward and sideways, respectively (Meylan et al., 2010). Each type of jump testing protocol offers its own benefits and limitations. Many of these jump testing protocols may involve motions and actions that make them more specific to certain athletic movements; however, the more degrees of freedom that are involved in the movement, the more movement variability will be involved, making monitoring general performance characteristics such as lower body force production more difficult. Therefore, for the purposes of using jump testing as an athlete monitoring tool, rather than simply a sport-specific performance assessment, the CMJ and SJ without arm movement are most often selected. The benefit the CMJ offers over the SJ is that some literature suggests that fatigued athletes will alter their movement strategy, especially during the eccentric portion of the jump in order to produce similar outcome measures (Cormack et al., 2008; R. Gathercole et al., 2015). If the eccentric portion of the jump is not included, some of these insights may be missed.

Use of the Vertical Jump as an Athlete Monitoring Tool

The definition of the word 'monitoring' includes the mention of "regularly checking the progress of something over time" (Oxford English Dictionary). Therefore, athlete monitoring tools need to possess the ability to check in on an athlete's performance progress regularly. More specifically, athlete monitoring can be broken up into two parts: program efficacy and fatigue management (Gleason et al., 2021; Stone, 2019; Suarez et al., 2020). Program efficacy refers to monitoring whether the training process is having the desired effects on the athlete. Fatigue management refers to monitoring the physical state of the athlete. The CMJ allows for a feasible and valid method of fulfilling both aspects.

An effective athlete monitoring tool should allow for a large amount of information to be gained from a small amount of intervention. Performing a vertical jump on a force plate takes little time, doesn't interrupt the training process, is a familiar movement to athletes, and allows for the quantification of a host of performance variables. Assessing and monitoring JH alone can be especially useful as jumping is a general athletic movement that occurs in many sports and has displayed strong relationships to other athletic movements such as sprinting and change of direction movements (Alemdaroğlu, 2012; Köklü et al., 2015; Shalfawi et al., 2011). Multiple additional metrics from jump testing can be used to assess the efficacy of a training program by monitoring how specific targeted physical attributes are being affected. For instance, a training block with an emphasis on developing rate of force development would be expected to affect the amount of force the athlete can apply in a certain time frame. This targeted adaptation can be assessed using metrics such as the ratio of flight time to contraction time. These very same metrics can also be used for fatigue management. Work by Gathercole et al. showed that fatigued athletes may be able to produce similar jump performance outcomes such as JH and PP; however, they may adopt a more extended, slower countermovement strategy to achieve those outcomes (Gathercole et al., 2015a; Gathercole et al., 2015b). Taking more time to produce a similar performance outcome is an obvious undesirable trend in athletes.

One aspect of jump monitoring that is often not considered is the effect that changes in body mass have on jump performance. The height that an individual can project themselves can be determined by the final velocity at takeoff (Moir, 2008). The takeoff velocity will depend on the net-impulse (net force x time) the athlete produces into the ground and the overall system mass (body mass plus any other mass being held or worn by the athlete). A heavier athlete will need to produce a greater impulse to achieve a similar velocity compared to a lighter athlete. Many sports, therefore, benefit from high levels of relative strength where athletes produce a high amount of force relative to their body weight and thus can achieve high velocities and move their mass through space faster. However, other sports and specific positions such as a heavyweight weightlifter or an American Football Lineman benefit from absolute strength where the total force is a greater performance benefit. For athletes such as these monitoring, their performance potential using JH may not be the most relevant performance measure from jump testing (Bishop et al., 2021; McMahon et al., 2022; Wells et al., 2022). Therefore, variables that more effectively reflect the performance outcomes most relevant to specific athlete populations should be considered. For example, Merrigan et al. (2022) et al. identified unique jump performance outcomes differentiated positional groups in NCAA Division 1 American football players. Since positional groups such as linemen and skill players differ vastly in the performance attributes necessary to succeed at their position monitoring the efficacy of their programming using the same metrics is likely, not optimal. Similarly, in weight class sports such as WL, performance metrics relative to bodyweight may be useful for between-athlete cross sectional analyses, however, since within a weight class absolute strength and force production abilities is what determines success variables that are not negatively affected by gains in body mass would be more warranted for monitoring performance changes within-individuals.

Commonly Measured Jump Variables

The most measured variable from jump testing is JH. In many sports scenarios, the ability to jump high is valuable. A basketball player going for a rebound, a volleyball player attempting to block, or most apparent a high jumper in track and field benefit greatly from projecting themselves higher than their competitors. However, what makes the measurement of JH so valuable to monitor in athletes is its relationships to a multitude of athletic movements and performance characteristics and its efficacy for monitoring the changing neuromuscular status of athletes. Relationships between JH and sprinting, throwing, and lifting, among other movements, have been observed (Berthoin et al., 2001; Carlock et al., 2004; Cronin & Hansen, 2005; McCluskey et al., 2010; Wells et al., 2022). Additionally, jump measures have been linked to vital performance characteristics such as strength, power, and rate of force development (Kraska et al., 2009; Stone et al., 2003). Despite some disagreement on what variables may be the most effective for monitoring neuromuscular status, multiple studies have found that various jump measures can assess some level of performance changes due to fatigue (Coutts et al., 2007; R. Gathercole et al., 2015a; R. J. Gathercole et al., 2015b; Jiménez-Reyes et al., 2019; Taylor et al., 2012; Twist & Highton, 2013; Watkins et al., 2017).

When conducted using force plates, JH is calculated most often in two ways. The first is by estimating the vertical displacement of the center of mass using flight time. Using the amount of time the athlete is in the air, their vertical displacement can be calculated using an equation of uniform acceleration (Moir, 2008). The flight time method is a highly practical and valid method of estimating JH (Aragón, 2000); however, it does assume that the position of the center of mass is the same at the beginning and end of the jump (Moir, 2008). If the subject delays contact between their feet and the ground and lands in a position that differs from their take-off, the estimated JH can be overestimated (Hatze, 1998; Linthorne, 2001). The second common method of estimating JH and what is considered the gold-standard method (McMahon et al., 2018) uses take-off velocity. The vertical velocity of the center of mass can be estimated by integrating the vertical net force and then using an equation of uniform acceleration (Moir, 2008; Vanrenterghem et al., 2001). By using the velocity at takeoff, this method is not affected by the subjects landing position; however, it does not consider the change in the vertical position of the center of mass before take-off caused by joint extension (Moir, 2008). Take-off velocity can also be estimated using the impulse-momentum relationship since the net impulse (force x time) equals the final momentum (mass x velocity) minus the initial. Since the initial velocity during a jump is zero, the final velocity can be solved for by dividing the measured net impulse by system mass (Wells et al., 2022). For this reason, accurate measurements of system mass are vital in order to accurately calculate JH using the take-off velocity or impulse-momentum methods (Moir, 2008).

In addition to JH, PP and peak force have historically been commonly measured variables from jump testing. Peak variables represent the highest instantaneous value obtained during the movement. When using force plates, peak force is calculated as the max force obtained during the jump. It typically occurs towards the end of the braking phase when athletes are switching from the eccentric to concentric portion of the movement (McMahon et al., 2018). Peak power represents the highest product of force and velocity and typically occurs after peak force and just before peak velocity. Additionally, certain equations can estimate peak power from flight time or JH (Sayers et al., 1999). While these variables have displayed relationships to other athletic movements, researchers have pointed out many limitations of using these peak variables (Ruddock & Winter, 2016; Wells et al., 2022; Winter, 2005). For instance, both CMJ peak force and power are highly affected by the depth of the countermovement (Kirby et al., 2011). In the same subject's, peak force was shown to be much higher when using a shallow countermovement despite higher jump heights occurring when using a deeper countermovement (Kirby et al., 2011; Sánchez-Sixto et al., 2018). As pointed out by Ruddock and Winter (2016), and having been discussed back in the 1800s by Marey (1894), it is not the magnitude or initial rise in force that determines the athlete's movement, but the force times the durations in which it is applied. The product of force and duration is Impulse, and it is Impulse along with the mass of the system that determines the movement outcome during a jump (Kirby et al., 2011). For these reasons, certain authors such as Ruddock and Winter (2016) have suggested moving away from peak variables that don't play as much of a causative role in movement outcomes. However, the variable Impulse is also not without its own limitations. A greater impulse applied will result in a greater velocity and, therefore, JH; however, increases in impulse can be caused by increases in the overall force or duration of the force application (Bishop et al., 2021). In many sports scenarios, increased durations of force application are undesirable because most movements in sports occur under time restraints or benefit from a movement happening in shorter periods of time. For these reasons, it is becoming more common for practitioners to account for the temporal aspects of the CMJ by assessing duration metrics such as phase (unweighing, braking, propulsive) durations or total contraction times (Bishop et al., 2021). Additionally, movement outcomes can be evaluated in relation to the duration using the flight time to contraction time ratio, also termed reactive strength index modified (Pleša et al., 2022). This metric represents the amount of time the athlete spends in the air relative to how long it took them to produce that movement. Multiple investigations have found that changes to temporal aspects of the CMJ may better represent and assess changes in the neuromuscular status of athletes across seasons and after fatiguing protocols (Cormack et al., 2008; Cormie et al., 2009; R. Gathercole et al., 2015a; R. J. Gathercole et al., 2015b). Therefore, to most appropriately monitor athlete performance longitudinally, performance variables that effectively represent movement outcomes such as JH and net impulse should be considered alongside variables representing the duration of those movements.

Phases of the Countermovement Jump

The initial phase of the CMJ has been termed the ‘quiet’ or ‘weighing’ phase (McMahon et al., 2018). This phase involves obtaining a stable baseline measurement of the system mass by having the athletes stand completely still. While no movement occurs during this phase, the accuracy of the data obtained from this phase is vital due to the measurement of system mass being used in the estimation and calculation of multiple variables. For instance, since the calculation of JH using the impulse-momentum relationship relies on determining the relative net impulse, any mismeasurement of system mass can cause gross under or overestimations in JH (McMahon et al., 2018; Moir, 2008). During this phase, the calculation of system mass typically involves taking the average force across a certain time frame (i.e., 1-2 seconds) (McMahon et al., 2018; Street et al., 2001). Next, the unweighing phase starts as soon as an initial movement is identified. Unweighing phase initiation is often determined using a set threshold that considers the measurement variability during the weighing phase. For instance, a change of five times the standard deviation of weighing force is a commonly recommended threshold (McMahon et al., 2018; Owen et al., 2014). During the unweighing phase, the athlete begins flexing at the hip, knees, and ankles and essentially begins a free fall towards the ground, resulting from an application of less force than their body weight, hence the term unweighing. The end of the unweighing phase is determined once the force trace returns to equaling the measured system mass (McMahon et al., 2018). The following phase involves the athlete beginning to stop themselves from descending towards the ground by applying vertical ground reaction forces above system mass. This phase is termed the braking phase. It continues until the athlete has applied enough force to stop their downward motion and the velocity of their center of mass reaches zero (McMahon et al., 2018). After the braking phase, the vertical ground reaction force applied by the athlete causes the athlete to move upward, and the knees, hips, and ankles rapidly extend until the athlete's feet leave the ground. This phase of the movement is termed the propulsive phase, and its end is commonly identified using a certain minimum threshold of force such as 6-10N or five times the SD of the force measured during the following flight phase (McMahon et al., 2018; Mizuguchi et al., 2015; Owen et al., 2014; Street et al., 2001). Once the measured force dips below this threshold the takeoff phase has begun, which continues until the force trace returns above that threshold again, marking the landing phase.

The separation of CMJ performance into specific phases is not only vital for accurately determining specific performance variables such as JH, peak force, or PP but also because evaluating certain characteristics of each phase can aid in assessing how the athlete is achieving those performance outcomes. Similar jump performance outcomes can be accomplished using a variety of jump strategies. For instance, athletes may achieve high jump heights by using a rapid and forceful countermovement marked by short phase durations and high braking forces or conversely can achieve similar or greater heights using a slower, deeper, longer duration countermovement marked with a high propulsive impulse (Bishop et al., 2021; McMahon et al., 2018). By evaluating both the performance outcomes (jump height, impulse, power, etc.) and certain jump phase characteristics (duration, displacement, etc.), a more comprehensive profile of the athlete's lower body force production capabilities can be obtained.

