UNIVERSITY OF CHICHESTER

An accredited institution of the

UNIVERSITY OF SOUTHAMPTON

THE EFFECTS OF APPLYING EXTERNAL LOADS ON HUMAN JUMPING MECHANICS

by

Peter Daniel Mundy

Thesis for the degree of Doctor of Philosophy

2018

UNIVERSITY OF CHICHESTER
An accredited institution of the
UNIVERSITY OF SOUTHAMPTON

ABSTRACT

Thesis for the degree of Doctor of Philosophy

THE EFFECTS OF APPLYING EXTERNAL LOADS ON HUMAN JUMPING MECHANICS

Peter Daniel Mundy

The effects of external loading on jumping mechanics have been extensively investigated; however, review of the body of knowledge revealed a number of methodological issues, as well as a common omission of key mechanical theory, with limited studies investigating the effects of changing the position of the external load. Therefore, the primary aim of this thesis was to investigate the effects of changing the position of the external load and training status on system centre of mass and lower limb joint mechanics during countermovement jumping, with a particular emphasis on power output. Section 3 (Mundy, Lake, Carden, Smith, & Lauder, 2016a) established that the force platform method and the combined method cannot be used interchangeably within practice for measuring power output, and argued that the force platform method should be adopted as the criterion method. Using the force platform method, section 4 (Mundy, Smith, Lauder, & Lake, 2016b) established that the effects of barbell loading on system centre of mass mechanics reported are often overemphasised, and it was argued that investigating the complex interaction between the underpinning force, temporal and spatial components is of interest to practitioners. Section 5 demonstrated that practitioners may overcome the constraints of barbell loading by changing the position of the external load to arms' length using a hexagonal barbell, which facilitated greater system centre of mass and lower limb joint mechanics in strength-power trained athletes. However, as the effects of external load have been posited to be population specific, section 6 demonstrated that regardless of the magnitude of the external load, strength-power trained athletes produced significantly greater hip joint peak power outputs than their recreationally trained counterparts. As such, the findings of the thesis support the hypothesis that practitioners should prescribe the position of external loading that maximise hip joint peak power output. In conclusion, this thesis has not only made significant steps towards providing a standardised method of measuring power output, but it has also offered a revealing insight into the effects of training status, as well as the effects of changing the position and magnitude of the external load on system centre of mass and lower limb joint mechanics during countermovement jumping.

Contents

List of Tables

List of Figures

Declaration of Authorship

I,

Peter Daniel Mundy,

declare that the thesis entitled

The Effects of Applying External Loads on Human Jumping Mechanics

and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- where I have consulted the published work of others, this is always clearly attributed;
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- parts of this work have been published as:

Peer Reviewed Journal Articles

Mundy, P. D., Lake, J. P., Carden, P. J., Smith, N. A., & Lauder, M. A. (2016). Agreement between the force platform method and the combined method measurements of power output during the loaded countermovement jump. *Sports Biomechanics*, *15*(1), 23-35.

Mundy, P. D., Smith, N. A., Lauder, M. A., & Lake, J. P. (2016). The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sports Sciences*, 1-7.

Peer Reviewed Conference Abstracts

Mundy, P., Lake, J., Smith, N. & Lauder, M. (2016). Effect of load on system and lower extremity joint power output during hexagonal barbell loaded countermovement jumps. *United Kingdom Strength and Conditioning Association National Conference*. Hinckley, England.

Mundy, P., Lake, J., Carden, P., Smith, N. & Lauder, M. (2015). Effect of load positioning on power output during loaded countermovement jumping. *United Kingdom Strength and Conditioning Association National Conference*. Kenilworth, England.

Mundy, P., Lake, J., Carden, P., Smith, N. & Lauder, M. (2015). A linear position transducer attached to a waist harness cannot estimate power during unloaded and loaded countermovement jumping. *United Kingdom Strength and Conditioning Association National Conference.* Kenilworth, England. (**3rd Prize – Best Poster Presentation, Original Research Category)**.

Lake, J., **Mundy, P.** & Carden, P. (2015). The effect of barbell load on vertical jump landing force-time characteristics. *National Strength and Conditioning Association National Conference.* Orlando, Florida, USA.

Mundy, P., Lake, J., Carden, P., Smith, N. & Lauder, M. (2014). Agreement between measurements of mean power output during the loaded countermovement jump. *British Association of Sport and Exercise Sciences Biomechanics Interest Group Meeting.* Manchester Metropolitan University, England. **(Summit Medical and Scientific 1st Prize - Best Poster Presentation).**

Signed:

Date: 30/10/2016

Acknowledgements

I would like to express my sincere gratitude to my supervisory team, Dr Jason Lake, Professor Mike Lauder, and Dr Neal Smith. I would also like to thank the rest of the amazing biomechanics team, past and present, at the University of Chichester, Dr Penny Hudson, Dr Matt Robbins, Dr Kathleen Shorter, and Patrick Carden. Further, I would also like to thank the members of the sport and exercise sciences postgraduate research team for providing moral support when it was needed most.

I would like to thank Thera-Band for funding the preliminary work investigating the effects of negative external loading on jumping mechanics, even if it did not make it into the final thesis. It is particularly important here to thank Dr Jason Lake for helping design the apparatus, and Patrick Carden for spending many hours in the Old Chapel laboratory with me validating it. I would also like to thank Dr Iain Fletcher for providing me with some perspective regarding the apparatus during my transfer viva.

I would like to thank Dr Paul Swinton, Dr Paul Comfort, and Dr Naoki Kawamori for taking their time to provide comments on various sections of this thesis. Further, I would like to thank Dr Philip Graham-Smith for his continued education and support, regardless of where he is in the world.

Finally, I would like to thank the patient support of my family and friends, for which nothing written in this section could ever do justice. Without your support, this thesis would not have been possible

Dedication

This thesis is dedicated to the memories of

Denis Kirkbride (1929-2016) and Kathleen Mundy (1936-2010)

"i carry your hearts with me

(i carry them in my heart)"

.

Key Terms

Agreement

How much a method is likely to differ from another: if this difference does not cause problems in clinical interpretation, then the two methods can be used interchangeably (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999).

Centre of Mass

The point on a body that move in the same way that a particle subject to the same external forces would move (Rodgers & Cavanagh, 1984).

Countermovement

A preliminary downward movement of the system centre of mass.

External Load

An external mass applied to the system.

Vertical Jumping

The vertical projection of the system centre of mass produced via the triple extension of the lower limb joints.

Maximum Dynamic Output Hypothesis

The hypothesis that the external load that maximises power output during countermovement jumping is the external load most commonly encountered by the individual (Jaric & Markovic, 2009).

Optimal Load

The external loading condition which maximises power output through an optimal compromise between submaximal force and submaximal velocity (Cormie, McGuigan, & Newton, 2011b).

Power Output

The rate of external mechanical work performed on the system centre of mass.

Push-off Phase

The phase of jumping referring to upward movement of the system centre of mass, defined between peak negative displacement of the system centre of mass during the countermovement and take-off.

System

The human body plus the external load applied.

1. General Introduction

The proximal to distal triple extension of the hips, knees, and ankles is integral to the successful execution of a multitude of dynamic athletic tasks (e.g. jumping, sprinting, and tackling). During such tasks, the lower extremities are inevitably loaded by the body's own mass, and often by the mass of an opponent. As such, training with external loads is an essential part of physical preparation for many athletes. More specifically, externally loaded jump training is a simple way of providing a mechanical overload that is highly specific to such tasks, ostensibly maximising sport-specific training adaptations (Crewther, Cronin, & Keogh, 2005; Frost, Cronin, & Newton, 2010; Haff & Nimphius, 2012; Kawamori & Haff, 2004).

Barbell loaded jumping is one of the most commonly used forms of externally loaded jump training. It is postulated that ballistic movements such as barbell loaded jumping enable the athlete to accelerate the system (body + external load) centre of mass (CM) throughout the entire push-off phase (commonly referred to as the concentric phase or the propulsion phase); producing greater velocity and power outputs than traditional non-ballistic movements (e.g. back squats) (Crewther et al., 2005; Frost et al., 2010; Kawamori & Haff, 2004). Therefore, the effects of barbell loading on system CM mechanics during countermovement jumping have been extensively investigated.

In particular, there has been a focus on the effects of barbell loading on the maximal production of power output (Cormie et al., 2011b; Jaric & Markovic, 2013). Such studies are typically based on the hypothesis that power output is a performance determining factor in a multitude of dynamic athletic tasks; however, it is important to note that the use of power output during jumping has also been heavily criticised (Knudson, 2009; Winter & Fowler, 2009; Winter & Knudson, 2011). In brief, “power” is often expressed as a “clearly defined, generic neuromuscular or athlete performance characteristic” rather than as an application of the actual mechanical definition (Winter et al., 2016). As such, this leads to considerable inaccuracy and confusion, primarily because it often fails to represent the performance being assessed (Winter et al., 2016). To date, the results of such studies have been used for optimising resistance training programmes (Cormie et al., 2011b; Haff & Nimphius, 2012; Kawamori & Haff, 2004; McGuigan, Cormack, & Gill, 2013), assessing and monitoring athletes (Baker, 2001; McGuigan et al., 2013; Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008a), discriminating between levels of competitive playing ability (Argus, Gill, & Keogh, 2012; Baker, 2002; Hansen, Cronin, Pickering, & Douglas, 2011e; Sheppard et al., 2008b; Sheppard, Nolan, & Newton, 2012; Young et al., 2005), and understanding the design and function of the locomotor system (Jaric & Markovic, 2009, 2013).

Despite the perceived importance of power output, the way in which power output is measured during countermovement jumping remains a contentious issue. To the author’s knowledge, there is no criterion method ubiquitously accepted within the body of knowledge (Dugan, Doyle, Humphries, Hasson, & Newton, 2004; Hori, Newton, Nosaka, & McGuigan, 2006; Jaric & Markovic, 2013; McMaster, Gill, Cronin, & McGuigan, 2014), with contradictory recommendations reported within method comparison studies (Cormie, Deane, & McBride, 2007a; Cormie, McBride, & McCaulley, 2007b; Crewther et al., 2011; Hansen, Cronin, & Newton, 2011b; Hori et al., 2007; Lake, Lauder, & Smith, 2012b; Li, Olson, & Winchester, 2008). Therefore, the results of previous studies investigating the effects of barbell loading on the power output during countermovement jumping may be confounded by fundamental methodological issues. As such, if the theoretical and practical importance of power output is to be investigated, it must be done so within a theoretically valid, Newtonian framework. Further, the majority of studies investigating power output during countermovement jumping have not been interpreted cognisant of the underpinning force, temporal, and spatial components (Crewther et al., 2005; McMaster et al., 2014), thus limiting the practical applications of their findings as the overload recommended may not be the overload inherently desired.