Measurement of Jump Strategy

While performance monitoring using jump testing has existed for decades, most of the variables of interest have focused on specific outcome metrics such as the JH achieved or peak variables, as discussed previously. For a number of reasons discussed so far in this review, these metrics can be valuable as part of an athlete monitoring program; however, now that force plates have become far more practical and commonly used in sports environments, much deeper insights can be obtained from jump testing. A more comprehensive insight into an athlete's performance abilities can be obtained by combining their jump performance outcome along with variables that help explain the strategy used to accomplish said performance (Bishop et al., 2021; Guess et al., 2020). The influence changes in jump strategy can have on performance outcomes is well demonstrated in studies where differences in the verbal cuing given to the athletes prior to the test effects their performance (Kirby et al., 2011; Sánchez-Sixto et al., 2021). Additionally, longitudinal studies have observed changes in certain strategy metrics such as phase durations or flight time to contraction time ratios despite maintained jump performance outcomes (R. J. Gathercole et al., 2015). Jump strategy can be inferred using additional discrete variables such as those mentioned or may more effectively be done by examining whole time-series waveforms (Cormie et al., 2009; Guess et al., 2020; Hughes et al., 2021).

Time-series waveforms can be compared between and within athletes by normalizing raw kinetic or kinematic data to the same time frame (Cormie et al., 2009; Floría et al., 2019; Kipp et al., 2019; Sole et al., 2018). By normalizing the time domain, changes or differences in kinetic or kinematic variables such as force, velocity, power, or displacement can be compared across the entire movement. In doing so, no data is wasted as it would be when solely examining discretized peak variables. This sort of analysis technique has been used to determine changes and differences in specific portions of jump-time series data after targeted training phases (Cormie et al., 2010; James et al., 2020; Suchomel et al., 2020), between better and worse jumpers (Floría et al., 2016; Sole et al., 2018), between different sports and positional groups (Guess et al., 2020), between sexes (McMahon, Rej, et al., 2017; Sole et al., 2018; Thomas et al., 2022), and between differing verbal cues (Sánchez-Sixto et al., 2021). Hughes et al. (2021) even used a waveform analysis to re-analyze previously published jump results that originally concluded no change in peak force occurred in athletes after a fatiguing protocol; however, when analyzing the force-time series waveforms, differences in the measured force application were found during specific portions of the jump performance. Therefore, by analyzing whole waveforms additional insights can be obtained from jump testing that may be otherwise missed using common discrete jump variable analyses.

Jump time-series waveforms can be statistically analyzed using multiple different methods. All methods typically start by normalizing the raw data to the same total amount of data points. For instance, normalizing the raw data down to 101 data points is a common method so that the movement can be expressed on a zero to 100 percent scale where 0 is the initiation of the movement and 100 is the take-off (Guess et al., 2020; Kipp et al., 2019; Sánchez-Sixto et al., 2021; Thomas et al., 2022). In doing so, statistically different portions can be explained as occurring at a certain percentage of the movement. The waveforms can be assessed visually or using various statistical analyses. Cormie et al. (2009) statistically compared jump waveforms by running t-tests across every normalized data point. Instead, multiple authors have used curve analyses where 95% confidence intervals are wrapped around aggregated curves and portions of the curves where the confidence intervals do not overlap are considered different (Sole et al., 2018; Suchomel & Sole, 2017). Recently, a statistical technique called Statistical Parametric Mapping (SPM), specifically designed to analyze continuous data, has gained popularity in the biomechanics literature. This procedure uses random field theory to assess the statistical significance (p-value) of calculated test statistics (t or F) along continuous data (Pataky, 2010). Kipp et al. (2019) compared SPM to the curve analysis technique and suggested that the curve analysis may increase the risk of committing type II errors. A limitation of all waveform analysis techniques is that they require time normalization, which can mask temporal differences in the performance. Therefore, waveform analysis techniques benefit from assessing temporal differences, which can be accomplished either by analyzing discretized duration variables or by more complex temporal analyses (Helwig et al., 2011; Pataky et al., 2022). Practically waveform analyses can be challenging to include in athlete monitoring programs as they require more robust data management to handle raw time-series data and more advanced data analysis skills by the practitioner. Therefore, future research needs to determine how often and to what degree changes in waveforms can be expected to occur in athletes longitudinally if it is ever to be applied in practice for informing training prescriptions and processes.

Effects of Training on Jump Performance

Evidence indicates that targeted jump training benefits from a combination of both strength and plyometric training (Perez-Gomez & Calbet, 2013). However, jump testing is often used with athletes as a surrogate measure of changes to general physical qualities such as lower body strength and power, where improvements in jumping may not be the primary target of the training program (Travis et al., 2018). Strength training studies, for example, often use changes in jump measures as evidence of a training program having a positive effect on general athletic performance (Carroll et al., 2019; Wetmore et al., 2020). The style of training used can have differing impacts on jump performance. Training strategies that emphasize high forces using heavy resistance can positively affect jump performance, especially in weaker individuals' (Cormie et al., 2010; Suchomel et al., 2018; Suchomel et al., 2016). Alternatively, training strategies with an emphasis on higher velocity movements have also shown to be beneficial for improving jump performance (Cormie et al., 2010). Any training strategy that can notably influence the force-velocity characteristics of an athlete should result in changes to jump performance since JH is determined by the athlete's velocity at take-off, and that velocity is determined by the total impulse applied by the athlete relative to their mass. Multiple studies have found positive trends in jump performance occurring in athletes participating in multiple years of resistance training (Kavanaugh et al., 2018; Sheppard & Newton, 2012). Even elite level

Volleyball players who are generally highly trained and skilled at jumping have been shown to be able to further improve their jump performance over periods of time when improving their leanness and muscular power (Sheppard et al., 2009; Sheppard & Newton, 2012), both of which are characteristics that resistance training influences greatly (Harries et al., 2012; Kraemer et al., 2002). Similarly, a meta-analysis on the effects of resistance training interventions on vertical jump performance in basketball players noted that resistance training significantly improves the vertical jump performance of basketball players (Sperlich et al., 2015).

Besides the effects that training can have on jump performance measures such as JH and peak power, different training strategies have been shown to influence the force-time waveforms of the jump differently. For instance, Cormie et al. (2009) found that power-focused training resulted in a more pronounced first peak (i.e., rate of force development) in the propulsive phase of the CMJ. In another study, Cormie et al. (2010) observed that ballistic-focused versus strength-focused training resulted in differing changes to the CMJ waveform. Both training styles resulted in significant changes to the shape of the CMJ during the unweighing phase. Cormie et al. (2009) noted that one of the most substantial changes from the training interventions consisted of a change in the mechanics the athletes used rather than any physiological change. After the training interventions, the athletes adopted a faster and deeper countermovement. By assessing both peak performance variables and the force, velocity, and power-time curves, a greater sense of the adaptations of the training intervention were able to be determined. More recently, James et al. (2020) also found that training interventions can have markedly different effects on the jump waveform depending on initial training status and that movement strategy is influenced in both stronger and weaker subjects. Therefore, further supporting the need to monitor performance outcomes and movement strategies when assessing training effects on jump performance.

Biomechanical Similarities Between Jumping and Weightlifting

The CMJ and WL movements (snatch and clean & jerk) are both bilateral multi-joint dynamic movements that involve high magnitudes and rates of vertical force application (Canavan et al., 1996; Garhammer & Gregor, 1992). The CMJ is characterized as a ballistic movement where after an impulse is applied, the system (body) continues moving and is projected into the air. The WL movements can be considered semi-ballistic actions where the barbell is projected into the air after an impulse is applied by the whole body; however, some force application may continue to be applied on the barbell as the lifter guides themselves underneath the bar and eventually receives the bar in the catch. The movements also share a countermovement where flexion of the lower body joints occurs before triple extension resulting in an unweighing phase in vertical force application that precedes the propulsive phase (Enoka, 1979; McMahon et al., 2018).

Garhammer and Gregor (1992) compared the patterns of force application that occur in both submaximal and maximal CMJ and snatch performances and found that when moving from submaximal to maximal attempts, athletes tended to use adjustments in the temporal pattern of force application rather than solely the magnitude. By producing similar magnitudes of force but increasing the duration and rates at which these forces were applied, the resulting impulse, which is what determines the change in momentum of a system, was increased. Canavan et al. (1996) compared the kinematic and kinetic relationships between a hang snatch and vertical jump and found that despite differences in the angular displacement of the hip, knee, and ankle, there were similar kinetic features shared between the movements during the propulsive phase.

Relationships Between Jump Measures and Weightlifting Performance

In addition to the movement similarities shared between jumping and weightlifting, several studies have identified statistical relationships between the two (Fry et al., 2006; Joffe & Tallent, 2020; Travis et al., 2018; Vizcaya et al., 2009). Among those studies, some of the strongest relationships observed are between the Sinclair WL total and JH and relative PP (Joffe & Tallent, 2020; Travis et al., 2018). Sinclair is a calculation used to scale WL performance to body mass so that weightlifters can be compared across weight classes (Poretti, 2017). Based on the similar muscle groups and movement similarities, it is sensible that relationships between a relative WL performance measure (Sinclair) and relative jump variables (JH and relative PP) are shared.

Among the many studies that have examined the shared relationships between WL performance and jumping, the majority were cross-sectional investigations that compared athletes' performance from a single instance of time against other athletes. Only one study has attempted to statistically quantify the relationship between a change in WL performance and a change in jumping performance within individual lifters. Joffe and Tallent (2020) conducted both a cross-sectional and longitudinal analysis of these relationships. They found that although there was a statistically significant relationship between CMJ PP and WL performance between athletes, there was no significant relationship between the change in WL performance and the change in PP over two years of competitions in 10 international level female weightlifters. Therefore, based on the current evidence, it is clear that better weightlifters tend to be better jumpers; however, what has not yet been clarified is whether individual lifters jumping performance improves as their weightlifting performance progresses. If a within-individual relationship exists between the two, this would validate the benefits of using jump testing to monitor competitive weightlifters and provide further support for the use of weightlifting style training with athletes seeking to improve their jump performance.

Summary

Based on a review of the literature it is clear that the practicality, reliability, and relevance of using jump testing measures to monitor competitive weightlifters has been well established. However, due to advances in both the technology and analyses available to assess athlete performance using jump testing, further development can be made to discern what metrics matter most to this athletic population. A strong theoretical link should exist between the ability to effect change in the momentum of an object and weightlifting performance. Therefore, a measure such as net-impulse should be further investigated for its ability to monitor and predict changes in WL performance potential. Deeper insight into the biomechanical jump strategies used to achieve jump performance outcomes can be evaluated by assessing jump time-series waveforms and temporal aspects of the jump phases. Currently, no literature exists that has assessed the jump time-series waveforms of competitive weightlifters or evaluated the relationship between impulse and WL performance. Additionally, very few truly long-term longitudinal studies (several months to years) have applied these types of analyses to the jump testing data of competitive athletes.

Chapter 3. Within-Athlete Relationships Between Vertical Jump Measures and Weightlifting Performance

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Abstract

The purpose of this study was to assess the efficacy of using vertical jump testing as a long-term athlete monitoring tool by accounting for possible individual variations over time in the relationship between jump measures and WL performance. Longitudinal athlete monitoring data from 21 collegiate Weightlifters was analyzed for this study. A linear mixed-effect model was used to assess and compare the ability of countermovement jump height and net-impulse to predict Sinclair weightlifting total. It was found that both JH and NI were significant predictors of Sinclair weightlifting total; however, likely due to changes in body mass within individuals over time, NI was a better predictor. Practitioners who work with athletes whose sport or position dictates that the ability to generate a large impulse and affect the momentum of another object is more important than the ability to project their own body should consider the use of alternative measures to JH, such as NI, when attempting to monitor long-term changes in the individual's performance potential.

Key words: Countermovement jump, athlete monitoring, impulse, jump height, force plate, force-time curve

Introduction

Vertical jump testing is one of the earliest established and most well-studied standardized physical tests of muscular performance and is potentially the most widely used performance assessment in sport (Petrigna et al., 2019; Sargent, 1921; Taylor et al., 2012). Organizations with an interest in sport performance will often use jump testing to identify potential talent or to monitor changes in an athlete's performance ability and physical state over time. Jump testing has become a valuable athlete assessment tool due to its practicality, relevance to many sports, reliability, familiarity, non-invasiveness, and its relationships to athletic performances (Kraska et al., 2009; Shalfawi et al., 2011; Vescovi & Mcguigan, 2008). Multiple investigations have related measures attained through jump testing such as jump height (JH) and peak power to performance in the sport of WL (Carlock et al., 2004; Joffe & Tallent, 2020; Vizcaya et al., 2009). The cross-sectional relationships that have been reported from these studies have been used as support for the use of jump testing as an athlete monitoring tool for weightlifters (Travis et al., 2018). Additionally, due to the observation that elite weightlifters are often relatively remarkable jumpers, WL movements (snatch and clean and jerk) and their derivatives are often touted to be effective training modalities for athletes striving to improve their jumping ability. However, when interpreting the results of cross-sectional analyses or making observations on individual elite athletes, it is difficult to ascertain what amount of contribution to the relationship between jumping and WL performance can be attributed to the athletes' training, versus what can be attributed to a predisposed talent in both activities. Currently, there is little evidence indicating that a strong relationship between changes in jumping ability and WL performance exists longitudinally within-individual athletes (Joffe & Tallent, 2020) and, therefore, warrants further investigation.

The definition of the word 'monitoring' includes the mention of "regularly checking the progress of something over time" (Oxford English Dictionary). Therefore, for a performance assessment to be deemed an effective athlete monitoring tool, it would need to be investigated longitudinally. Several previous investigations have established that strong cross-sectional relationships exist between WL performance and measures such as JH and peak power (Carlock et al., 2004; Joffe & Tallent, 2020; Travis et al., 2018; Vizcaya et al., 2009); and while the findings support the use of these variables for talent identification (Fry et al., 2006) and assessment purposes, there is currently a lack of evidence to suggest that they are also valuable monitoring tools since a significant relationship between changes in jump measures and WL performance has not been observed within-individual athletes (Joffe & Tallent, 2020).

The most common jump measures evaluated in weightlifters have been JH and peak power (Carlock et al., 2004; Joffe & Tallent, 2020). While absolute and relative peak power have demonstrated strong relationships to absolute and Sinclair WL total, peak power is a summary output that quantitatively represents the product of force and velocity at an instantaneous point in time and therefore may not offer as much insight into an athlete's changing physical abilities as a variable like impulse which plays a causative role in the motion of an object (Knudson, 2009; Ruddock & Winter, 2016). Logically, JH, typically calculated from flight time or take-off velocity, is a commonly measured variable from jump testing and has displayed strong relationships to relative WL performance values, like Sinclair, in cross-sectional studies (Travis et al., 2018). This is because net impulse (NI) scaled to system mass yields take-off velocity (i.e., relative net impulse = jump height) (Kirby et al., 2011), making JH an inherently relative performance variable. Therefore, when evaluated cross-sectionally, it is logical that athletes who can project their own mass higher also lift heavier loads relative to their size. However, it is common for strength athletes to gain body mass across their career, especially if they start training at a relatively early age. Over time an individual who gains body mass will have to generate greater net impulses to achieve the same JH, meaning beneficial improvements in their ability to generate force may not exhibit itself as noticeable increases in JH. Since a lifter's success within a weight-class is not dependent on their relative performance, a gain in body mass is not necessarily a negative development and therefore, should not be represented as such by variables used to monitor performance changes. McMahon et al. (2022); McMahon et al. (2020) recently presented a convincing rationale for the use of a jump variable they termed take-off momentum (take-off velocity x body mass), which is mathematically identical to NI (net force x time), to evaluate Rugby League athletes whose ability to generate momentum and displace an opponent can be more important than their ability to displace themselves in certain scenarios. Similarly, in the sport of WL an athlete must be able to generate a large impulse against another object, the barbell. Therefore, further investigation may be valuable to determine if a jump measure, like NI, can be a beneficial addition to long term longitudinal monitoring programs among athletes whose sport logically relies more on their ability to generate greater impulses than being able to displace themselves higher during a jump. This is especially relevant for weight-class athletes who are purposefully gaining mass in order to fill out their weight class or who compete in the super-heavyweight category, where there is no upper weight limit, and may therefore be unnecessarily penalized for being heavier if evaluated with relative performance variables.

Despite some of its limitations, jump testing is a highly practical athlete assessment tool that has shown potential to be used for talent identification purposes and to assess athlete readiness throughout tapering periods in competitive weightlifters (Bazyler et al., 2017; Travis et al., 2020). However, to determine its utility for monitoring performance in individual weightlifters and evaluate the legitimacy of the purported benefits of WL training for improving jumping ability, a within-athlete analysis is needed. Therefore, this investigation's objective was to assess the efficacy of using vertical jump testing as a long-term athlete monitoring tool by accounting for possible individual variations over time in the relationship between jump measures and WL performance and compare the measures NI and JH with regard to their ability to predict changes in individual WL performance outcomes.

Methods

Participants

Longitudinal athlete monitoring data from 21 collegiate Weightlifters were analyzed for this study. Athlete characteristics from the initial and final time points included in the analysis are summarized in Table 3.1. Approval for the study was obtained from the University's Institutional Review Board (IRB# c0321.1sw) and all athletes signed an informed consent allowing for their athlete monitoring data to be used for research purposes.

Table 3.1

Initial and Final Athlete Characteristics; Mean ± SD

	Initial	Final
Comp BM (kg)	75.10 ± 19.59	78.62 ± 21.25
Testing SM (kg)	76.65 ± 20.18	79.84 ± 21.75
Total (kg)	205.81 ± 63.18	220.81 ± 65.98
Sinclair (kg)	242.83 ± 75.41	254.76 ± 76.84
JH (cm)	35.10 ± 8.19	36.90 ± 7.97
NI (N•s)	205.21 ± 66.70	220.47 ± 69.93

NOTE: Comp BM = Official Body Mass from competition weigh-in, Testing SM = System Mass collected from force plates, JH = Jump Height, NI = Net Impulse.

Data Collection

Athletes came into the lab for testing in the morning (~7:00 – 9:00 am) approximately 3-5 days after competing in a USA Weightlifting or International Weightlifting Federation sanctioned competition in which their training program was designed to achieve a peak in performance. All testing sessions began with the athletes first having to pass a hydration test and then proceeding to perform a standardized warm-up. For the jump testing, athletes held a near weightless poly-vinyl chloride (PVC) pipe across their shoulders in a back-squat position. Athletes were instructed to jump as high as possible during each trial and given a 3,2,1 countdown before performing at least two maximal countermovement vertical jumps. If the difference in JH between trials was >2cm, additional trials were performed. The jump testing was performed on dual force plates (91.0 cm 3 91.0 cm; Rice Lake Weighing Systems, Rice Lake, WI, USA) sampling at a frequency of 1000 Hz and custom LabVIEW (LabVIEW 2018, National Instruments Co., Austin, TX) programs were used to collect and analyze the data during the testing sessions. Timepoints (competition + testing session) in which the athletes failed to achieve a competition total or where performance may have been affected by injury or illness were not included in the analysis. Therefore, individual time points for each athlete ranged from 3-10 spanning over 1-5 years. This resulted in a dataset of 108 total data points with an average of five individual timepoints per athlete.

Data Analysis

A fourth-order low-pass Butterworth filter with a cutoff frequency of 13 Hz was used to reduce the noise associated with the acquired signals (Pinto & Callaghan, 2021). Optimal cutoff frequencies were calculated for the testing data (Winter, 2009) that spanned several years and 13 Hz was identified as the lowest optimal frequency necessary to reduce the noise associated with the data collected at a certain time point, and therefore was used for the entire dataset. The average values of the two best jump trials selected based on JH were used for all subsequent analyses. JH was calculated from flight time and NI through the integration of net force using the Trapezoidal method (Linthorne, 2001; Mizuguchi et al., 2015). In order to normalize WL performance to body mass, Sinclair total was calculated by multiplying the actual achieved competition total (best snatch + best clean and jerk) by a standardized coefficient which is derived statistically based on WL total world records in various bodyweight categories (Poretti, 2017; Sinclair, 1985). The resulting Sinclair value is meant to represent the total load the individual would theoretically be capable of lifting if they were in the highest bodyweight category.

Variable Selection

The decision to include JH based on flight time as a performance variable of interest within this study was primarily due to it being the most common and practically obtainable metric from jump testing and therefore the findings of its relationship to performance would be the most applicable to practitioners. The inclusion of NI as a second variable of interest was threefold. The first and primary reasoning was due to its link to a change in momentum which theoretically should be strongly related to a sport like WL that requires the movement and projection of another object. Second, was the contention that a variable to be used to monitor performance for WL should not necessarily represent an increase in body mass as a negative adaptation (Bishop et al., 2021) as discussed in the introduction. The final reasoning was due to the overall lack of existing literature that discusses the relationship between Impulse and WL performance. The decision to compare these jump variables to Sinclair WL total over absolute total was to better represent the individual athletes' progressions of WL ability regardless of their potentially changing body mass and weight categories over time and as an attempt to standardize WL performance across the sample.

Statistical Analysis

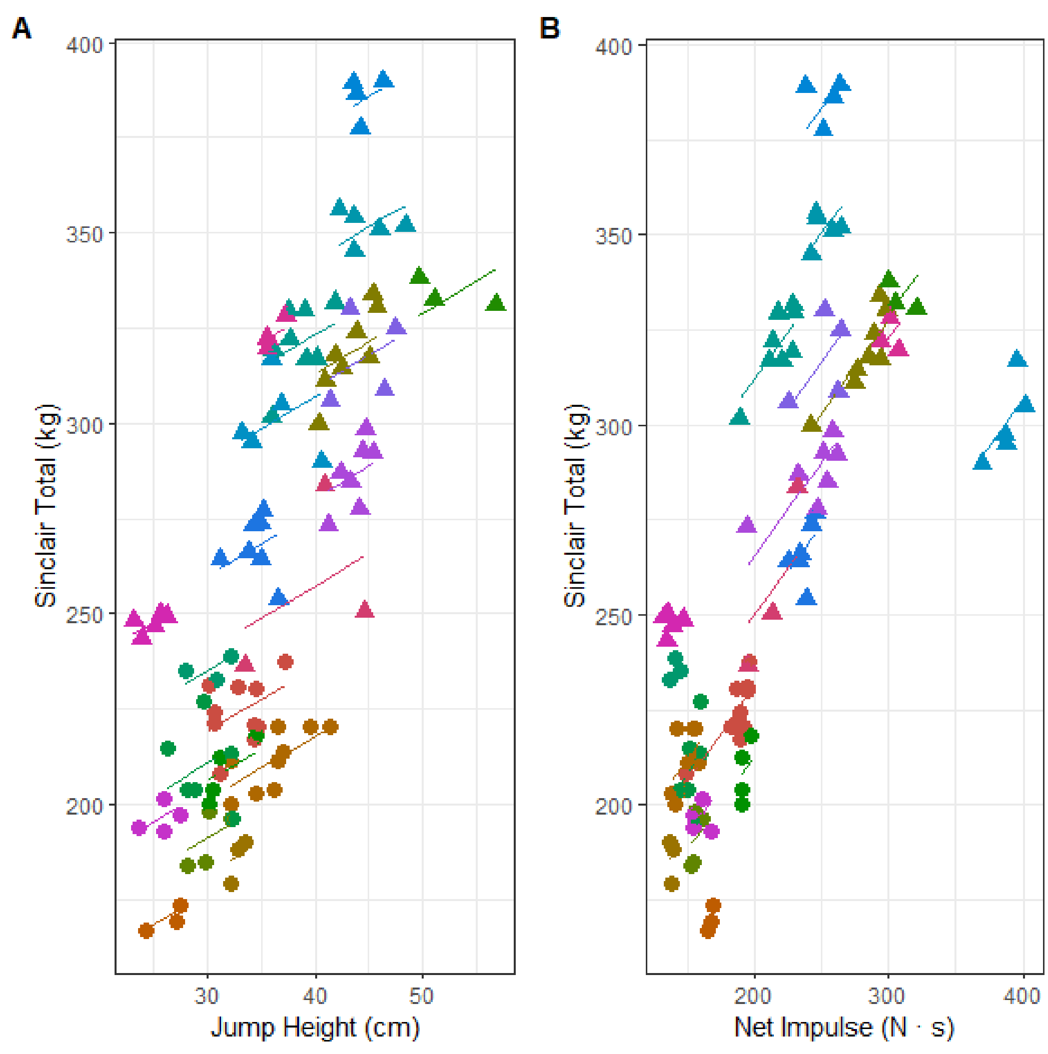
To identify whether a relationship exists between vertical jump measures and WL performance while accounting for individual variation over time, a stepwise approach was used to develop two linear mixed-effect models (LMMs) with Sinclair WL total as the dependent variable and jump height (JHmodel) or net impulse (NImodel) as the sole independent variables within each model. The necessity of using LMMs was determined by testing if accounting for the individual athlete as a random effect within the model intercept and/or slopes significantly ($p < 0.05$) improved the models. Assumptions for LMM were checked, including normal distribution of residuals and random coefficients, homoscedasticity, and influential cases. To compare the goodness of fit of the two LMMs log-likelihood values were calculated for each. Pseudo R^2 was calculated for the LMMs before (marginal) and after (conditional) considering the contextual variable ‘athlete’ (Nakagawa et al., 2017). To allow for comparison and better interpretation of the LMMs regression coefficients and to estimate the magnitude of their fixed effects (Lorah, 2018), standardized regression coefficients were calculated and reported alongside the unstandardized coefficients by group mean centering and standardizing (i.e., mean = 0, sd = 1) the variables before running the analysis. The alpha criterion for determining statistical significance for all analyses was set at 0.05. For the purposes of this study, the use of null hypothesis significance testing was primarily used to develop appropriate models rather than for determining the practical significance of any specific variable. Confidence (or compatibility) intervals (CIs) were included to emphasize the uncertainty and precision of the parameter estimates and to make inferences about the potential efficacy of using the predictor variables (JH and NI) to monitor changes in the outcome variable (WL performance) within a specific athletic population. Rank order test-retest reliability was assessed using a two-way mixed model intraclass correlation coefficient and absolute reliability with the typical error expressed as a coefficient of variation percentage (CV). All statistical analyses were conducted with the open-source software R, within the Rstudio interface (Version 1.4.1106) using the packages*: car* (Fox & Weisberg, 2018), *nlme* (Pinheiro et al., 2021), *and performance* (Lüdecke et al., 2021).