A further issue with the contemporary focus on the effects of external load on system CM mechanics is that although it may provide important global information, it does not necessarily provide information about lower limb joint mechanics (Jandacka, Uchytil, Farana, Zahradnik, & Hamill, 2014; Kipp, Harris, & Sabick, 2011; Moir, Gollie, Davis, Guers, & Witmer, 2012). As specificity of training is a function of the task-inherent biomechanics, not simply the external movement characteristics, knowledge of lower limb joint mechanics provides important descriptive information that must also be considered during the physical preparation of athletes (Aragón-Vargas & Gross, 1997; Kipp et al., 2011). This may be highlighted by the potential constraints imposed by barbell loading. For example, as barbell load increases, the position of the barbell may restrict trunk inclination by increasing the moment arm of the resistance (Swinton, Stewart, Lloyd, Agouris, & Keogh, 2012). This may limit hip joint extensor work (Vanrenterghem, Lees, & Clercq, 2008), which is proposed to be a particularly important contributor to countermovement jump performance (Aragón-Vargas & Gross, 1997; Marshall & Moran, 2015). As such, practitioners prescribing external loading parameters based on system CM mechanics alone may be unknowingly altering the athlete’s movement strategy, thus limiting the effectiveness of their physical preparation programme.

It has been postulated that the constraints imposed by barbell loading may be attenuated by changing the position of the external load (Swinton et al., 2012). For example, by using a hexagonal barbell (Swinton et al., 2012; Turner, Tobin, & Delahunt, 2015) or a weighted vest (Driss, Vandewalle, Quievre, Miller, & Monod, 2001), athletes may maximise power output at external loads greater than body mass as they appear more able to maintain an effective jumping strategy, ensuring that the overload provided is both intended and task specific. Interestingly, there is evidence to suggest that only resistance trained ‘strength-power’ athletes demonstrate a load associated increase in power output (Driss et al., 2001). This may be explained by the Maximum Dynamic Output hypothesis, which suggests that the external load that maximises power output during countermovement jumping is a strength-dependent behaviour, and as such associated with the loads most commonly encountered by the individual (Jaric & Markovic, 2009). Conversely, more recently, it has been argued that due to the evolutionary design of the locomotor system, the external load that maximises power output during countermovement jumping is the individual’s own body mass, regardless of the strength of the lower limb muscles (i.e., strength-independent behaviour) (Jaric & Markovic, 2013).

The contradictory theories presented raise a philosophical question regarding the prescription of externally loaded jump training during the physical preparation of athletes. For the practitioner, it is currently unclear whether physical preparation programmes should be guided by the external load at which an athlete currently maximises power output at, or at an external load at which it is desirable to do so. Further, although differences in the optimal load have been previously investigated at a system level, it is unclear to practitioners how the training status of the athlete influences lower limb joint mechanics. As such, if the effectiveness of externally loading jump training is to be improved, further investigation is warranted regarding the effects of both the position of the external load, as well as the magnitude of the external load on athletes of differing levels of training status.

1.1 Aim

The primary aim of this thesis was to investigate the effects of changing the position of the external load and training status on system CM and lower limb joint mechanics during countermovement jumping, with a particular emphasis on power output. More specifically, the aim of each section of this thesis was to:

i. Assess agreement between the force platform method and the combined method measurements of power output during unloaded and barbell loaded countermovement jumping (section 3);
ii. Investigate the effects of external (barbell) loading on system CM mechanics during countermovement jumping (section 4);
iii. Investigate the effects of changing the position (straight barbell vs. hexagonal barbell) of external loading on system CM and lower limb joint mechanics during countermovement jumping (section 5);
iv. Investigate the effects of training status and external (weighted vest) loading on system CM and lower limb joint mechanics during countermovement jumping (section 6).

2. Literature Review

2.1 Introduction

This section of the thesis focuses primarily on studies investigating the effects of positive external loading on system CM or lower limb joint mechanics during countermovement jumping, with a particular emphasis placed on those that have studied power output. Studies investigating concentric only jumping (commonly referred to squat jumping) are also considered within this section of the thesis due to the similar body configuration at the start of the push-off phase, as well as the similar coordination during the push-off phase (Bobbert, Gerritsen, Litjens, & Van Soest, 1996). Unless otherwise distinguished, jumping refers to both countermovement jumping and concentric only jumping. For the sake of brevity, other topics were included only when a relevant feature has been highlighted particularly well via another aspect of human analysis. The key underpinning themes of this section of the thesis are based around the theoretical framework of Bobbert and Van Soest (1994): 1. Which factors determine (limit) athletic performance? 2. Which of these factors can be changed? 3. On which of the changeable factors should we focus in training? As such, this section of the thesis is divided into five main sub-sections:

i. Power Output during Jumping (section 2.2);
ii. Measuring Power Output: Methodological Issues (section 2.3);
iii. The Effects of Positive External Loading on Jumping Mechanics (section 2.4);
iv. The Effects of the Position of Positive External Loading on Jumping Mechanics (section 2.5);
v. The Effects of Negative External Loading on Jumping Mechanics (section 2.6).

2.2 Power Output during Jumping

External mechanical work must be performed to accelerate and/or raise the CM of the body during dynamic athletic tasks (Cavagna, 1975). Hence, the rate of external mechanical work, defined as the external mechanical power output (referred simply to as power output hereafter), is commonly hypothesised to be one of the main performance determining factors in a multitude of time constrained dynamic athletic tasks, particularly those requiring one movement sequence to produce a high velocity at take-off or impact (Cormie, McGuigan, & Newton, 2011a; Cormie et al., 2011b; Kawamori & Haff, 2004; Newton & Kraemer, 1994). Previously, it has been suggested that athletes who produce greater power outputs during unloaded (no positive or negative external loading applied) and externally loaded jumping perform better in dynamic athletic tasks such as jumping, sprinting and weightlifting (Baker & Nance, 1999; Cronin & Hansen, 2005; Cunningham et al., 2013; Dowling & Vamos, 1993; Gonzalez-Badillo & Marques, 2010; Hansen et al., 2011e; Hori et al., 2008; Kawamori et al., 2005; Nimphius, McGuigan, & Newton, 2010; Sheppard et al., 2008a; Young et al., 2005). Consequently, the power output during jumping appears to discriminate between individual activity profiles (Caia, Doyle, & Benson, 2013; Driss et al., 2001; McBride, Triplett-McBride, Davie, & Newton, 1999; Nibali, Chapman, Robergs, & Drinkwater, 2013b; Nuzzo et al., 2010; Pazin, Berjan, Nedeljkovic, Markovic, & Jaric, 2012; Stone et al., 2003; Vuk, Markovic, & Jaric, 2012), as well as levels of competitive playing ability (Argus et al., 2012; Baker, 2002; Hansen et al., 2011e; Sheppard et al., 2008a; Sheppard et al., 2012; Young et al., 2005). Therefore, to optimise periodic testing and training prescription, a great deal of research has focused on the relationship between external loading and the power output during jumping.

It is commonly argued that the influence of external loading on the power output during jumping is underpinned by the inverse association between external loading and the velocity of the system CM (Cormie, McBride, & McCaulley, 2008; Cormie, McCaulley, Triplett, & McBride, 2007d; Dayne et al., 2011; Leontijevic et al., 2012; Markovic & Jaric, 2007; McBride, Haines, & Kirby, 2011; Nibali et al., 2013b; Pazin et al., 2012; Suzovic, Markovic, Pasic, & Jaric, 2013; Turner, Unholz, Potts, & Coleman, 2012; Vuk et al., 2012). As external loading dictates the force generating capacity of the lower extremities, this association is often ascribed to the hyperbolic relationship between force and velocity demonstrated in isolated muscles (Hill, 1938, 1953): as force generating capacity increases, a concomitant decrease in contraction velocity occurs, and vice versa. As such, it is argued that power output is maximised under the external loading condition which facilitates an optimal compromise between submaximal force and submaximal velocity (Cormie et al., 2011b), which is referred to as the optimal load hereafter. However, readers should be cognisant that the importance of the intrinsic force-velocity-power relationship is argued to only play a small part of the effects of external loading reported within the body of knowledge, with musculoskeletal modelling data demonstrating that it is more likely associated with optimised control (or a lack thereof) (Bobbert, 2014).

The identification of the optimal load is believed to be an important consideration during the physical preparation of various athletic populations (Baker, Nance, & Moore, 2001; Cormie et al., 2007d; Cormie et al., 2011b; Dugan et al., 2004; Kawamori & Haff, 2004; Li et al., 2008; Smilios et al., 2013; Wilson, Newton, Murphy, & Humphries, 1993). It is argued that jump training with the optimal load facilitates time efficient improvements in the maximal production of power output, as well as in the performance of dynamic athletic tasks (Cormie, McGuigan, & Newton, 2010a; Lyttle, Wilson, & Ostrowski, 1996; Markovic, Vuk, & Jaric, 2011; McBride, Triplett-McBride, Davie, & Newton, 2002; Newton, Rogers, Volek, Hakkinen, & Kraemer, 2006; Wilson et al., 1993). However, both the load-power profile and the optimal loading parameters for jumping remain equivocal, with reports of the optimal load occurring as low as negative external loads of 30% of bodyweight (Markovic & Jaric, 2007; Markovic et al., 2011; Vuk et al., 2012), to as high as positive external loads of approximately 60% of a 1 repetition maximum (1-RM) back squat (Baker et al., 2001; Lake & Lauder, 2012; Lake, Mundy, & Comfort, 2014; Sleivert & Taingahue, 2004; Smilios et al., 2013).