Results

Both jump variables displayed excellent test-retest reliability (ICCs = 0.98-0.99 & CV = 1.2-1.8%). Individual performance values, the models' fixed slopes, and randomly varying intercepts are displayed in Figure 3.1 The residuals of the fixed and random effects for both models were normally distributed. Neither model displayed Heteroscedasticity. Two subjects were determined as influential cases within the NImodel, likely due to having near-perfect correlations between their resulting Sinclair and NI over three and seven competitions, respectively. When the subjects' data were removed from the dataset, and the data was re-analyzed, the resulting model coefficients were unaffected (*B* coefficient of .496 versus .493 and intercept of 156.76 versus 157.56*)* therefore, the final analysis retained the two influential cases. The statistical analysis revealed that including 'athlete' as a random effect on the model intercepts significantly improved ($p<0.0001$) both the NImodel and JHmodel compared to intercept-only models. Further, the inclusion of the independent variables 'NI' and 'JH' significantly improved both LMMs fit ($p<0.0001$). Accounting for 'athlete' as a random effect on the independent variables' slopes did not improve either model ($p = 0.9966$ & 0.9988). Point estimates and the associated 95% CIs for the standardized and unstandardized fixed and random coefficients are summarized in Table 3.2. Based on the data, an increase in one standard deviation (SD) of NI and JH was compatible with an increase in Sinclair total ranging from 0.43 to 0.67 and 0.11 to 0.29 SDs, respectively. When the LMMs were compared for their goodness of fit, the NImodel displayed a better fit than the JHmodel based on the Log-likelihood values (Table 3.2).

Figure 3.1

Visualization of the Linear Mixed-Effect Models



NOTE: Male datapoints are represented by triangles and females' circles.

Table 3.2

Linear Mixed-Effect Models' statistics

	NImodel			JHmodel		
	Estimate	**95% CI**	**SE**	**Estimate**	**95% CI**	**SE**
Fixed Effects						
(Intercept)	157.56	127.44 – 187.69	15.30	203.17	168.20 – 238.13	17.76
B	0.49	0.38 – 0.60	0.06	1.68	0.94 – 2.42	0.38
β	0.55	0.43 – 0.67	0.06	0.21	0.11 – 0.29	0.05
Random Effects						
SD(Intercept)	42.36	31.10 – 57.70	6.92	51.57	37.71 – 70.58	8.33
Model Fit						
Log-Likelihood		-416.68			-436.93	
Marginal R^2		0.35			0.05	
Conditional R^2		0.98			0.98	

NOTE: B = unstandardized beta coefficients, β = standardized beta coefficients, SD = standard deviation, CI = confidence interval, SE = standard error

Discussion

The findings of this investigation demonstrate that generalizable relationships exist between Sinclair and both JH and NI within-individual athletes. The intercept of the relationship is likely to randomly vary between individuals; however, the slope of the relationship can be expected to be fixed within the population. Meaning that, on average, weightlifters of a similar level as those included in this study can not only be expected to display a positive relationship between WL performance and the examined jump measures but also the rate of change in both measures can be expected to be stable between individuals. Therefore, increases in NI or JH can be considered indicators of greater Sinclair total potential within individual lifters. Multiple studies have previously reported relationships between jump values and WL performance when compared between-athletes (Carlock et al., 2004; Fry et al., 2006; Travis et al., 2018; Vizcaya et al., 2009). When considering the previous literature and the results of this investigation, JH may be an effective variable for both talent identification and athlete monitoring purposes when used with weightlifters. This study is the first to report a within-individual relationship between any jump measure and WL performance and the only study that has tested the relationship of NI to WL performance. The ease of measurement and practicality of collecting JH by measuring flight time, make it a valuable metric for practitioners working with weightlifters. However, since it can be substantially affected by changes in body mass and increases in body mass over WL careers are so common, it is likely of value to embrace NI as a jump metric of interest for monitoring long-term physical performance changes in weightlifters if access to force plates is available. If force plates are not available, practitioners conducting longitudinal jump testing using jump mats or other means should consider and account for body mass changes. Practical ways to go about this would be to use equations that include body mass and JH in the calculation to get an estimate of absolute power (Harman et al., 1991; Sayers et al., 1999) or JH and System mass can be used to work backwards to calculate impulse using the following equations (Moir, 2008):

$$JH = TOV^2/2g$$
$$TOV = \sqrt{JH \cdot 2g}$$
$$NI = TOV \cdot SM$$
$$NI = \sqrt{JH \cdot 2g} \cdot SM$$

Where JH = Jump Height (m), TOV = Take-off velocity (m/s), g = acceleration of gravity (m/s^2), NI = Net Impulse (N·s), SM = System Mass (kg)

If substantial gains in body mass have occurred between testing sessions, small decreases or a maintenance in JH should not be interpreted as a lack of positive adaptation for a weightlifter (Bishop et al., 2021), especially if they are still within the same weight-class or if they are a super-heavyweight. This line of thinking can also be applied to the monitoring of any athletes whose sport or position relies more on generating a large NI and displacing another object, compared to the ability to displace themselves.

Conducting long-term performance testing with athletes under similar conditions and around major competitions is difficult and does not occur without certain limitations. This study's primary limitation was that the testing took place 3-5 days after the day of competition, meaning differences in travel logistics and competition results between timepoints could have influenced the results. It is not unreasonable to expect that very positive or negative competition outcomes could have influenced the athletes' mental state and motivation to perform during the testing sessions. Therefore, there is a possibility that the relationships between the competition and testing performances observed within this investigation could have been influenced by this as an individual coming off a very successful performances may be more motivated during the proceeding testing sessions compared to when they perform poorly. Additionally, although this study found that JH was a statistically significant predictor of Sinclair when accounting for individual differences, the beta coefficients of the JHmodel suggest the shared relationship cannot be expected to be as strong as it is for NI (Table 3.2). Based on the model an increase of 1 cm in JH can be expected to relate to an increase in Sinclair ranging from 0.94 to 2.42 kg. Since changes in JH often occur at magnitudes near or less than a centimeter, caution should be taken when attempting to infer changes to an athlete’s performance ability based on small fluctuations in their achieved JH. Practitioners can determine what is and isn’t a meaningful change in jump performance by assessing the change in performance relative to the normal amount of variation due to measurement error and/or biological variation using concepts such as the smallest worthwhile change (Hopkins, 2004).

This study's results are among the first to demonstrate that individual weightlifters can continue to achieve a higher JH as their WL performance relative to body mass (Sinclair) improves, despite not doing any dedicated jump training and already being relatively well-trained. Therefore, weightlifters' impressive jumping ability is likely affected by both their genetic talent and their style of training. This provides further support for the use of resistance training exercises such as the WL movements and their derivatives with athletes seeking to improve jumping performance (Berton et al., 2018; Hackett et al., 2016). The relationship between jumping and WL is logical as the WL movements can be considered semi-ballistic actions that share biomechanical similarities to jumping (Canavan et al., 1996; Garhammer & Gregor, 1992) and have been shown to develop physical qualities that are related to jumping performance (Suchomel et al., 2015; Tricoli et al., 2005). However, it is important to note that jump outcome measures such as JH and NI do not provide insight into how the athlete is achieving the jump. Athletes can achieve higher jump outcome measures by using jump strategies characterized by a deeper and more prolonged countermovement (Kirby et al., 2011; Sánchez-Sixto et al., 2018) which may be an undesirable adaptation in the context of certain sports. Therefore, further research needs to be performed to evaluate how certain training strategies such as the use of the WL movements and their derivates can influence specific jump strategy metrics in the long-term and to clarify the potential causal relationships that exist between WL and jumping.

Practical Application

Performance in sport is complex and multi-faceted, and therefore, we would not suggest the use of statistical models for predicting WL total accurately. However, the results of jump monitoring can help inform coaches as they make training decisions. For instance, a weightlifter who generates a NI value that predicts a relatively low total compared to previous timepoints might be considered physically under-prepared for an upcoming competition. Alternatively, an athlete whose predicted WL total based on NI ends up being substantially higher than their achieved total may be considered to have been physically well-prepared. Therefore, other factors such as technical or psychological issues may be evaluated more closely moving forward to determine why that athlete's performance did not meet the desired and expected outcomes. Since the results of this study indicate that the positive slope of the relationship between jump measures and WL performance can be expected to be similar between individuals,' longitudinal trends in a weightlifter's jump testing results can be used to make inferences about the physical state of that athlete. However, testing procedures must be standardized so that the measures collected are reliable and can be compared over time. Collecting and monitoring JH is both practical and valuable; however, it is suggested that changes in its results be considered alongside changes in body mass when used to evaluate weightlifters. Practitioners who work with athletes whose sport or position dictates that the ability to generate a large impulse and affect the momentum of another object is more important than the ability to project their own body should consider the use of alternative measures to JH, such as NI, when attempting to monitor long-term changes in the individual's performance potential.

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Chapter 4. A Comparison of the Force Application Patterns Exhibited During Countermovement Jump Phases Between Higher and Lower Performing Weightlifters

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Abstract

The purpose of this study was to better understand the biomechanical countermovement (CMJ) strategies of higher-performing weightlifters by comparing their patterns of force application and temporal aspects of the jump phases to a lower-performing group. The Sinclair weightlifting (WL) total achieved at a sanctioned competition closest to the testing session was used to rank 51 competitive collegiate weightlifters and separate them into groups by selecting the top and bottom tertiles for comparison. The high and low groups patterns of force application throughout the force-time curve and jump performances were compared using Statistical Parametric Mapping and unpaired t-tests. The primary differentiator between higher and lower-performing weightlifters within the CMJ was the magnitude of force produced during the propulsive phase and jump height (JH). Since the primary characteristic differentiating the higher-performing weightlifters in this sample were higher propulsive forces, training strategies for improving a lifter's physical performance should likely be targeted towards enhancing this ability.

Keywords: Countermovement jump, waveform, jump height, weightlifting

Introduction

The height achieved during a maximum effort jump attempt and the amount of load able to be lifted in barbell movements (squat, clean, press, etc.) are two performance measures commonly used to assess general athleticism in athletes. Vertical jumping and the WL movements (Snatch and Clean & Jerk) share many physical qualities such as lower body strength and power that are related to success in both activities. Multiple investigations have reported strong relationships between various jump measures and WL performance (Carlock et al., 2004; Joffe & Tallent, 2020; Travis, Goodin, Beckham, & Bazyler, 2018; Vizcaya, Viana, del Olmo, & Acero, 2009) indicating that better weightlifters often tend to be better jumpers; however, it has not been fully clarified within the literature what aspects underpin this relationship. Potentially, it may be solely differences in the ability to produce high forces (strength) that allow these athletes to achieve higher jump heights and lift heavier loads. However, due to the importance of timing and positioning during the execution of WL movements (Enoka, 1979), the pattern of force application may also differentiate higher and lower-level lifters.