Predominantly, a systematic linear decline in power output has been reported as external loading increases, with power output maximised either at the lowest external loading condition investigated (Markovic & Jaric, 2007; Smilios et al., 2013; Turner et al., 2012; Vuk et al., 2012) or under unloaded conditions (Argus, Gill, Keogh, & Hopkins, 2011; Bevan et al., 2010; Caia et al., 2013; Cormie et al., 2007d; Dayne et al., 2011; Leontijevic et al., 2012; Markovic & Jaric, 2007; McBride et al., 2011; McBride et al., 1999; Moir et al., 2012; Nibali et al., 2013b; Nuzzo et al., 2010; Pazin et al., 2012; Sheppard et al., 2008a; Suzovic et al., 2013; Swinton et al., 2012). Therefore, when interpreting the present body of knowledge, practitioners must consider the type of jump performed (countermovement jump vs. squat jump [concentric only]), the type and position of the external loading applied (barbell, hexagonal barbell, smith machine, dumbbells, weighted vest, elastic resistance), the subsequent external loading spectrum constraints (negative vs. positive external loading), the external loading parameters (single external load, incremental absolute external loads, incremental relative external loads [%1-RM vs. % of body mass]), and the population investigated (trained vs. untrained, male vs. female, etc).

Further, interpretation of the present body of knowledge is confounded by the specific qualifiers (average power output vs. peak power output, absolute vs. normalisation [allometric vs. ratio]), and measurement (instruments, calculations) details related to power output which are required to meaningfully explore load-power data (Knudson, 2009), of which are not currently standardised.

Cognisant to the aforementioned issues, the following sub-sections of this section of the thesis aim to establish the effects of the type and position of positive and negative external loading on system CM and lower limb joint mechanics, with a particular emphasis on power output. However, before doing so, it is important to discuss the limitations associated with the use of power output as a performance determining factor and the use of the optimal load as a training tool.

2.2.1 Counterpoint: Power Output as a Performance Determining Factor

The importance of power output is commonly established using the statistical relationship between the power output and the outcome of dynamic athletic tasks (e.g. correlations, regressions). However, this statistical relationship is not the same as a mechanistic relationship between increased power output and the outcome of dynamic athletic tasks. The statistical relationship between power output and the outcome of dynamic athletic tasks may exist for numerous reasons; however, not all of them indicate the mechanistic role of greater power output.

In the context of jumping, there is theoretically a direct cause and effect relationship between the work performed on the system CM and the height jumped (work-energy theorem). Similarly, there is theoretically a direct cause and effect relationship between the impulse applied to the system CM and the height jumped (impulse-momentum theorem). The work-energy theorem and the impulse-momentum theorem are both re-expressions of Newton's 2nd Law in an integral form. That is, the work-energy theorem and the impulse-momentum theorem simply describe motion in different dimensions - one spatial and one temporal. In brief, changes in the system CM's momentum are due to the impulse applied to the system CM, which depends on the time over which the net force is applied. Conversely, kinetic energy of the system CM changes when work is performed on the system CM, which depends on the displacement over which the net force is applied.

When considering the mechanistic role of the work performed and the impulse applied, the statistical relationship between the power output and the outcome of dynamic athletic tasks can be brought into question (Knudson, 2009; Winter, 2009; Winter et al., 2016; Winter & Knudson, 2011). For example, an increase in the work performed and the impulse applied would result in an increase in the height jumped. An increase in work and impulse may also increase the power output, which may create a statistical relationship between the power output and the height jumped even in the absence of a mechanistic relationship. This may explain why power output is sometimes poorly correlated with the outcome of dynamic athletic tasks, although such information is often not acknowledged (Cronin & Sleivert, 2005; Knudson, 2009). However, is it important to reiterate that correlation does not equal causation, and that these associations have commonly been confounded by the method of calculation, body mass, and countermovement depth (Aragón-Vargas & Gross, 1997; Markovic, Mirkov, Nedeljkovic, & Jaric, 2014).

At first, the importance of power output may not be readily apparent from either the work-energy theorem or the impulse-momentum theorem. During the push-off phase of jumping, the system CM gains kinetic energy when work (the product of net force and displacement) is performed on the system CM (work-energy theorem). The kinetic energy gained is proportional to the square of the vertical velocity of the system CM, and therefore determines the peak vertical displacement of the system CM during the flight phase (jump height). However, during the push-off phase of jumping, the lowering of the system CM is constrained by human anatomy. As such, greater work performed on the system CM results in a shorter push-off phase duration, as the push-off phase is performed at a greater average velocity (displacement divided by time). Therefore, although work is not by definition constrained by time, the greater work performed on the system CM during the push-off phase of jumping, the less time there is available to perform the work. As average power output is the rate at which work is performed over the push-off phase of jumping, the greater the peak vertical displacement of the system CM during the flight phase (jump height), the greater the average power output required. Hence, it may be postulated that average power output is a performance limiting factor.

To avoid premature take-off and therewith a premature termination of work production, power output must continue to increase during the push-off phase (Bobbert, 2014). Therefore, peak power output may also be an important factor for performance (Bobbert, 2014). However, it should be stressed that the development of a high peak power output does not necessarily mean a parallel development of average power output (Bosco, Luhtanen, & Komi, 1983), despite the correlations previously presented (Hori et al., 2007). As such, if practitioners are interested in the effects of external loading on power output and the optimal load, it may be prudent to consider both peak and average power output.

2.2.2 Counterpoint: the Optimal Load

Regardless of whether peak power or average power output is investigated, the importance of identifying and assessing the optimal load is still debated within the body of knowledge. Primarily, it is argued that training at the optimal load is no more effective than training at heavy external loads in untrained individuals (Cormie et al., 2010a), moderately resistance trained individuals (Smilios et al., 2013), and professional team sport athletes (Harris, Cronin, Hopkins, & Hansen, 2008b). This may be because the mechanisms driving the improvements observed within the aforementioned studies are specific to the training stimulus, and as such jump training with a single external load, whether that be the optimal load or a heavy external load, may limit the transfer of training to athletic performance (Cormie et al., 2010a). However, when the optimal load is combined with strength training (back squats at 90% 1-RM back squat), the overall impact on the load-power, load-force, and load-velocity relationships indicate that such training may transfer to improvements in a wide variety of on-field demands associated with ‘strength-power sports’ (Cormie, McCaulley, & McBride, 2007c). This is not surprising, given that an increase in strength or power without a concurrent increase in control during a given task is unlikely to improve performance, with musculoskeletal modelling data actually suggesting this may result in a decline in performance during jumping (Bobbert & Van Soest, 1994). Therefore, if the optimal load is prescribed, the findings of the present body of knowledge suggest that it should be as part of a periodised strength and conditioning programme (Haff & Nimphius, 2012).

A further criticism of the optimal load is that changes in power output values either side of the optimal load are often insubstantial (Cormie et al., 2007d; Dayne et al., 2011; Harris, Cronin, & Hopkins, 2007; Markovic & Jaric, 2007; McBride et al., 2011; Nibali et al., 2013b; Pazin et al., 2012; Suzovic et al., 2013; Turner et al., 2012). Perhaps this is explained by the optimal load varying on an individual basis, which in turn may be explained by the optimisation of performance under the external loading conditions most commonly encountered within the individuals sport or strength and conditioning programme (Bobbert, 2014). As such, the group analysis commonly reported within the body of knowledge may mask differences even within populations that are perceived to be homogeneous. Therefore, it may be that the identification of a single population optimal load (e.g. unloaded) is fundamentally flawed due to the potentially large inter-individual differences in the optimal load (Cronin & Sleivert, 2005).

It is further contended that the identification of a single optimal load may mask sport specific and idiosyncratic contributions of submaximal force and submaximal velocity to performance (Bourque & Sleivert, 2003; Cormie & Flanagan, 2008), thereby neglecting the principles of specificity (Cronin & Sleivert, 2005). For example, the power output during jumping may be the same at two different external loads as a product of different submaximal force and submaximal velocity contributions (Cormie & Flanagan, 2008; Cronin & Sleivert, 2005). Therefore, perhaps it might be prudent to identify a spectrum of external loads that maximise power output for the individual (Harris et al., 2007; Nibali et al., 2013b), particularly at the external loads encountered within the individual's sport (Cormie & Flanagan, 2008). As such, it is suggested that load-power data should be explored periodically on an individual basis in conjunction with the underpinning force, temporal, and spatial components to identify and prescribe external loading parameters based on individual training needs (Cronin & Sleivert, 2005; Nibali et al., 2013b; Sheppard et al., 2008a).

Perhaps more importantly, and as previously alluded to; specificity of training is a function of the task-inherent biomechanics, not simply the external movement characteristics (Kipp et al., 2011). This premise is highlighted by the theoretical model of relevant factors in jumping performance presented by Aragón-Vargas and Gross (1997) (Figure 1). In brief, the model highlights that jumping performance is made up of highly interrelated variables, and must be considered at different levels of analysis. So far, this thesis has been concerned with the first and second levels of analysis, which are variables that have a functional relationship, and mathematically define jumping performance, as well as those that can be manipulated at a system CM level to maximise jumping performance. However, the third and fourth levels of analysis are concerned with segmental kinetics and kinematics, as well as skeletal muscle characteristics and anthropometric characteristics. This third and fourth level is of significant importance to practitioners, as they relate to task specificity, and can be directly addressed during the physical preparation of athletes.

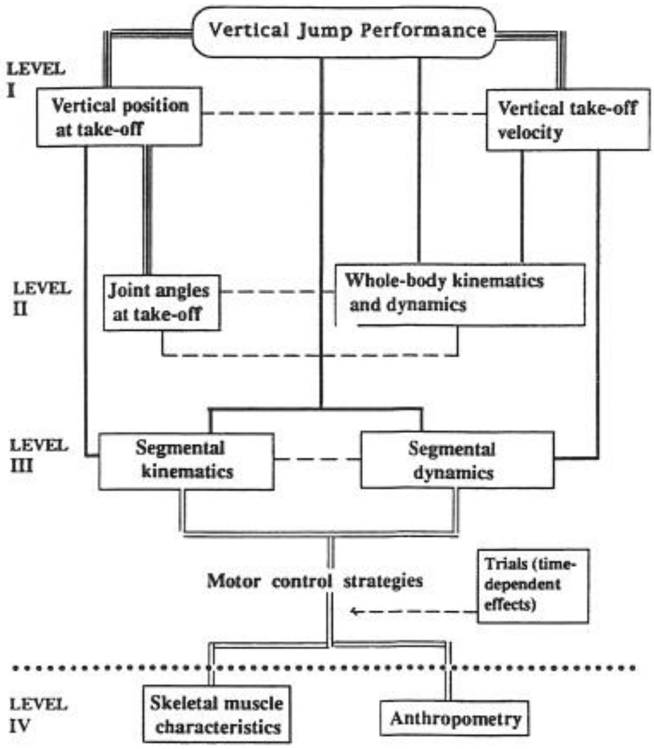


Figure 1. Theoretical model of vertical jump performance (Aragón-Vargas & Gross, 1997).