The CMJ and WL movements (snatch and clean & jerk) are both bilateral multi-joint dynamic movements that involve high magnitudes and rates of vertical force application (Canavan et al., 1996; Garhammer & Gregor, 1992). The CMJ is characterized as an impulsive movement where after an impulse is applied, the system (body), continues moving and is projected into the air (Sole et al, 2022, Winter et al, 2016). Similarly. the WL movements involve impulsive actions where the barbell is projected into the air after an impulse is applied by the whole body; however, some force application may continue to be applied on the barbell as the lifter guides themselves underneath the bar and eventually receives the bar in the catch. The movements also share a countermovement where flexion of the lower body joints occurs before triple extension resulting in an unweighing phase in vertical force application that precedes the propulsive phase (Enoka, 1979; McMahon et al., 2018). Garhammer and Gregor (1992) compared the patterns of force application that occur in both submaximal and maximal CMJ and snatch performances and found that when moving from submaximal to maximal attempts athletes tended to use adjustments in the temporal pattern of force application rather than solely the magnitude. By producing similar magnitudes of force but increasing the duration and rates at which these forces were applied the resulting impulse, which is what determines the change in momentum of a system, was increased. Due to the nature of the sport, it can be expected that better weightlifters may demonstrate greater rates of force development during the CMJ exemplified as a steeper rise in the force-time waveform and potentially a bimodal shaped curve (Peng et al, 2019). However, since this initial study by Garhammer no other investigation has evaluated the pattern of force application and temporal aspects of the CMJ in weightlifters.

Based on previous literature that has reported relationships between jump measures and WL performance (Carlock et al., 2004) and described the biomechanical similarities shared between the movements (Canavan et al., 1996) it was hypothesized that higher performing weightlifters would achieve higher jump heights. However, higher jump heights can be achieved using different movement strategies that will result in varying patterns of force application and shapes of the force-time curve (Kirby et al., 2011; Pérez-Castilla et al., 2019; Rauch et al., 2020; Sánchez-Sixto et al., 2018). Differences in jump strategy and phase characteristics have been used previously to differentiate better and worse jumpers and higher and lower-level performers in multiple sports (Floría et al., 2016; McMahon, Murphy, et al., 2017; Sole et al., 2018); but no investigation has determined if differences in the temporal or force application patterns during the CMJ can differentiate performance levels in weightlifters. Therefore, the purpose of this study was to investigate the biomechanical CMJ strategies of higher-performing weightlifters by comparing their patterns of force application and temporal aspects of the jump phases to a lower performing group. Through identification of these potential differences' improvements may be made to athlete monitoring and talent identification programs that use jump testing to monitor or assess WL performance ability.

Methods

Participants

Jump testing data from 51 (30 male and 21 female) competitive weightlifters were gathered for this study. The Sinclair WL total achieved at a sanctioned competition closest to the testing session was used to rank the males and females separately. The groups were separated into high, middle, and low performing groups which consisted of 10 males and 7 females each. The participants whose Sinclair total placed them in the middle group were excluded from the analysis in order to isolate high and low performers within the sample. The High group Sinclair totals ranged from 322-390 kg and 218-249 kg and the Low group ranged from 192-277 kg and 124-190 kg for the males and females within each group respectively. The final sample for the analysis consisted of 34 athletes (20 males and 14 females). Subject characteristics for each group are summarized in Table 4.1. All athletes signed an informed consent allowing for their data to be used for research purposes. The University Institutional Review Board (IRB# c0321.1sw) also approved the use of this data for the purposes of this investigation.

Table 4.1

Subject Characteristics for High and Low Performing Groups. Mean ± SD

	High	Low
Body Mass (kg)	81.02 ± 20.64	85.59 ± 18.11
Age (years)	21.94 ± 2.54	23.12 ± 5.17
Height (cm)	166.17 ± 8.37	168.53 ± 12.11
Total (kg)	242.65 ± 57.21	182.29 ± 46.83
Sinclair (kg)	293.73 ± 56.22	214.08 ± 48.625

Data Collection

Athletes reported to the lab for testing in the morning (~7:00 am – 9:00 am) approximately 3-5 days after competing in either a USA Weightlifting or International Weightlifting Federation sanctioned competition in which their training program was designed to achieve a peak in performance. All testing sessions began with the athletes first having to pass a hydration test (urine-specific gravity < 1.020) and then proceeding to perform a standardized warm-up. For the jump trials, athletes held a near weightless PVC pipe across their shoulders in a back-squat position in order to isolate the performance to the lower body. Athletes were instructed to jump as high as possible during each trial and given a 3,2,1 countdown before performing at least two maximal countermovement vertical jumps. If the difference in JH between trials was >2cm, additional trials were performed. The jump testing was performed on dual force plates (91.0 cm 3 91.0 cm; RiceLake Weighing Systems, Rice Lake, WI, USA) sampling at a frequency of 1000 Hz and custom LabVIEW (LabVIEW 2018, National Instruments Co., Austin, TX) programs were used to collect and analyze the data during the testing sessions.

Data Analysis

The data analysis was performed using custom LabVIEW programs. A fourth-order low-pass Butterworth filter with a cutoff frequency of 13 Hz (Pinto & Callaghan, 2021) was used to reduce the noise associated with the acquired signals. Optimal cutoff frequencies were calculated for the testing data (Winter, 2009) at different timepoints that spanned several years, and this cutoff frequency was identified as the lowest optimal frequency necessary to reduce the noise associated with data collected at a certain timepoint, and therefore was used for the entire dataset. The average values of the two best jump trials selected based on JH (calculated from flight time) was used for all subsequent analyses. The average vertical force during one second of quiet stance was used to determine system mass. Initiation of the jump was recognized as the first data point that crossed within the first 2.5% of the data distribution curve established using the data from the 1s weighing period. The Unweighing phase started at this initiation point and continued until the force returned to system mass. The Braking phase was analyzed as the point when system mass was re-acquired until the center of mass velocity reached 0 m/s. The Propulsive phase was represented as the timeframe between the end of the braking phase until jump take-off. Take-off and landing were identified as the point when the ground reaction forces fell below and crossed above 7.5N, respectively. This 7.5N threshold was found to match closest compared to visual inspection and identification of take-off and landing when using the force-plate instrumentation within our laboratory. For the Waveform analysis the raw force-time data from each trial was first divided by system mass in kilograms to be expressed as relative force (N/kg). The raw data were then separated into the three primary phases (Unweighing, Braking, and Propulsive) and each phase was normalized to an equal number of samples so that every participant's pattern of relative force application within a particular phase could be compared.

The re-sampled data consisted of 446, 219, and 262 data points per trial for the Unweighing, Braking, and Propulsive phases respectively. Since normalization of the jump phases could mask any sort of temporal differences that could be observed the duration of each phase was calculated in seconds before normalization and compared in a separate analysis. In order to normalize WL performance to body mass Sinclair total was calculated by multiplying the actual achieved competition total (best snatch + best clean and jerk) by a standardized coefficient which is derived statistically based on WL total world records in various bodyweight categories (Poretti, 2017; Sinclair, 1985).

Statistical Analysis

A Shapiro-Wilk test of normality was used to examine the distribution of residuals for discrete variables before analysis. To determine if differences in JH and phase durations existed between the High and Low groups Student's t-tests with Bonferroni corrections for multiple comparisons were conducted. In cases where data was non-normally distributed Wilcoxon test was used in place of the Student's T. Cohen's *d* effect sizes and associated 95% confidence intervals were calculated to estimate the magnitude of difference and precision of estimates and interpreted using the following scale: d = 0.0–0.2 (trivial), d = 0.2–0.6 (small), d = 0.6–1.2 (moderate), d = 1.2–2.0 (large), and d = 2.0 (very large) (Hopkins et al., 2009). For the waveform analysis, normalized force-time curves were compared to assess for statistically significant differences along the curves using a two-sample statistical parametric mapping (SPM) t-test. SPM procedures use random field theory to assess the statistical significance (p value) of calculated test statistics (t or F) along continuous data (Pataky, 2010). Rank order test-retest reliability was assessed using a two-way mixed model intraclass correlation coefficient and absolute reliability with the typical error expressed as a coefficient of variation percentage (CV).

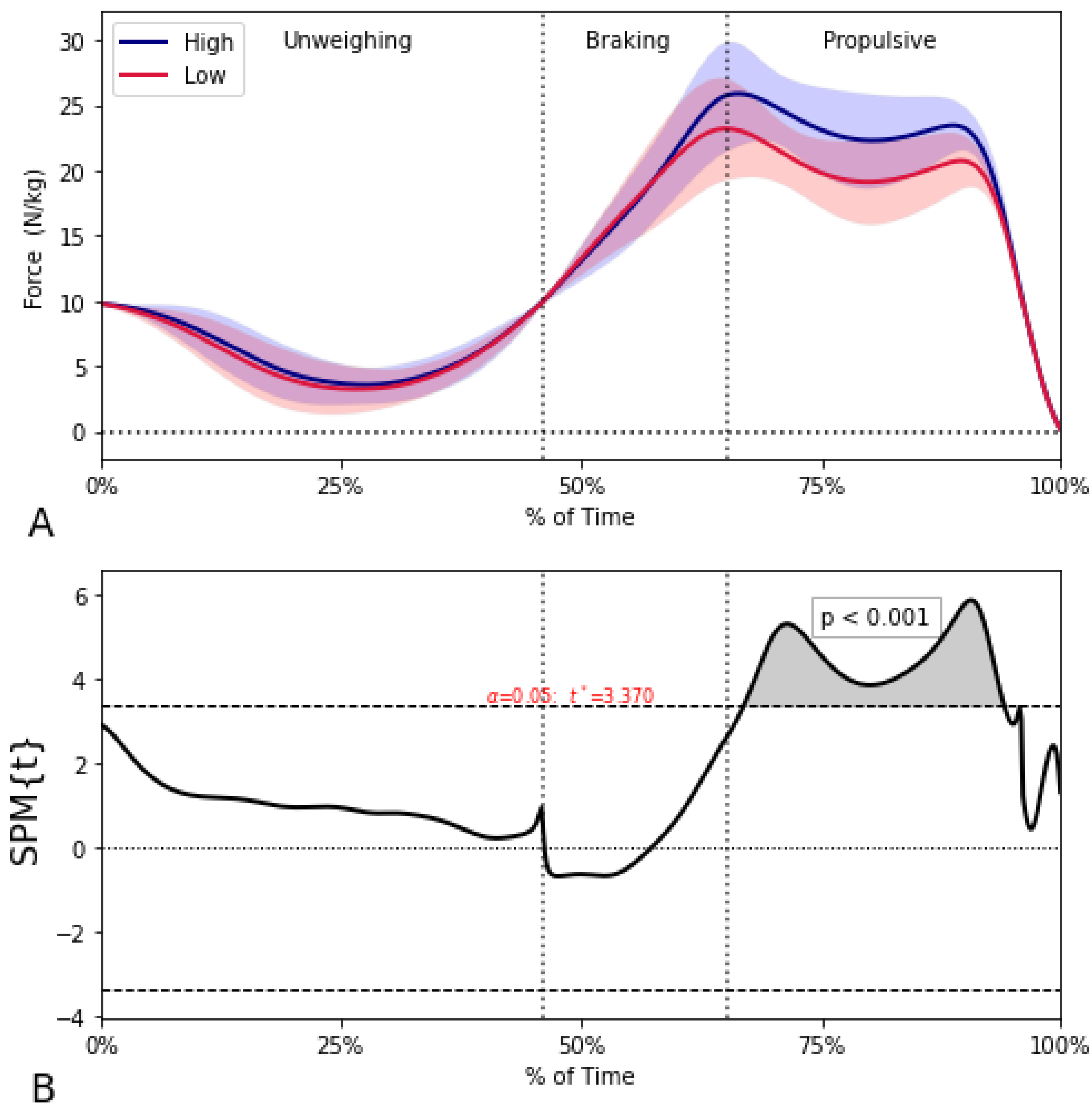
The alpha criterion for all analyses was set at 0.05. The t-test and effect sizes were conducted with the *rstatix* package using the programming language R, within Rstudio (Version 1.4.1106). The SPM analysis was conducted using the *SPM1D* package (Pataky, 2012) in Python (Version 3.9.5).