When considering the power output of the individual lower limb joints, it has been demonstrated that peak hip joint power output is most associated with jumping performance (Aragón-Vargas & Gross, 1997), as well as improvements in jumping performance (Marshall & Moran, 2015). Greater peak hip joint power output may be due to fibre type composition, as well as coordination strategies (Aragón-Vargas & Gross, 1997). It is logical to suggest that better coordination strategies would allow the hip joint muscles to act at a more advantages range of the force-velocity curve (Aragón-Vargas & Gross, 1997). For example, a lower muscle-fibre shortening velocity at the same joint angular velocity would allow the muscle to generate greater force (Aragón-Vargas &

Gross, 1997; Bobbert, Huijing, & van Ingen Schenau, 1986). This highlights the importance of training modalities that improve the muscles ability to combine high joint peak net moments with relatively high joint peak angular velocities (Aragón-Vargas & Gross, 1997). Conversely, however, it appears that the knee joint power output contribution to jumping performance is limited in order to maintain balance throughout the push-off phase (Vanrenterghem et al., 2008). Moreover, ankle power output doesn't alter with jumping effort (Lees, Vanrenterghem, & De Clercq, 2004), or trunk inclination (Vanrenterghem et al., 2008), which suggests it contributes maximally to jumping performance. As such, it may be argued that both the exercises and the magnitude of external loading prescribed to improve jumping performance should aim to enhance power output at all lower limb joints, with a particular emphasis on enhancing hip joint peak power output (Aragón-Vargas & Gross, 1997; Marshall & Moran, 2015). Therefore, in order to maximise the transfer of externally loaded jumping to unloaded jumping, it is also important for practitioners to understand the effects of the magnitude of external loading on the individual lower limb joint power outputs during jumping, and not just the effects on the system CM.

Despite the contributions made by the individual lower limb joints to jumping performance, it appears that the power output of the lower limb joints does not alter in proportion to the system power output, with the power output at the hip, knee, and ankle joints maximised at different external loads (Jandacka et al., 2014; Moir et al., 2012). For example, Moir et al. (2012) reported that system CM peak power output was maximised at the same load as the knee and ankle, but not the hip, whereas Jandacka et al. (2014) reported that system CM, hip, knee, and ankle peak power outputs were all maximised at different loads. Therefore, not only may practitioners need to periodise across a spectrum of external loads to improve both the force and velocity capabilities of the athlete, but they may also need to periodise across a spectrum of external loads to satisfy individual lower limb joint demands (Moir et al., 2012). However, regardless of how the effects of external loading on power output are used, a number of issues associated with measuring power output exist within the body of knowledge.

2.2.3 Measuring Power Output: Methodological Issues

The two most commonly used methods for investigating the effects of external loading on the power output during jumping, the force platform method and the combined method, have been described extensively within the body of knowledge (Cormie et al., 2007a; Cormie et al., 2007b; Crewther et al., 2011; Dugan et al., 2004; Hansen et al., 2011b; Hori et al., 2007; Li et al., 2008). In brief, both methods ostensibly calculate the power output as the product of the force applied to and the velocity of the system CM. However, neither method is ubiquitously accepted as the criterion ('gold standard') method, with contradictory recommendations commonly reported within previous method comparison studies (Cormie et al., 2007a; Cormie et al., 2007b; Crewther et al., 2011; Hansen et al., 2011b; Hori et al., 2007; Lake et al., 2012b; Li et al., 2008). Therefore, within this section of the thesis, the force platform method and the combined method are described for theoretical clarity, and associated contradictions discussed. Further, due to issues associated with the practicality of the aforementioned methods, commonly used pragmatic alternatives are also discussed. This methodological discussion is of particular importance to the thesis, as without considering the way in which power output is calculated, methodological integrity may be compromised, rendering the discussion and comparison of both previous and future results inappropriate (Knudson, 2009).

2.2.4 Force Platform Method

Historically, power output has been measured during unloaded jumping using a force platform (Cavagna, 1975). Mathematically, there are several ways in which power output can be calculated using a force platform; however, formally, this method calculates the rate of change of the effective energy of the system CM (Bobbert, 2014). Within the body of knowledge, power output is commonly obtained as the product of the vertical ground reaction force and the vertical velocity of the system CM. Within this method, vertical ground reaction force is used to represent the force applied to the system CM (Newton's 3rd Law). The vertical velocity of the system CM is then obtained by time integration of acceleration data; that is, vertical ground reaction force minus system weight divided by system mass (Cavagna, 1975). For each time point, power output is then calculated as the scalar product of the vertical ground reaction force and the vertical velocity of the system CM. Alternatively, vertical ground reaction force can be integrated with respect to time, which is then divided by system mass to calculate the vertical velocity of the system CM, and then combined with the vertical ground reaction force data to calculate power output, or vertical ground reaction force can be integrated with respect to displacement to calculate mechanical work, and then divided by push-off time to calculate power output. It is important to note that only the vertical component of the ground reaction force is commonly considered as approximately 97% of the total power output during the push-off phase of unloaded countermovement jumping is used for vertical propulsion (Hatze, 1998). However, to the best of the author's knowledge, this has yet to be established under externally loaded conditions, and thus the information must be extrapolated with caution.

Theoretically, the force platform method is derived from Newton's 2nd Law, whereby the motion of the system CM is fully determined by the system's mass, the forces applied to the system CM, and the initial velocity of the system CM (Cavagna, 1975). Assuming a valid quiet standing or squatting period prior to the initiation of movement to ensure an initial velocity of zero, the possible sources of error originate from the force platform electronics, the analog-to-digital conversion, and the data processing methods (Kibele, 1998). Recently, Owen, Watkins, Kilduff, Bevan, and Bennett (2014) presented excellent guidelines for calculating peak power output during unloaded countermovement jumping, which produced errors of less than 1%. Further, the possible sources of error when integrating vertical ground reaction force data have been extensively documented, and necessary precautions for minimising error within vertical ground reaction force and velocity data presented (Kibele, 1998; Street, McMillan, Board, Rasmussen, & Heneghan, 2001; Vanrenterghem, De Clercq, & Van Cleven, 2001). Cognisant to the aforementioned methodological rigor, the force platform method can accurately determine both the force applied to and the vertical velocity of the system CM during jumping. Therefore, in the author's opinion, the force platform method is the theoretical criterion method ('gold standard') for calculating power output during jumping.

The most common criticisms of the force platform method are the cost and practicality (Chiu, Schilling, Fry, & Weiss, 2004; Crewther et al., 2011; Cronin, Hing, & McNair, 2004). However, it should therefore be noted that excellent guidelines for constructing single axis force platforms have previously been published (Major, Sands, McNeal, Paine, & Kipp, 1998), with some commercially available single axis force platforms cheaper than the commonly proposed commercially available single point field alternatives (e.g. linear position transducers). However, more recently, the use of the force platform method as the criterion method has been criticised within the strength and conditioning body of knowledge (Cormie et al., 2007b; Dugan et al., 2004), with an alternative criterion method proposed: the combined method.

2.2.5 Combined Method

Within the strength and conditioning body of knowledge, the combined method appears to be the most commonly used method for investigating the effects of external loading on power output during jumping. Similar to the force platform method, vertical ground reaction force data is used to represent the force applied to the system CM (Newton's 3rd Law). However, in contrast to the force platform method, the vertical velocity of the system CM is calculated by the differentiation of displacement-time data of an Olympic barbell (or an aluminium, plastic, or wooden bar alternative during unloaded jumping), which is collected using various motion capture equipment (e.g., a high-speed digital camera system (Li et al., 2008), a linear position transducer (Cormie et al., 2007a; Cormie et al., 2007b), two linear position transducers (Cormie et al., 2007a; Cormie et al., 2007b), or an optoelectronic motion capture system (Moir et al., 2012)).

It has been suggested that the combined method uses accurate force platform vertical ground reaction force values to represent the force applied to the system CM, but ostensibly requires less 'data manipulation' than the force platform method to calculate the velocity of the system CM, thus decreasing the risk of accumulating error (Dugan et al., 2004). However, both the force platform method and the combined method require only a single 'data manipulation' to obtain the velocity of the system CM, whereby data is either integrated (force platform method) or differentiated (combined method) once, respectively. Upon comparison, the two types of 'data manipulation' yield a different outcome with regards to noise: integration suppresses noise in the velocity signal, whereas differentiation amplifies noise in the velocity signal. As such, the combined method often requires filtering, which introduces potential error due to over smoothing or under smoothing of the true signal (Winter, 2009).

Interestingly, within the body of knowledge, there also appears to be little consideration for the potential error introduced by the different motion capture equipment used (Cormie et al., 2007a; Cormie et al., 2007b), the sampling frequency used (McMaster et al., 2014), the method of differentiation used, or the error associated with asymmetric lifting technique (Chiu, Schilling, Fry, & Salem, 2008). Therefore, paradoxically, not only does the extra equipment make the combined method less accessible to practitioners, but the combined method does not logically improve the measurement of power output. This is further evidenced by little, if any differences in the between session reliability of peak velocity and peak power output between the force platform method and the combined method (Hansen et al., 2011b).

Perhaps a more important concern regarding the combined method pertains to the fundamental underpinning biomechanical premise (Hansen et al., 2011b; Hori et al., 2007; Lake et al., 2012b; Li et al., 2008). The combined method acquires displacement-time data from the external load, assuming synchronous movement with the system CM (Cormie et al., 2007b; Dugan et al., 2004). When compared to the force platform method, both peak power (Hansen et al., 2011b; Hori et al., 2007) and average power (Hori et al., 2007) outputs values generated by the combined method (force platform and one linear position transducers) were significantly greater during an externally loaded (40 kg) countermovement jump. Further, a non-systematic overestimation of average power but not peak power output was observed when the combined method (force platform and one linear position transducer) and a combined method corrected for horizontal barbell motion (force platform and two linear position transducers) were compared to the force platform method across an external loading spectrum of 0 to 85% of a back squat 1-RM (Cormie et al., 2007b).

As the vertical ground reaction force data used in the force platform method and the combined method are often identical, this systematic overestimation is logically a product of the external load moving at a significantly greater velocity than that of the system CM (Lake et al., 2012b; Li et al., 2008). However, statistical tests designed to test for significant differences (t-tests, ANOVA models, effect size) are not be appropriate for determining whether two measurement methods are in agreement (McLaughlin, 2013). In context, agreement refers to how much the combined method is likely to differ from the force platform method: if this difference does not cause problems in clinical interpretation, then the two methods can be used interchangeably (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999). To the author's knowledge, agreement between the force platform method and the combined method has yet to be assessed. Further, the influence that the magnitude of external load may have on agreement has also yet to be assessed. Therefore, previous studies investigating the effects of external loading on power output during jumping may be confounded by fundamental methodological issues. Assessing the agreement between the force platform method and the combined method may help determine the most appropriate method for measuring power output, as well as aid the interpretation and application of the results of previous studies.

2.2.6 Single Point Methods

In the absence of a force platform, a video camera or linear position transducer (e.g. potentiometer or encoder) can be utilised to estimate both the force applied to and the velocity of the system CM. Within these methods, a single point upon the system is chosen to represent the system CM. Velocity of the system CM is estimated by differentiating the displacement of this single point with respect to time, which in turn is differentiated with respect to time to calculate the acceleration of the system CM. The force applied to the system CM is estimated as the product of system mass and the summation of the acceleration of the system CM and the acceleration due to gravity (Newton's 2^{nd} Law). For each time point, power output is then calculated as the product of the estimated force applied to and the velocity of the system CM.

Unlike the force platform method or the combined method, concerns regarding the 'data manipulation' required by single point methods are commonly expressed. The differentiation process amplifies noise in both the velocity and acceleration records (Winter, 2009; Wood, 1982), compromising the validity of the calculated force and power output values (Cormie et al., 2007b; Dugan et al., 2004). Therefore, single point methods may depend largely on the equipment (Cormie et al., 2007a; Cormie et al., 2007b), the sampling frequency (McMaster et al., 2014), the method of differentiation, and the data smoothing procedures used to remove this amplified noise (Harris, Cronin, Taylor, Boris,

& Sheppard, 2010), ensuring an adequate description of the underlying process (Winter, 2009; Wood, 1982).

As with the combined method, perhaps the most important issue is related to the fundamental biomechanical premise. To correctly apply Newton's 2^{nd} law, the calculation of force should use compatible mass and acceleration (Li et al., 2008). Thus, if the point does not represent that of the system CM, an inappropriate acceleration value will be combined with the mass of the system, producing a force value that does not represent the force applied to the system CM, resulting in a miscalculation of power output (Li et al., 2008). Therefore, it is imperative that the single point represents the mass of interest regardless of whether that is the CM of the body, the barbell, or the system (Lake et al., 2012b).

As with the combined method, when investigating the effects of external loading on jumping, using the external load as the single point (Chiu et al., 2004; Cormie et al., 2007a; Crewther et al., 2011; Hansen et al., 2011b; Hori et al., 2007) appears to be the preferred method to represent the system CM. However, as alluded to in the combined section, this method assumes that the external load moves in parallel with the system CM under all conditions of external loading (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004). Upon investigating countermovement jumping and squat jumping across external loads of 30%, 50%, and 70% of a 1-RM back squat, Chiu et al. (2004) reported no differences between the linear position transducer and force platform methods for peak force. This may suggest that the displacement of the barbell represents that of the system CM as they both appear to move in a vertical and linear path, and that the single point is arbitrary (Chiu et al., 2004). However, Chiu et al. (2004) did not report or compare velocity or power output values between the two methods. Further, Chiu et al. (2004) stringently controlled the jumping range of motion to 10% of the participant's height, which although improved the representation of peak force, perhaps did so by reducing ecological validity (Argus et al., 2011) as athletes are likely to have optimised control under the given conditions (Bobbert, 2014).

Conversely, there is a growing body of evidence to suggest that this assumption of synchronous movement is erroneous (Hori et al., 2007) and is a misapplication of mechanical principles (Li et al., 2008). During externally loaded (40 kg) countermovement jumping, both Hori et al. (2007) and Hansen et al. (2011b) demonstrated that peak velocity of the barbell calculated using a single linear position transducer was significantly greater than that of the system CM, indicating percentage differences of 12.1% and 42.8%, respectively. Further support has been presented across various external loads using two linear position transducers (Cormie et al., 2007a), video systems (Lake et al., 2012b), and on-line motion capture systems (McBride et al., 2011). Most notably, McBride et al. (2011) demonstrated a linear increase in percentage difference from 20.8% to 70.2% in peak velocity across an external loading spectrum of 0 to 90% 1-RM back squat, in 10% increments. Therefore, regardless of the equipment used, it appears that when a barbell is chosen to represent the system CM, it will overestimate the velocity of the system CM due to a poor estimation of the system CM motion. However, due to the statistical methods commonly used, little is known about the agreement between the methods (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999; McLaughlin, 2013).

It is important to note that if barbell mass only is used in the calculation instead of system mass, the power applied to the barbell can be calculated (Hori et al., 2007; McBride et al., 2011). Biomechanically, this is a fundamentally sound estimation of power output; however, this may not reflect the power output by the lower extremities, specifically during conditions of lighter external loading (Hori et al., 2007). By excluding body mass, the load-power relationship appears to be reversed, with the force component of the power output calculation greatly reduced during lighter external loads (Dugan et al., 2004). This is of particular concern during unloaded jumping, whereby if the mass component is zero, then the force component is zero. As power output is the product of force and velocity, it too will be zero, providing little, if any, information to practitioners. Conversely, at higher external loads, the exclusion of body mass is a smaller relative reduction in the system load, thus the power output value is less affected (Dugan et al., 2004; Smilios et al., 2013). Therefore, the point used to represent the object of interest and the mass values used are important considerations when using single point field methods (Hori et al., 2007).

An alternative, yet still practical single point method is to use a point approximating the pelvis (Chiu & Salem, 2010; Cronin et al., 2004; Gard, Miff, & Kuo, 2004; Gullstrand, Halvorsen, Tinmark, Eriksson, & Nilsson, 2009; Ranavolo et al., 2008). For example, when investigating both countermovement jumping and squat jumping, Cronin et al. (2004) reported no differences in peak and average force between a linear position transducer attached to a waist harness and the force platform method. However, as with the majority of the studies discussed so far, comprehensive statistics for assessing the agreement were not reported (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999; McLaughlin, 2013), and nor was the influence of external loading investigated. Therefore, as the system CM position changes with external loading, uncertainty arises regarding the extrapolation of these findings to conditions of external loading, which limits the use of this method for the practitioner.

2.2.7 Body Segmental Analysis Methods

Due to the issues associated with single point methods, it is important to note that the displacement of the system CM may also be calculated using the body segmental analysis method (Gard et al., 2004; Gullstrand et al., 2009; Kibele, 1998; Ranavolo et al., 2008), which is based on marker position data acquired via either videography systems or on-line systems. The body segmental analysis method calculates the total body or system CM position as the weighted average of the individual segments' CM (Gard et al., 2004; Gullstrand et al., 2009; Ranavolo et al., 2008; Winter, 2009). After calculating the displacement of the body or system CM, the power output may be calculated using the methods described in sections 2.2.6 and 2.2.5 of the thesis (Lake et al., 2012b). However, hardware and software for on-line systems are often expensive and require a skilled and knowledgeable operator, with hardware setup, data collection, and data processing time consuming. As such, further discussion is outside the scope of the present thesis. Conversely, although less accurate, videography systems, including digitisation software, are readily available to practitioners (Garhammer & Newton, 2013). However, due to its limited use within research, this method will not be discussed further, with readers referred to Garhammer (1993) for common methodological issues, and Garhammer and Newton (2013) for videography setup considerations.

2.2.8 Computation Method

A simple, alternative method proposed for measuring force, velocity and power output during jumping is the computation method (Samozino, Morin, Hintzy, & Belli, 2008). The computation method relies solely on body mass, jump height, and push-off distance. In concept, jump height can be measured using videography or a jump mat, assuming adequate control over landing position is enforced. Upon comparison to the gold standard force platform method, Samozino et al. (2008) reported a mean bias of 11 N, 0.017 ms^{-1} and 2 W for force, velocity, and power output, respectively. Although the 95% limits of agreement were not reported numerically; the methods appear interchangeable within practice based on the plots presented. However, although promising, the sample size was likely too small to establish validity (n = 11), as the 95% confidence intervals around the limits would have been unacceptably large (± root (3 standard deviation^2/sample size)). Further, the trials were pooled without controlling for multiple observations (Bland & Altman, 1999). Perhaps more importantly, use of the computation method either requires the push-off distance (countermovement depth) to be constrained, or calculated alternatively. As alluded to earlier, constraining the push-off distance decreases ecological validity (Argus et al., 2011) as athletes are likely to have optimised control under the given external loading conditions (Bobbert, 2014), whereas calculating countermovement depth alternatively potentially decreases the practicality of the computation method.

2.2.9 Additional Testing Precautions

Prior to discussing the effects of external loading on countermovement jumping performance, it is first important to highlight other potential precautions for practitioners. If such precautions are not controlled for, the true effects of external loading on countermovement jumping performance may be confounded. Firstly, prior to testing, the instructions provided to participants regarding their preparedness and nutritional status must be addressed. Due to the effects of neuromuscular fatigue on physical performance, it is recommended that athletes refrain from strenuous activity for at least 48 hours prior to testing (McLellan, Lovell, & Gass, 2011a). Further, as carbohydrate and caffeine ingestion (Gant, Ali, & Foskett, 2010) and hydration status (Judelson et al., 2007) appear to influence jumping performance, it is recommended that athletes are provided standardised instructions, such as report to the laboratory in a hydrated state, a minimum of two and a maximum of four hours post prandial, and having abstained from caffeine and alcohol consumption. Secondly, as a distinct effect of circadian rhythm can be observed on physical performance, the time of day testing is held, and the type and duration of warmup provided, are also key precautions to consider. It is recommended that testing occurs during the afternoon, and kept consistent between testing sessions (Teo, Newton, & McGuigan, 2011). Further, it is also recommended that testing sessions are preceded by a standardised dynamic warm-up (Fradkin, Zazryn, & Smoliga, 2010), which includes submaximal attempts at the desired task. Thirdly, due to the effects of focus of attention on physical performance (Wulf, 2013), the instructions provided to athletes must also be standardised, whereby an external focus of attention is encouraged (Wulf, Zachry, Granados, & Dufek, 2007). Moreover, as countermovement depth and technique also influence performance, they too must be considered. As with focus of attention, it is important that practitioners refrain from coaching and simply provide athletes with standardised instructions. It is recommended that practitioners follow NSCA guidelines for technique, and do not attempt to control for the depth of the countermovement to ensure ecological validity (Argus et al., 2011). Finally, to prevent neuromuscular fatigue occurring during testing sessions, practitioners must also consider the rest periods provided between trials, as well as conditions. It is recommended that practitioners provide one-minute rest between trials, and four-minutes rest between each conditioning (Nibali, Chapman, Robergs, & Drinkwater, 2013a).