Results

The test-retest intraclass correlation coefficients (ICC) and coefficients of variation (CV) for each variable were: JH (ICC = 0.99, CV 2%), NI (ICC = 0.99, CV = 1%), Unweighing duration (ICC = 0.38, CV = 10%), Braking duration (ICC = 0.86, CV = 7%), Propulsive Duration (ICC = 0.93, CV = 4%). The Braking and Propulsive phase duration residuals were non-normally distributed; however, all other variables satisfied assumptions of normality. There was a statistically significant ($p = 0.01$) and moderate effect ($d = 1.11$) for JH with the High group exhibiting greater heights (Figure 4.1). The difference in Unweighing, Braking, and Propulsive phase durations did not reach statistically significant values. The waveform analysis revealed a statistically significant ($p = 0.001$) difference existed in the magnitude of force applied throughout the Propulsive phase with the high group tending to produce higher overall propulsive force (Figure 4.2).

Figure 4.1

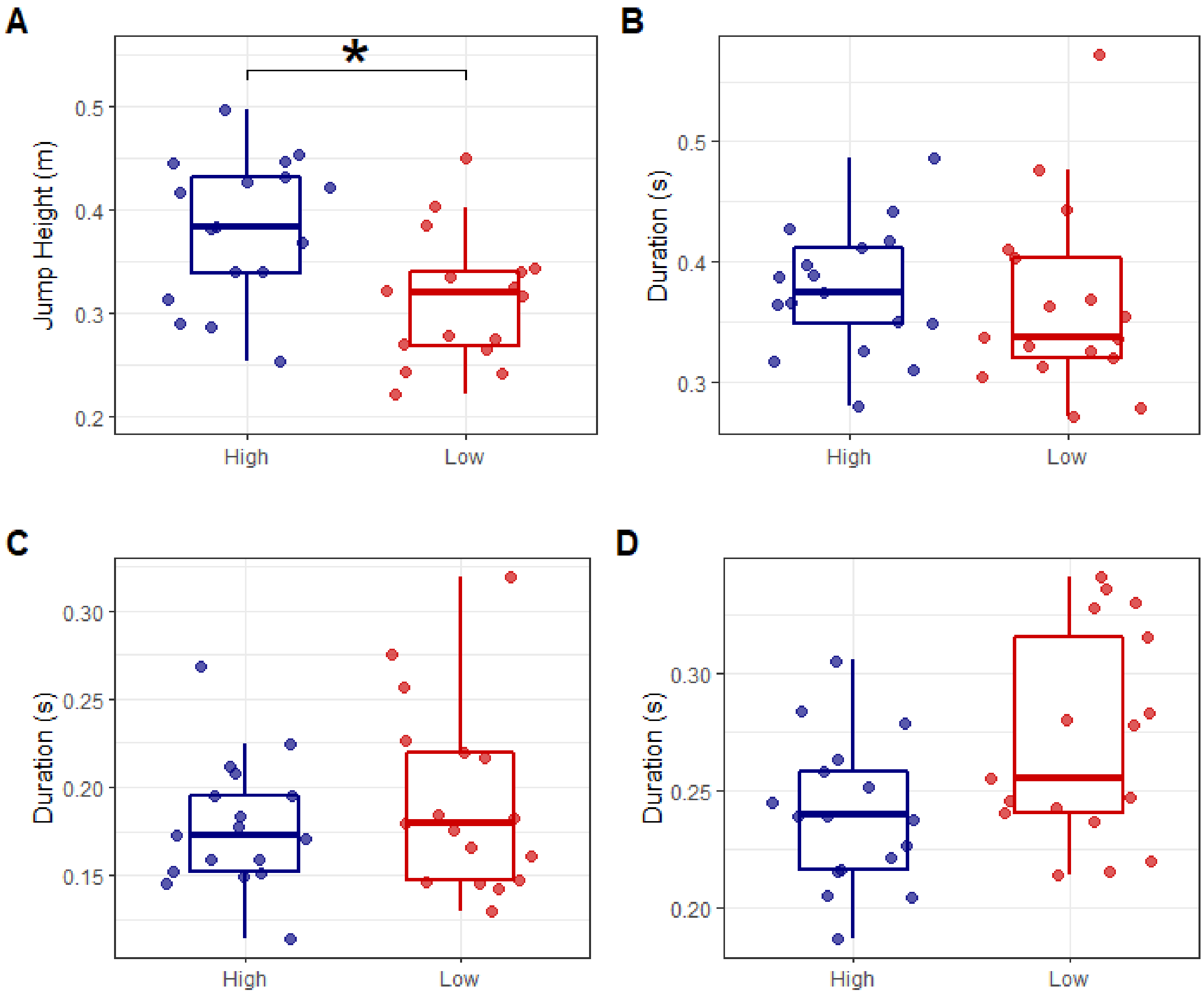
Statistical Parametric Mapping Results



NOTE: A) Normalized force-time curves of performance groups expressed as a percentage of the total movement. High and low group means are represented by the blue and red lines respectively. The shaded areas represent the group standard deviations. B) Statistical Parametric Mapping t-statistic across the force-time curve. Crossing the top horizontal line represents reaching a statistically significant ($p < 0.05$) difference in the waveforms at that point in time.

Figure 4.2

Discrete Jump Measures Results



NOTE: A) Group differences in jump height. B) Group differences in Unweighing phase duration. C) Group differences in Braking phase duration. D) Group differences in Propulsive phase duration. Dots represent individual athletes. *$p < 0.05$

Discussion

The primary finding of this investigation was that higher performing weightlifters achieved higher jump heights and produced greater relative propulsive force during a CMJ compared to a lower performing group. No other distinct differences in the shape of the force-time waveform or temporal aspects of the CMJ phases were observed between these groups. Meaning the primary differentiator identified was the ability to produce concentric propulsive forces (i.e., strength). A previous investigation that compared jump phase characteristics and waveforms of senior and academy level rugby players found similar findings where the primary kinetic differentiator was in the concentric impulse applied (McMahon, Murphy, et al., 2017). However, in that sample of Rugby players there was a small effect size supporting an increase in concentric phase time in the Senior athletes that suggested the use of a deeper countermovement. Conversely, this study found greater magnitudes of propulsive force production and no statistical difference in phase durations. Therefore, rather than increasing the applied impulse during this phase by lengthening the duration of force application the High group in this sample of weightlifters produced more force in a similar or potentially lesser time frame as the Low group. No differences were found in the pattern of force application or duration of the Unweighing phase between the groups meaning the High group did not appear to use a different countermovement strategy to achieve higher jump heights but rather just had a greater ability to produce concentric force. This difference in findings could be because the WL movements primarily rely on concentric force production (Stone et al., 2006) and eccentric actions are confined to the pulling transition phase (Cedar et al., 2019) and countermovement of the jerk (Squillante, 2018). Kauhanen et al. (1984) compared the biomechanics of WL technique between elite and district level weightlifters and came to similar conclusions as this study where the primary differentiators of the levels were in the greater kinetics of the lifts. Therefore, while kinematics and movement strategies in the WL movements and in jumping can have an influence on performance outcomes, kinetics seem to be the primary differentiator of performance levels. This is supported by multiple studies which have reported strong relationships between strength, which is the ability to produce force, and WL performance (Joffe & Tallent, 2020; Lucero et al., 2019; Stone et al., 2005).

A limitation of cross-sectional studies of this type are that the performances described are only representative of a snapshot in time of each individual participant's athletic career. Therefore, it is difficult to determine how much of an impact an improvement of a weightlifter's propulsive force during a CMJ would relate to improvements in WL performance. An additional limitation of this study is that in order to directly compare the force application pattern of the CMJ phases each individual phase was normalized rather than the whole force-time waveform. This sort of normalization technique could have masked some differences in the shape of the full waveforms; however, since no statistically significant difference in the phase durations were found it is unlikely a whole waveform normalization technique would have changed the results considerably. In order to conduct the waveform analysis, it was necessary to split the whole sample into groups thus lowering the overall statistical power of the analysis as compared to developing a general linear model with Sinclair as the dependent variable and various CMJ metrics as the independent variables. Therefore, a primary limitation of this study is that certain jump phase characteristics that could be statistically related to WL performance may not have been able to be identified using the group waveform analysis approach. Future studies should investigate the relative importance of various CMJ metrics to WL performance, especially focusing on metrics that may influence the propulsive phase since that is where this investigation observed the largest difference.

It has been well established by multiple previous investigations that jump performance outcomes like JH and peak power are correlated to WL performance. This study now adds some explanation for why this relationship exists. According to the results of this study better weightlifters are able to jump higher because of a greater ability to produce propulsive forces. This is useful information as CMJ testing can be used to monitor and assess this specific physical characteristic in weightlifters. Several previous investigations have discussed applications of jump testing with weightlifters; however, this is the first study to compare any sort of jump phase characteristics and only study to statistically analyze the jump waveforms within the sport. While the results of this study show there are few differences in the CMJ between higher and lower performing weightlifters other than in the magnitude of propulsive force produced it is still unknown to what extent force application patterns and temporal aspects of the CMJ phases may change within-individuals from different training strategies over time. James, et al. (2020) reported some training phase specific alterations in jump strategy in trained males undergoing WL style training; however, no study has investigated these characteristics in competitive weightlifters. Currently, very little is known about how CMJ strategy changes in athletes over extended periods (years) of training. Therefore, future longitudinal research is still needed in weightlifters and other athletic populations to determine what aspects of the CMJ are most relevant for athlete monitoring and talent identification purposes.

Practical Application

Since the primary differentiator between the higher and lower performing groups was solely in the concentric propulsive phase of the CMJ it may be tempting for athlete monitoring and talent identification programs that test weightlifters to only pay attention to kinetic variables collected from this phase. However, it is important to note that not only did the High group in this sample produce more propulsive force, but they produced that higher force in a similar or potentially shorter time frame and still achieved greater jump heights. Therefore, it would be of benefit to include both kinetic and temporal variables in these programs to assess not only the magnitude of force production but the timeframe in which it is applied. Although no differences were noted in this group in the movement strategy used during the CMJ previous investigations have found that CMJ strategy can change within individuals under certain circumstances (Cormie et al., 2009; James, et al., 2020). Therefore, it still may be worthwhile to include strategy type metrics like phase duration within longitudinal monitoring programs to determine how athletes are achieving the jump heights being measured. Since the primary characteristic differentiating the higher performing weightlifters in this sample were higher propulsive forces training strategies for improving a lifters physical ability (strength characteristics) should likely be targeted towards enhancing this ability.

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Chapter 5. Changes in Countermovement Jump Performance and Time-Series Waveforms Over Multiple Years of Periodized Weightlifting Training

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Abstract

The purpose of this study was to examine and compare how basic jump performance measures and the pattern of force applied during the countermovement jump (CMJ) may change over extended periods of training in competitive weightlifters. Athlete monitoring data collected over three testing sessions separated each by a year from 17 competitive collegiate weightlifters were analyzed. Changes in the athlete's force application patterns and jump performance were assessed using Statistical Parametric Mapping and repeated measures ANOVAs. The primary change occurring in the CMJ was an increase in net impulse (NI). Despite an increase in NI, statistically, significant changes in jump height (JH) were not observed, which may be due to the athletes gaining body mass over the two-year period. No statistically significant changes in the force-time waveforms were observed. Since little change was observed to the CMJ force application patterns and resulting JH over years of periodized WL training, long-term longitudinal athlete monitoring programs with weightlifters can primarily focus on assessing changes in the total amount of force applied during the CMJ (i.e., Impulse).