2.3 The Effects of Positive External Loading on Jumping Mechanics

An Olympic barbell loaded with weight plates placed across the posterior aspect of the shoulders is the most commonly applied form of external loading during jumping. This conventional barbell loading provides a method of positive external loading, whereby inertia and weight is added to the system by their external mass (Leontijevic et al., 2012). Therefore, understanding the effects of barbell loading on system CM mechanics during jumping may help practitioners make more evidence-based decisions during the physical preparation and monitoring of athletes.

The effects of barbell loading on power output during countermovement jumping and squat jumping can be observed in Table 1 and Table 2, respectively. Barbell loading is typically prescribed relative to a percentage of a back squat or externally loaded jumping 1-RM, although prescribing barbell loading relative to a percentage of body mass or as arbitrary perturbations such as absolute external loads likely encountered within a given sport may be more informative. By assigning barbell loads relative to a percentage of body mass, power output may be investigated independent of maximal strength (Jaric & Markovic, 2013; Sheppard et al., 2008a). Alternatively, by assigning absolute barbell loads (in particular external loads encountered within a given sport), power output can be investigated during assessment conditions which are consistent across periods of time and between populations (Nibali et al., 2013b).

Regardless of the barbell loading spectrum investigated, the majority of studies investigating barbell loading have demonstrated a systematic linear decline in peak power and average power output as barbell loading increases. This linear decline in power output may be explained by the greater force required to overcome the increased system weight and inertia provided by the external mass, which, as per the concentric force-velocity relationship, reduces movement velocity (due to the increased phase duration, decreased lowering of the CM, or both). Alternatively, it may be explained by an inability of humans to produce a truly maximal performance at each experimental condition due to their inability to rapidly tune their control (Bobbert, 2014). However, regardless of the proposed mechanism, it is important to reiterate that when considering the information presented in Table 1 and Table 2, the reader should remain cognisant to the methodological issues discussed within section 2.2. In particular, it should be highlighted that the majority of studies have used the combined method to calculate power output. As such, these studies must be interpreted with caution until the agreement between the force platform method and the combined method has been assessed.

Interestingly, the majority of studies presented in Table 1 and Table 2 only report peak power output, with few reporting both peak power and average power output (Nibali et al., 2013b; Swinton et al., 2012). Moreover, only a minority of these studies reported other equally important variables, such as the underpinning force, temporal and spatial components (McMaster et al., 2014). Despite the criticisms of power output, the author is unaware of any studies using the force platform method to specifically examine the effects of barbell loading on the power output during jumping cognisant to the work, impulse, and underpinning force, temporal and spatial components. As such, the complex interactions between the prerequisites for performance derived using work-energy theorem remain unclear, meaning external loads may be inappropriately prescribed. To demonstrate this complexity, power output may be different between two loads due to an increase in the force applied, an increase in the displacement of the system CM, a decrease in time, or a combination of all three, all of which have very different implications for the practitioner. Further, the effects of intra-individual variation on power output remain largely ignored, limiting the practical applications of the findings. However, considerable attention has been given to alternative parameters, a number of which arguably possess limited validity and reliability.

Due to the time constraints imposed on a number of sporting activities, those that have criticised power output have postulated that the rate of force development, that is, vertical ground reaction force differentiated with respect to time, is an important parameter for practitioners to consider (Knudson, 2009; Mizuguchi, Sands, Wassinger, Lamont, & Stone, 2015). When describing performance using the impulse-momentum relationship, rate of force development is commonly suggested to be the performance limiting factor within a time constrained sporting environment. As such, it has been suggested that practitioners focus on maximising the push-off rate of force development during the physical preparation of athletes (Knudson, 2009; Mizuguchi et al., 2015; Winter & Fowler, 2009).

To the author's knowledge, there is no ubiquitously accepted method of calculating rate of force development (Hansen, Cronin, & Newton, 2011d). Within the context of the countermovement jump, average rate of force development during the push-off phase is mathematically meaningless, as it often requires the practitioner to erroneously calculate a linear function on a non-linear signal. A proposed alternative is to calculate rate of force development within given time bands (Hansen, Cronin, & Newton, 2011a; Maffiuletti et al., 2016). However, whether or not these time bands are of practical or physiological importance is not clear. Another alternative is to calculate the peak instantaneous rate of force development. However, without considerable signal processing, the instantaneous rate of change largely appears to be noise, although that has not been raised previously within the body of knowledge. These issues likely explain why the reliability of the commonly used methods to calculate rate of force development are not acceptable in practice (Hansen et al., 2011a; Mizuguchi et al., 2015). As such, if rate of force development as a concept, as well as if the effects of external loading on rate of force development, are to be investigated, then the way in which rate of force development is calculated must first be improved, and then standardised (Knudson, 2009). It is important to note that these criticisms pertain to the use of concentric rate of force development in stretch shortening cycle tasks. There is evidence to suggest that calculating the slope of the breaking phase of the countermovement jump may theoretically represents the rate of eccentric loading (McLellan, Lovell, & Gass, 2011b), which may provide useful information regarding task intensity as prestretch enhances the maximum work output that muscles can produce during the concentric phase (Schenau, Bobbert, & Haan, 1997a, 1997b). However, this is erroneously called rate of force development, when due to the eccentric nature it is physiologically a rate of force absorption.

A further point of interest is that despite the considerable body of work investigating the effects of barbell loading on power output, very few studies have investigated the effects of barbell loading on the system CM and lower limb joint power output during jumping (Jandacka et al., 2014; Moir et al., 2012). This is of particular interest to practitioners, as despite the contributions made by the individual lower limb joints to jumping performance, as demonstrated in figure 2, it appears that the power output of the lower limb joints does not alter in proportion to the system power output, with the power output at the hip, knee, and ankle joints maximised at different external loads (Jandacka et al., 2014; Moir et al., 2012).

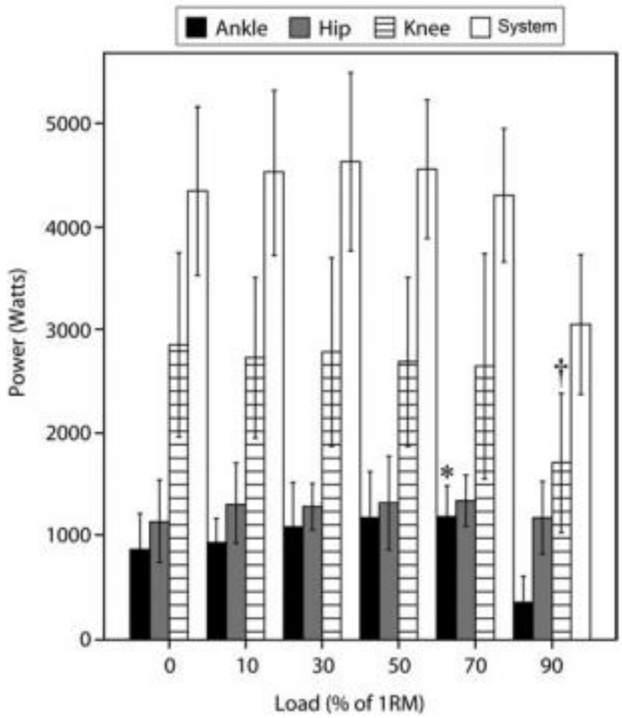


Figure 2. Mean ± SD of the absolute peak positive ankle, knee, hip, and system CM power outputs (Jandacka et al., 2014).

For example, Moir et al. (2012) reported that system CM peak power output was maximised at the same load as the knee and ankle joint, but not the hip joint, whereas Jandacka et al. (2014) reported that system CM, hip, knee, and ankle joint peak power outputs were all maximised at different loads. This has considerable implications for the practitioner, as prescribing external loads based on system CM power output alone may fail to overload the hip joint extensors, which appears integral to facilitating a transfer of training effect to unloaded jumping (Marshall & Moran, 2015), as well as other dynamic tasks. Therefore, not only may practitioners need to periodise across a spectrum of external loads to improve both force and velocity capabilities of the athlete, but they may also need periodise across a spectrum of external loads to satisfy individual lower limb joint demands (Moir et al., 2012). Such information may provide a greater mechanical understanding of the effects of barbell loading on jumping mechanics, as well as help us understand the nature of the of the acute mechanical stimulus and its contributions to strength and power adaption (Crewther et al., 2005).

Table 1. Studies investigating the effects of barbell loading on the power output during countermovement jumping.