Keywords: Countermovement jump, force-time waveform, impulse, jump height, weightlifting

Introduction

Due to its correlation with many general athletic movements (Köklü et al., 2015; Markström & Olsson, 2013; Nuzzo et al., 2008) and its relevance to so many sports, the CMJ is a widely used athlete monitoring tool (Taylor et al., 2012). Often, single discrete performance metrics collected from CMJ testing such as JH are used as surrogate measures of performance potential in athlete monitoring programs. Up until recently, little attention has been given to the biomechanical strategy that the athletes use to achieve the jump performance and whether these strategies change over time between testing sessions. Longitudinally, how an athlete is achieving a jump is an important aspect to consider alongside changes to jump performance measures (i.e., height, power force, etc.) since many of these metrics can be influenced by the strategy the athletes use during the jump (Cormie et al., 2009; Kirby et al., 2011; Sánchez-Sixto et al., 2018). Certain authors have recently suggested that further context into jump performances can be obtained by conducting jump testing using force plates and comparing the whole force-time series waveforms rather than isolating the performance down to discrete variables (Floría et al., 2019; Sole et al., 2018). Previous investigations have used waveform analyses to identify characteristics of higher jumpers (Floría et al., 2016; Sole et al., 2018), differentiate higher and lower-level performers (James, et al., 2020; McMahon, et al., 2017), determine adaptations brought about by different training strategies (Cormie et al., 2009; James, et al., 2020; Suchomel et al., 2020), and capture changes in jump strategy within individuals due to differing verbal cues (Sánchez-Sixto et al., 2021). However, no study has yet to investigate changes in the CMJ waveform over extended periods (several months to years) of training in well-trained athletes.

The influence that factors such as changes to body mass and CMJ strategy can have on jump performance measures raises important implications for their use during athlete monitoring programs since certain performance improvements/decrements may be masked when solely looking at single CMJ metrics (James & Lake, 2021). For instance, improvements in an athletes' force production capabilities could be masked by increases in body mass when solely monitoring JH since a heavier athlete will need to produce a greater NI to achieve at least the same height. Additionally, athletes may achieve higher jump heights by using a deeper and longer countermovement that will allow them to apply a greater overall NI and, therefore, a higher JH (Kirby et al., 2011; Sánchez-Sixto et al., 2018). However, this force application strategy may be counterintuitive for certain sports that rely on rapid and reflexive movements with short contraction times. Therefore, analyzing both jump performance and jump strategy measures together may be most beneficial to identify long-term adaptations and potential changes to an athlete's neuromuscular status. Using a waveform analysis James, et al. (2020) observed specific changes in the force-time waveform occurred in resistance-trained subjects after ten weeks of WL style training. However, they observed that the waveforms of the stronger and weaker subjects adapted differently. The weaker subjects showed significant changes in multiple portions of the waveform at mid-test and post-test timepoints, whereas the stronger group only showed differences in one portion of the waveform from baseline to post-test. In the long term (months to years), if the force application pattern of well-trained athletes remains relatively stable, then jump strategy metrics may not be as effective for determining chronic performance changes once a baseline of training has been achieved as compared to outcome metrics like JH and NI. Currently, the literature offers little insight into what the expected magnitude or timeline of changes in the CMJ force-application pattern can be over extended periods (several months to years) of training.

While no literature currently exists on changes to CMJ waveforms in competitive weightlifters over time it has been observed and is logically expected that WL training affects an athlete's ability to produce force (Hakkinen et al., 1988; Joffe & Tallent, 2020; Suarez et al., 2019). Additionally, observations by Garhammer and Gregor (1992) showed that lifters could use adjustments in the temporal pattern of force application rather than solely the magnitude to generate a higher impulse and project either themselves (jump) or the bar (snatch) further. Therefore, it is probable that over multiple years of WL training, weightlifters will generate larger CMJ net impulses and higher jump heights. However, since a significant amount of effort during the training of weightlifters goes into effecting the technical execution and timing of force production during the WL movements, changes to the pattern of force application may also occur within the CMJ. Since changes to the pattern of force application cannot be observed by single jump performance measures alone, it may be valuable to also compare the whole force-time waveforms. Therefore, the purpose of this investigation is to examine and compare how basic jump performance measures and the pattern of force applied during the CMJ may change over extended periods of training in competitive weightlifters.

Methods

Participants

Athlete monitoring data from 17 (10 male and 7 female) competitive collegiate weightlifters (age: 20.47 ± 2.32 yrs, height: 165.95 ± 10.72 cm, body mass: 76.14 ± 21.27 kg) was used for this study. Approval for the study was obtained from the University's Institutional Review Board (IRB# c0321.1sw), and all athletes signed an informed consent allowing for their athlete monitoring data to be used for research purposes.

Table 5.1

Subject Characteristics Across Testing Sessions. Mean ± SD

	T1	T2	T3
Combined			
System Mass (kg)	77.13±22.24	79.62±24.34	79.58±23.78
Age (years)	20.47±2.32	21.47±2.32	22.47±2.32
Jump Height (m)	0.35±0.07	0.35±0.06	0.36±0.07
Net Impulse (N*s)	207.56±67.10	214.39±67.42	216.18±71.22
Males			
System Mass (kg)	87.84±23.37	91.75±24.67	92.10±23.04
Age (years)	21.50±2.32	22.50±2.32	23.50±2.32
Jump Height (m)	0.39±0.07	0.37±0.06	0.39±0.07
Net Impulse (N*s)	245.11±62.80	253.02±61.45	257.45±63.57
Females			
System Mass (kg)	63.44±6.97	62.29±8.48	61.71±8.83
Age (years)	19.00±1.41	20.00±1.41	21.00±1.41
Jump Height (m)	0.30±0.04	0.31±0.03	0.31±0.03
Net Impulse (N*s)	157.26±20.28	159.20±20.38	157.21±23.87

Experimental Design

This study used data from a long-term athlete monitoring program to compare the JH, NI, and CMJ force-time-series waveforms of weightlifters across three testing sessions that spanned two years. Each athlete trained under the supervision of USA Weightlifting certified coaches using a block periodized approach (Suarez et al., 2019) and performed jump testing sessions for at least two consecutive years. Each jump testing session was separated by 10-12 months and occurred 3-5 days after the athletes competed in a WL competition where their training program was designed to achieve a peak in performance.

Data Collection

All testing sessions began with the athletes having to pass a hydration test (urine-specific gravity < 1.020) and perform a standardized warm-up. For the jump trials, athletes held a near weightless PVC pipe across their shoulders in a back-squat position to remove the influence of arm-swing actions on the measured performances. Athletes were instructed to jump as high as possible during each trial and given a 3,2,1 countdown before performing at least two maximal countermovement vertical jumps. If the difference in JH between trials was >2cm, additional trials were performed. The jump testing was performed on dual force plates (91.0 cm 3 91.0 cm; RiceLake Weighing Systems, Rice Lake, WI, USA) sampling at a frequency of 1000 Hz and custom LabVIEW (LabVIEW 2018, National Instruments Co., Austin, TX) programs were used to collect and analyze the data during the testing sessions.

Variable Selection

The decision to include JH based on flight time as a performance variable of interest within this study was primarily due to it being the most common and practically obtainable metric from jump testing and therefore the findings of how it changes over time would be the most applicable to practitioners. The inclusion of NI as a second variable of interest was due to it not being negatively affected by gains in body mass that are common within the selected athlete population, and because of its strong theoretical link to the ability to move another mass (impulse-momentum relationship), which is highly relevant to the sport of WL.

Data Analysis

A fourth-order low-pass Butterworth filter with a cutoff frequency of 13 Hz was used to reduce the noise associated with the acquired signals (Pinto & Callaghan, 2021). Optimal cutoff frequencies were calculated for the testing data (Winter, 2009) that spanned multiple years, and 13 Hz was identified as the lowest optimal frequency necessary to reduce the noise associated with the data collected at a particular time point and therefore was used for the entire dataset. The average values of the two best jump trials selected based on JH were used for all subsequent analyses. JH was calculated from flight time and NI through the integration of net force using the Trapezoidal method (Linthorne, 2001; Mizuguchi et al., 2015). For the Waveform analysis, the raw force-time data from each trial were first divided by system mass in kilograms to be expressed as relative force (N/kg). The raw data were then normalized to an equal number of samples so that the pattern of relative force application across the whole movement could be compared over time (Sole et al, 2018).

Statistical Analyses

To identify differences in the discrete jump variables over time (Testing 1, 2, and 3), two 2x3 (Sex x Year) repeated-measures analyses of variance (ANOVA) were conducted. Assumptions of normality, heteroscedasticity, and sphericity were checked during the analysis. When necessary, sphericity corrections were applied to the data. Statistically significant main and interaction effects were followed up with *post hoc* pairwise comparisons using a Scheffe adjustment. Cohen's *d* effect sizes were calculated to determine the magnitude of differences. For the waveform analysis, Statistical Parametric Mapping (SPM) (Pataky, 2010) was used to analyze the normalized force-time curves from each testing session (1, 2, &3) and compare if statistically significant differences occurred throughout the curves between testing sessions in a similar manner as a repeated measures ANOVA (James et al., 2020; Kipp et al., 2019). The alpha criterion for all analyses was set at 0.05. The statistical assumptions, ANOVA, and effect sizes were analyzed with the *ez, emmeans,* and *car* packages using the programming language R within the Rstudio interface (Version 1.4.1106). The SPM analysis was conducted using the *SPM1D* package (Pataky, 2012) in Python (Version 3.9.5).

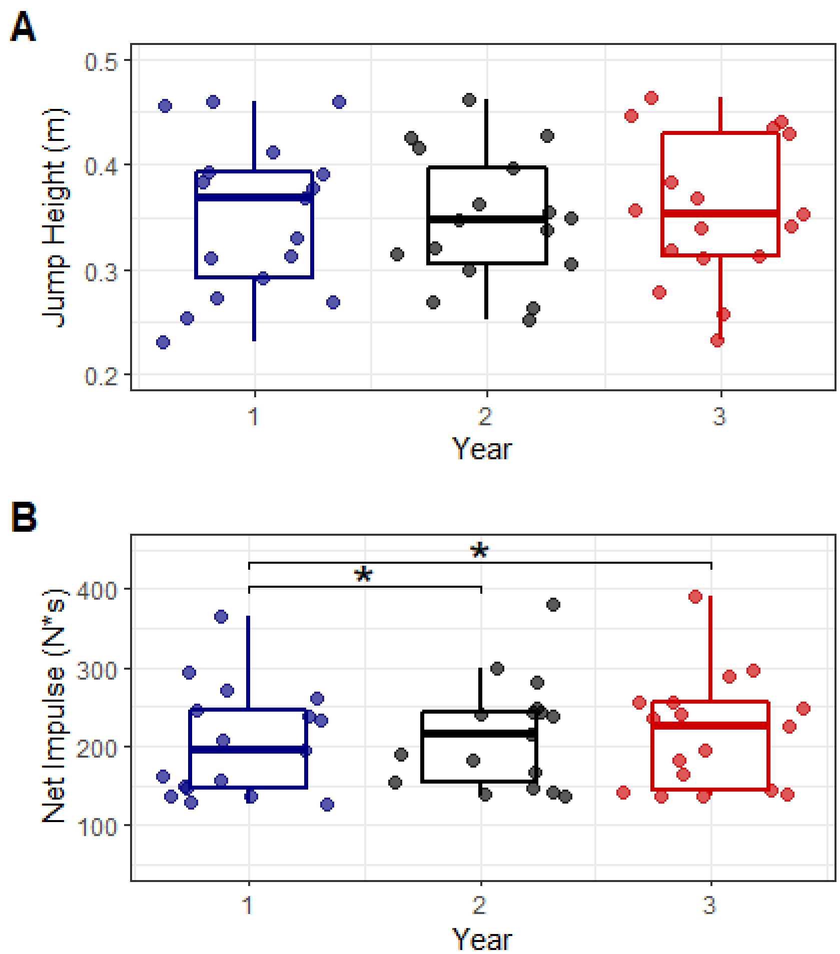
Results

All data satisfied assumptions of normality and homoscedasticity. Statistically significant ($p < 0.001$) effects of sex were found for both JH and NI, where males tended to produce higher values. There was a statistically significant interaction effect between sex and year on JH ($p =$

0.03). The *post hoc* comparisons did not reveal any statistically significant differences; however, from testing 1 to 2, the decrease in the males JH (p = 0.061) neared the selected alpha criterion of 0.05. After correcting for Sphericity violations with a Greenhouse-Geisser adjusted p-value, there was a statistically significant main effect of Year on NI (p = 0.009) and no statistically significant interaction effect (p = 0.55). *Post hoc* comparisons revealed statistically significant differences in NI occurred between Year 1 and 2 (p = 0.007; d = 1.14 [CI_{95} = 0.37-1.9]) and Year 1 and 3 (p = 0.003; d = 1.26 [CI_{95} =0.47-2.04]) but not Year 2 and 3 (p = .94; d = 0.12 [CI_{95} = -0.59-0.82]) (Figure 4.1). No statistically significant main or interaction effects were observed in the CMJ Waveforms (Figure 4.2).

Figure 5.1

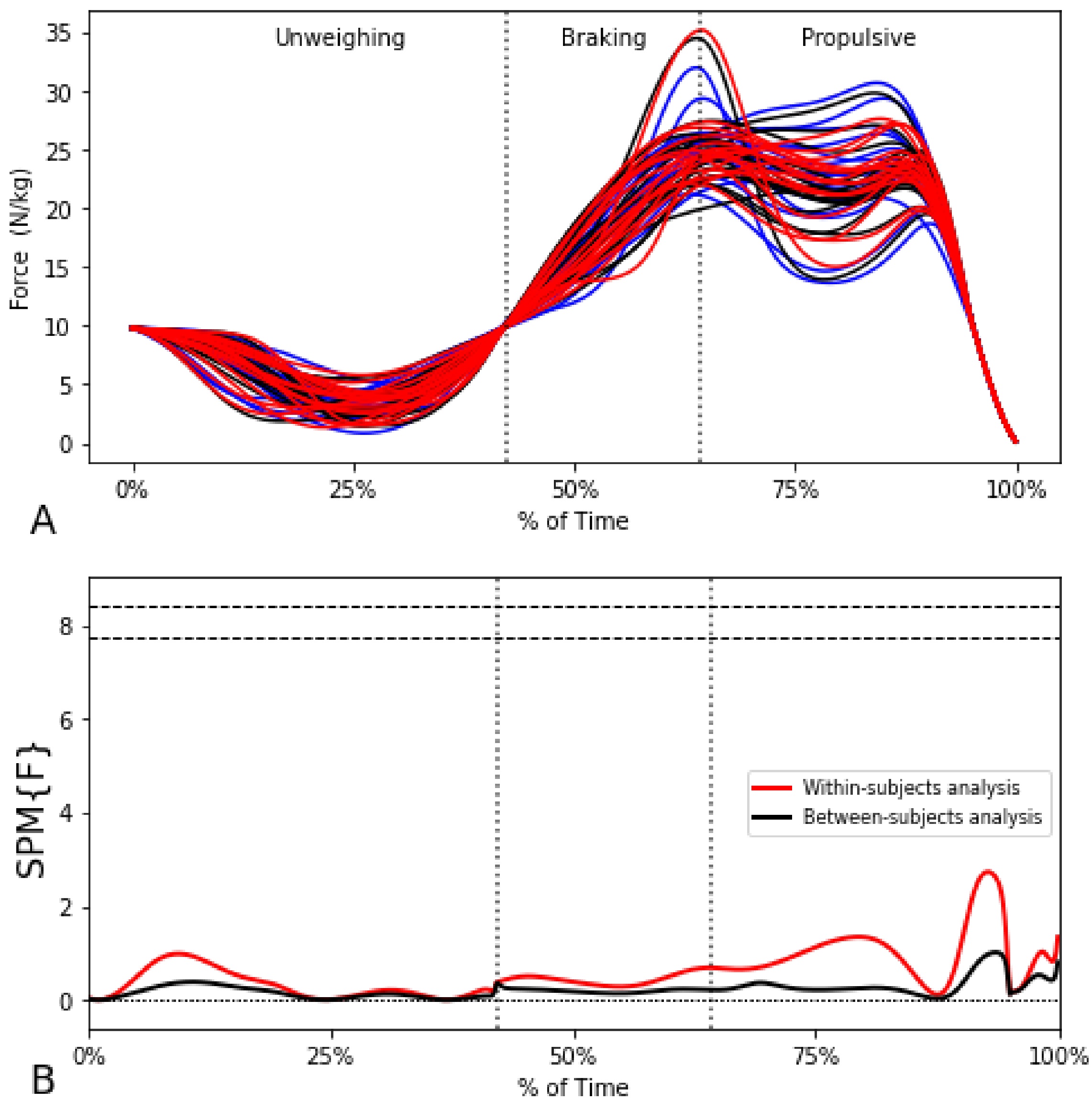
Changes in Discrete Jump Measures Over Time



NOTE: A) Group and individual JH results over the three testing sessions. B) Group and individual NI results over the three testing sessions. Dots represent individual athletes. *$p < 0.05$

Figure 5.2

Statistical Parametric Mapping Results Over the Three Testing Sessions



NOTE: A) Normalized force-time curves expressed as a percentage of the total movement. Year 1, 2, and 3 are represented by the blue, black, and red lines respectively. B) Statistical Parametric Mapping F-statistic across the force-time curves. Crossing of the top horizontal lines would represent reaching a statistically significant ($p < 0.05$) difference in the waveforms at that point in time.

Discussion

The primary finding of this investigation was that over three testing sessions separated each by a year, the primary change occurring in the CMJ within this sample was an increase in the NI applied. Despite an increase in NI, statistically significant changes in JH were not observed, which may be due to many of the athletes gaining body mass over the two-year period. Since the sport of WL relies on the ability to move another mass in addition to their own, rather than the projection solely of the athlete's own mass, increases in NI without increases in JH are not necessarily representative of a lack of positive adaptation. The waveform analysis did not reveal any changes over time in the pattern of force application. Since the force-time waveforms were expressed as relative force (N/kg), the increased NI was not observable in the waveforms; however, the primary purpose of conducting the waveform analysis in this study was to assess changes in the pattern and timing of force application rather than the magnitude. James et al. (2020) observed statistically significant changes in portions of the force-time waveform over ten weeks of WL style training in resistance-trained subjects; however, they reported more changes to portions of the waveform throughout the training period in a weaker subject group. Considering the results of that study and the lack of changes within the force-time waveform that occurred within the current long-term investigation using already well-trained competitive weightlifters, it seems possible that the jump force-time waveform may stabilize after initial periods of strength and power training when tested under similar conditions. As pointed out by Gathercole et al. (2015), acute changes due to training and/or fatigue seem to influence CMJ strategy, whereas chronic training adaptations are more likely to result in changes in jump outcome measures.

The finding that JH did not increase within this sample of weightlifters despite increases in NI over the two-year period comes down to the physics of the movement. The subject characteristics in table 5.1 show that, on average, the group gained body mass, and since JH is determined by the relative (per kg of mass) NI applied, this gain in mass at least partially prevented any notable increases in JH. Since the sport of WL depends on an athlete's ability to move another mass, this adaptation is likely beneficial and exemplifies the limitations of using JH or relative performance metrics for monitoring developing strength athletes. No clear differences were observed in the changes over time between the sexes; however, this study was limited in sample size to determine between-sex differences in these measures effectively.

No significant effects were observed in the force-time waveforms over the two-year period. Previous studies that have found changes in the jump force-time waveform conducted testing sessions throughout a single training cycle, finding differences in the waveform occurred during differing periods/phases (Cormie et al., 2009; James et al., 2017; Suchomel et al., 2020). Conversely, the athletes in this study were always tested during the same part of their training cycle (post-peak/taper) over multiple macrocycles to determine if changes in the waveform occurred over extended periods of training. It is, therefore, possible that if these athletes were tested within a single training cycle that phase-specific changes in the waveform may have been observed. There is good evidence that conditions of fatigue can influence the jump strategy used by an athlete (Gathercole et al., 2015a; Gathercole et al., 2015b) and therefore jump waveform analyses may be more useful for acute monitoring (days to weeks) rather than as a long-term (months to years) indicator of adaptation, especially when tested under similar conditions and phases of a training cycle.

A limitation of this investigation that prevents any identification of the timeline in which changes in the jump force-time waveform occur in athletes is that all participants began with multiple years of training experience. Because of this, it is difficult to discern whether the force-time waveform in strength athletes remains stable across a strength athlete's career or if it changes early and then stabilizes once a certain training status has been reached. Future long-term studies should be conducted using participants of an initially lower training status to clarify this study's findings.

Practical Application

Since little change was observed to the CMJ force application patterns and resulting JH over years of periodized WL training, long-term longitudinal athlete monitoring programs with weightlifters can primarily focus on assessing changes in the total amount of force applied during the CMJ (i.e., Impulse). Increases in force application abilities can be masked by increases in body mass over time when monitoring JH, so NI may be a more applicable measure of long-term performance changes in strength athletes.

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Chapter 6. Summary and Future Investigations

The purposes of this dissertation were to evaluate the effectiveness of alternative approaches to using vertical jump testing data to monitor competitive weightlifters and add to the relatively scarce literature that involves long-term longitudinal monitoring programs in trained athletes. To do so, this project 1) aimed to identify if there was a relationship between changes in specific jump measures and WL performance within-individual athletes, 2) examined if differences in biomechanical patterns of force application during a jump differentiated higher and lower performing weightlifters, and 3) determined if and to what extent jump performance and force application patterns change over extended periods of training.

The findings of study 1 demonstrated that generalizable relationships exist between Sinclair and both JH and NI within-individual athletes. This study is the first to report a within-individual relationship between any jump measure and WL performance and the only study that has tested the relationship of NI to WL performance. This study validates the use of jump testing to monitor competitive weightlifters and established a within-athlete relationship between improvements in WL performance relative to bodyweight (Sinclair) and jumping ability. Therefore, further supporting the use of WL derivates and resistance training for improving jumping ability in athletes. Since JH can be substantially affected by changes in body mass and increases in body mass over WL careers are so common, it is likely of value to embrace NI as a jump metric of interest for monitoring long-term physical performance changes in weightlifters. This line of thinking can also be applied to the monitoring of any athletes whose sport or position relies more on generating a large NI and displacing another object compared to the ability to displace themselves.

While not groundbreaking, the findings of study 2 established that the primary differentiator of higher and lower performing weightlifters within the CMJ was in the JH achieved and relative propulsive force produced. No other distinct differences in the force-time waveform and temporal aspects of the CMJ phases were observed. Meaning the primary differentiator identified was the ability to produce concentric propulsive forces (i.e., strength). Kauhanen et al. (1984) compared the biomechanics of WL technique between elite and district level weightlifters and came to similar conclusions as this study, where the primary differentiators of the levels were in the greater kinetics of the lifts. Therefore, while kinematics and movement strategies in the WL movements and jumping can influence performance outcomes, kinetics seem to be the primary differentiator of performance levels.

The primary finding of study 3 was that over three testing sessions separated each by a year, the primary change occurring in the CMJ within a sample of competitive weightlifters was an increase in the NI applied. Despite an increase in NI, statistically significant changes in JH were not observed, likely due to the athletes gaining body mass over the two-year period. These findings support the findings of study 1, where JH may be an applicable metric to compare weightlifters cross-sectionally, but positive adaptations in the ability to produce force may be masked by increases in body mass within athletes over long periods of time.

The primary takeaway from this dissertation is that CMJ NI is a highly relevant and useful metric to monitor competitive weightlifters over their careers. NI demonstrated an ability to predict changes in WL performance within individual athletes over time, differentiated higher and lower performers, displayed changes over two years of training when JH did not, and in every study demonstrated very high levels of reliability. Collectively these results support the validity, reliability, sensitivity, and relevance of using NI as an athlete monitoring tool for this athletic population.

Overall, the time-series waveform analyses revealed little additional insight that could not be gathered by measuring discrete outcome measures like NI. However, this may be due to the training level of this sample in addition to only assessing the jumps at the beginning and end of training cycles. Previous studies that have found changes to the jump force-time waveform conducted testing sessions throughout a single macrocycle, finding differences in the waveform occurred during differing periods/phases of a single training cycle (Cormie et al., 2009; James et al., 2017; Suchomel et al., 2020). Therefore, jump waveform analyses may be more useful for acute monitoring (days to weeks) rather than as a long-term (months to years) indicator of adaptation, especially when tested under similar conditions and phases of a training cycle. Future study in this area would benefit from long-term assessments of force-time waveforms with subjects of an initially low training age to determine if and when force-time waveforms stabilize. Additionally, to further determine the usefulness of this analysis technique for monitoring competitive strength athletes, future studies should conduct this sort of analysis pre and post specific training phases to determine if phase-specific changes in the CMJ time-series waveforms can reveal any insight into specific adaptations or the neuromuscular status of weightlifters at important points throughout a training cycle (Suarez et al., 2019).

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