Study	Participants	Measurement Method	Loading Spectrum	Optimal load	
				Peak Power	Average Power
Baker et al. (2001)	Male professional/semi-professional RL (n=32), College RL (n=24) and Professional RL (n=17)	1LPT	40 to 120 kg	N/A	85-95 kg 55-59% 1-RM
Stone et al. (2003)	17-30 year old males (n=22)	V-Scope	10 to 100% 1-RM CMJ	10%	N/A
Cormie et al. (2007d)	Male NCAA D1 athletes (n=12)	FP + 2LPT	0 to 85% 1-RM BS	0%	N/A
Cormie et al. (2007c)	Recreationally trained males (n=26)	FP + 2LPT	BM to 80 kg	BM	N/A
Cormie et al. (2007b)	Male NCAA D1 athletes (n=10)	FP + 2LPT, FP + 1LPT, 2LPT, 1LPT, and FP	0 to 85% 1-RM BS	0%	N/A
Cormie et al. (2008)	Sedentary males (n=18)	FP + 2LPT	BM to 80 kg	BM	N/A
Sheppard et al. (2008a)	Professional/scholarship volleyball (n=26)	FP + 1LPT	BM to 50% of BM	BM	N/A
Nuzzo et al. (2010)	Male overweight adolescents (n=8) Female overweight adolescents (n=13)	FP + 2LPT	BM to 40% ISPF	BM	N/A
Cormie, McGuigan, and Newton (2010b)	Strong (>1.97 1-RM/BM) males (n=8) Weak (<1.40 1-RM/BM) males (n=24)	FP + 2LPT	0 to 80% 1-RM BS	N/A	0%
Crewther et al. (2011)	Resistance trained males (n=12)	FP, 1LPT, and Accelerometer	20 to 80 kg	20kg	N/A
Dayne et al. (2011)	Male HS American football (16y) (n=11)	FP + 2LPT	0 to 80% 1-RM BS	0%	N/A
McBride et al. (2011)	Resistance trained males (n=9)	FP	0 to 90% 1-RM BS	0%	N/A
Wright, Pustina, Mikat, and Kernozek (2012)	Physically active males (n=30) Physically active females (n=30)	FP	20 to 60% of BM	20%	N/A
Swinton et al. (2012)	Male RU (n=29)	FP	0 to 60% 1-RM BS	0%	0%
Lake and Lauder (2012)	Male University athletes (n=12)	FP	0 to 80% 1-RM BS	20-60%	N/A
Moir et al. (2012)	Male athletes (n=12)	FP + OPTOE	0 to 85% 1-RM BS	N/A	0%
Nibali et al. (2013a)	Resistance trained males (n=10)	FP + 1LPT	BM to 60 kg	BM	BM
Nibali et al. (2013b)	Male Professional AFL (n=16)	FP + 1LPT	BM to 60 kg	BM	N/A

	Male Highly trained RU (n=20)				
Caia et al. (2013)	Male elite AFL (n=18) Male sub-elite AFL (n=12)	FP + 1LPT	0 to 40% 1-RM BS	0%	N/A
Lake et al. (2014)	Resistance trained males (n=8)	FP	10 to 90% 1-RM BS	52%±25%	38%±34%

RL: Rugby League; NCAA: National Collegiate Athletic Association; D1: Division One; 1-RM: One Repetition Maximum; BS: Back Squat; HS: High School; RU: Rugby Union; AFL: Australian Rules Football; FP: Force Platform; LPT: Linear Position Transducer; OPTOE: Optoelectronic Motion Capture System; CMJ: Countermovement Jump; BM; Body Mass; ISPC: Isometric Peak Force: N/A: Not Applicable.

Table 2. Studies investigating the effects of barbell loading on the power output during squat jumping.

Study	Participants	Measurement Method	Loading Spectrum	Optimal load	
				Peak Power	Average Power
McBride et al. (1999)	Male PL (n=7), OL (n=7), Sprinters (n=7) and Moderately active controls (n=7)	FP + 1LPT	30 to 90% 1-RM BS	30%	N/A
Stone et al. (2003)	17-30 year old males (n=22)	V Scope	10 to 100% 1-RM SJ	10%	N/A
Sleivert and Taingahue (2004)	Male RU and basketball (n=30)	Accelerometer	30 to 70 1-RM	60%	40%
Thomas et al. (2007)	Male NCAA D1 Soccer (n=19) Female NCAA D1 Soccer (n=14)	1LPT	30 to 70% 1-RM BS	30% 40%	N/A
Patterson, Raschner, and Platzer (2009)	Male junior alpine skiers (n=20) Female junior alpine skiers (n=17)	FP	0 to 100% of BM	N/A	25% 0%
Bevan et al. (2010)	Male professional RU (n=36)	1LPT	0 to 60% 1-RM BS	0%	N/A
Thomasson and Comfort (2012)	Male professional RL (n=17)	FP + 1LPT	0 to 60% 1-RM BS	0%	N/A
Turner et al. (2012)	Male professional RU (n=11)	FP + 1LPT	20 to 100% 1-RM SJ	20%	N/A
Caia et al. (2013)	Male Elite AFL (n=18) Male sub-elite AFL (n=12)	FP + 1LPT	0 to 40% 1-RM BS	0%	N/A
Smilios et al. (2013)	Resistance trained males (n=43)	1LPT (waist)	20 to 80% 1-RM BS	N/A	20-37%
Jandacka et al. (2014)	Experienced male throwers (n=7)	FP FP + OPTOE	0 to 90% 1-RM BS	30% 10%	30% N/A

PL: Power Lifter; OL: Olympic Lifter; RU: Rugby Union; NCAA: National Collegiate Athletic Association; D1: Division One; RL: Rugby League; AFL: Australian Rules Football; FP: Force Platform; LPT: Linear Position Transducer; OPTOE: Optoelectronic Motion Capture System; 1-RM: One Repetition Maximum; BS: Back Squat; SJ: Squat Jump; BM: Body Mass; N/A: Not Applicable.

2.4 The Effects of the Position of Positive External Loading on Jumping Mechanics

The effects of the type and position of positive external loading on the power output during jumping can be observed in Table 3. It appears that by adjusting the position of the external load, both peak power (Driss et al., 2001; McBride et al., 1999; Swinton et al., 2012) and average power output (Driss et al., 2001) may be maximised at external loads greater than the mass of the body (unloaded) in resistance trained athletes. Further, it is postulated that changing the position of the external load may also improve the safety and comfort when performing externally loaded jumps (Swinton et al., 2012). Therefore, the effects of the type and position of positive external loading may be of particular interest to the practitioners. However, to the author's knowledge, there is limited research directly comparing the type and position of positive external loading on system CM mechanics during jumping.

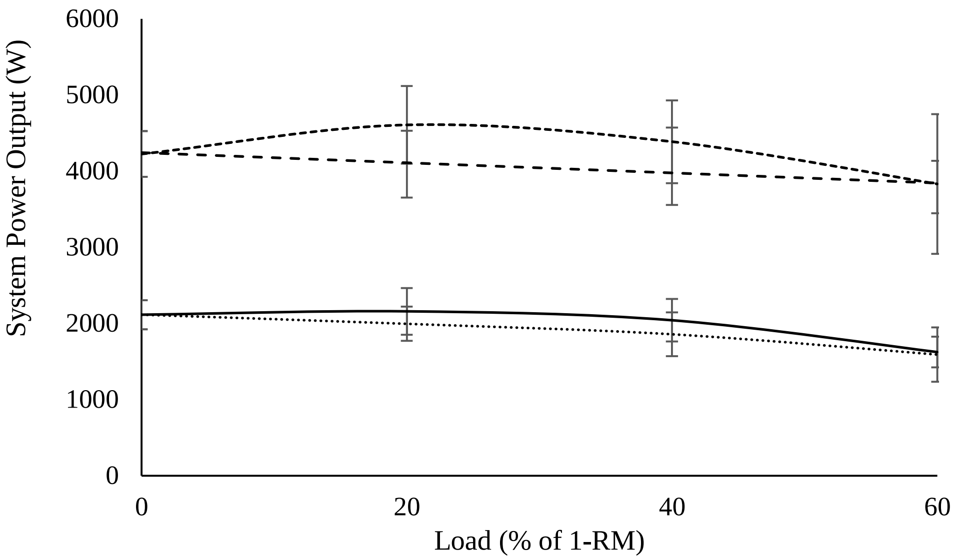


Figure 3. Mean ± SD of absolute system power outputs across external loading conditions and positions in trained athletes (Swinton et al., 2012). The top two lines represent relative peak power output, whereas the bottom two lines represent relative average power output. For both relative peak power output and relative average power output, the hexagonal barbell was greater than the straight barbell.

Swinton et al. (2012) demonstrated that greater power output can be achieved during countermovement jumping by changing the position of the external load from the shoulders (barbell) to arms' length by using a hexagonal barbell (Figure 3). Further, by using a hexagonal barbell, Swinton et al. (2012) also reported that peak power output was maximised at external loads greater than the mass of the body (20% 1-RM back squat). Conversely, Leontijevic et al. (2012) demonstrated an external load associated linear decline in both peak power and average power output with weight and inertia (weighted vest), weight (elastic resistance), and inertia (combination of the weighted vest and elastic resistance). However, this may have been expected as Leontijevic et al. (2012)

investigated countermovement jumping with an arm swing in a recreationally active sample group that had no resistance training experience. As such, these results are in line with the results presented by Driss et al. (2001), who reported that during weighted vest loaded squat jumping, only resistance trained ‘strength-power’ athletes observed an external load associated increase in the peak power and average power output (Figure 4).

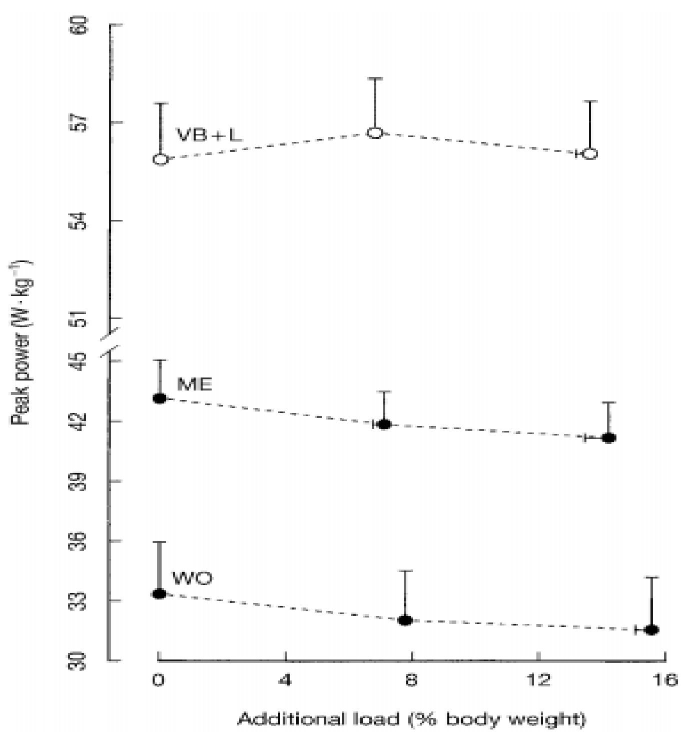


Figure 4. Mean ± SD of relative system CM peak power outputs between different training statuses across external loading conditions (Driss et al., 2001).

In order to explain this apparent strength-dependent phenomenon, Jaric and Markovic (2009) presented the Maximum Dynamic Output hypothesis. The Maximum Dynamic Output hypothesis proposed that the muscular system of the lower limbs is predominantly designed to provide maximal power output at an external loading condition most closely related to the individual's 'lifestyle' (commonly performed tasks). For example, a physically active individual that regularly overcomes their own body weight and inertia during daily activity (i.e. through participation in jump dominant sporting activities) may maximise power output when loaded only by the weight and inertia of their own body. Conversely, it was postulated that due to mechanical unfamiliarity, a physically inactive individual may maximise power output during unloaded conditions, whereas an individual that regularly performs strength and power resistance training may maximise power output during externally loaded conditions. However, after conducting several experimental studies, Jaric and Markovic (2013) redefined the Maximum Dynamic Output hypothesis, arguing that optimal loading in human jumping is a strength-independent phenomenon due to the particular design of the locomotor system (e.g. the force-velocity-power relationship of muscles).

In particular, it is argued that based on the force-velocity-power relationship of the muscles within locomotor system, the system it is designed to maximise power output during conditions of no external loading (Jaric & Markovic, 2013). Although an appealing evolutionary argument, Bobbert (2014) has heavily criticised the refined strength-independent Maximum Dynamic Output hypothesis. Bobbert (2014) argues that it may be that participants within previous studies have been inadvertently affected by the inability to quickly tune their control to unaccustomed external loading conditions, which may be commonly demonstrated by the deviations in CM displacement between conditions. As such, Bobbert (2014) argues that a more straightforward theory is that participants produce the highest power output in the external loading conditions to which they are most accustomed to in their training because they will have optimised their control by painstaking practice under these conditions. As such, strength-power trained athletes may maximise their output at higher external loading conditions than untrained controls due to fine-tuned control under the conditions investigated.

The increase in the peak power output observed by Swinton et al. (2012) may also be explained at the lower limb joint level. For example, the hip joint extensors work maximally only when there is an opportunity to extend the trunk from a forward inclined position (Lees et al., 2004; Vanrenterghem et al., 2008). However, when an external load is positioned across the shoulders, trunk inclination is restricted to prevent the moment arm of the external resistance becoming too large, minimising resistive torque and shear forces experienced at the lumbar spine (Fry, Smith, & Schilling, 2003; Swinton et al., 2012). Conversely, when the position of the external load is changed the range of motion at the hip may not be limited to the same degree, if at all (Lees et al., 2004). However, to the author’s knowledge, no research has specifically examined the effects of the position and magnitude of positive external load on both CM and lower limb joint mechanics during jumping. Therefore, by prescribing barbell loaded jumping, practitioners may fail to overload the hip joint extensors, of which appear not only integral to maximal jumping performance (Aragón-Vargas & Gross, 1997), but to facilitating a transfer of training effect to unloaded jumping (Marshall & Moran, 2015), as well as other dynamic tasks.

Table 3. Studies investigating the effects of alternative positive external loading on the power output during jumping.

Study	Participants	Jump Type (Loading Method)	Measurement Method	Loading Spectrum	Optimal load	
					Peak Power	Average Power
McBride et al. (1999)	Male PL (n=7)	CMJ (DB)	FP	BM to 40 kg	20 kg	N/A
	Male OL (n=7)				20 kg	N/A
	Male Sprinters (n=7)				BM	N/A
	Moderately active controls (n=7)				20 kg	N/A
Davies and Young (1984)	Male and female children (n=10) Male adults (n=4)	CMJ (customised overalls)	FP	BM to 40%	N/A	BM
Driss et al. (2001)	Sedentary male and female (n=20)	SJ (WV)	FP	BM to 10 kg	BM	BM
	Volleyball (n = 16) and OL (n=6)				5 kg	5 kg
Harris et al. (2007)	Male national RL (n=18)	SJ (hack squat machine)	1LPT	10 to 100% 1-RM SJ	21%±7%	39±8%
Harris, Cronin, Hopkins, and Hansen (2008a)	Male elite RL (n=18)	SJ (hack squat machine)	1LPT	20 to 80% 1-RM SJ	23%±5% 26%±7%	N/A
Leontijevic et al. (2012)	Active college students (n=15)	CMJa (Bands, Bands + WV, WV)	FP	Unloaded to 40% BW	Unloaded	Unloaded
Swinton et al. (2012)	Male RU (n=29)	CMJ (HB)	FP	0 to 60% 1-RM BS	20%	20%

PL: Power Lifter; OL: Olympic Lifter; RL: Rugby League; RU: Rugby Union; CMJ: Countermovement Jump; DB: Dumbbell; SJ: Squat Jump; WV: Weighted Vest; CMJa: Countermovement Jump with Arm Swing; HB: Hexagonal Barbell; FP: Force Platform; LPT: Linear Position Transducer; BM: Body Mass; g: Gravitational Acceleration; 1-RM: One Repetition Maximum; BS: Back Squat; BW: Bodyweight; N/A: Not Applicable.

2.5 The Effects of Negative External Loading on Jumping Mechanics

The application of an upward pulling force to approximately the CM of the body is operationally defined as negative external loading. A limitation of the positive external loading methods discussed so far (e.g. Olympic barbell, hexagonal bar, weighted vest, etc) is that they do not allow for the application of negative external loading. Therefore, as power output is often maximised when loaded only by the mass of the body (unloaded), it remains plausible that the external loading conditions that maximises power output during jumping could be below the loading originating from the mass of the human body (Bobbert, 2014; Markovic & Jaric, 2007; Markovic et al., 2011; Vuk et al., 2012).

The effects of positive and negative external loading on peak power and average power output during countermovement jumping (with and without arm swing) and squat jumping can be observed in Table 4. When considering only studies which have applied positive and negative external loading using technical approaches based on long and compliant elastic material (Markovic & Jaric, 2007; Markovic et al., 2011; Pazin et al., 2012; Suzovic et al., 2013; Vuk et al., 2012), the effects of negative external loading on the peak power and average power output during jumping have been contradictory. These contradictions may be confounded by: the population investigated (trained vs. untrained); the type of jump investigated (squat jump, countermovement jump, countermovement jump with arm swing); the way in which power output is reported (absolute vs normalisation [allometric scaling vs. ratio scaling]), the apparatus used (different height, different lengths of elastic material); and the experimental controls (depth, familiarisation, etc).

Although logical to assume, it may be unlikely that the population investigated, the type of jump investigated, or the way in which power output is reported are responsible for the contradictions observed. Upon investigating the influence of training history on the effects of positive and negative external loading on countermovement jumping, Vuk et al. (2012) reported maximum absolute and normalised ($kg^{0.67}$) peak power and average power outputs values at negative external loads of 30% of bodyweight, regardless of training history. These findings were further supported in recreationally trained jumpers by Markovic et al. (2011), who reported that when countermovement jumps were performed with negative external loads of 30% of bodyweight, absolute power output was over 1000 W greater than the unloaded condition.

Conversely, when investigating countermovement jumping with arm swing and squat jumping without arm swing, Pazin et al. (2012) reported that normalised ($kg^{0.67}$) peak power and average power output were maximised approximately at the unloaded condition in strength, speed, active, and sedentary groups almost identical to those studied by Vuk et al. (2012). Pazin et al. (2012) suggested that these differences may be due to the type of jump performed. However, upon investigating the effects of positive and negative external loading on squat jumping, countermovement jumping, and countermovement jumping with arm swing, Suzovic et al. (2013) reported that absolute peak power and average power output were maximised approximately at the unloaded condition. Alternatively, Pazin et al. (2012) suggested that the apparatus used by Vuk et al. (2012) added a light external mass during negative external loading, and therefore inertia. Therefore, as it is not possible to explain the differences observed, it may be prudent to instead consider the results observed via musculoskeletal modelling, which allows issues associated with the practical application of negative external loading to be eliminated.

Upon simulating the effects of positive and negative external loading of 30 and 60% of bodyweight on countermovement jumping and squat jumping, Bobbert (2014) demonstrated that positive and negative external loading has only a small effect on both peak power and average power output. In contrast to the results of a number of the previously discussed studies (Markovic & Jaric, 2007; Pazin et al., 2012; Suzovic et al., 2013), negative external loading of 30% of bodyweight caused a small increase in both peak power and average power output. In agreement with all of the previously discussed studies (Markovic & Jaric, 2007; Markovic et al., 2011; Pazin et al., 2012; Suzovic et al., 2013; Vuk et al., 2012), positive external loading of 30% of bodyweight caused a decrease in both peak power and average power output, although the decrease appeared much smaller than previously observed. It is important to note that the muscle simulation over time input of the musculoskeletal model was optimised to ensure maximal performance, and lowering of the CM was kept constant by setting a penalty on deviations of the minimum height of the CM from a pre-defined value. As such, the pure effects of positive and negative external loading on maximal output could be studied (Bobbert, 2014). Therefore, the differences observed within the body of knowledge may be associated with the unconstrained jumping typically investigated (Markovic & Jaric, 2007; Markovic et al., 2011; Pazin et al., 2012; Suzovic et al., 2013; Vuk et al., 2012).

Bobbert (2014) reported that making a smaller countermovement, which is typically associated with increased positive external loading, caused a reduction in power output. This is likely due to the change in the length-tension relationship, as well as the decreased distance to perform work over. The results of previous studies may be further confounded by the participants' inability to quickly optimise their control during unfamiliar positive and negative external loading conditions, despite anecdotal claims to the contrary (Markovic & Jaric, 2007; Markovic et al., 2011; Pazin et al., 2012; Suzovic et al., 2013; Vuk et al., 2012). As such, it may be that participants' produce the highest peak power and average power outputs at the external loading conditions to which they are most accustomed to from their training, because they will have optimised their control by extensive practice (Bobbert, 2014). These findings suggest that training across a spectrum of external loads, particularly the external loads likely encountered within the athletes given sport, may be superior to the optimal load approach. However, as previously alluded to, the effects of positive and negative external loading on system CM mechanics does not necessarily provide information about the lower limb joint mechanics. Therefore, further research is warranted to first corroborate previous experimental findings at the system level, and second to identify the effects of both positive and negative external loading on lower limb joint mechanics.

Table 4. Studies investigating the effects of positive and negative external loading on the power output during jumping.

Study	Participants	Jump Type	Measurement Method	Loading Spectrum	Optimal load	
					Peak Power	Average Power
Cavagna, Zamboni, Faraggiana, and Margaria (1972)	Untrained males (n=2)	CMJ SJ	FP	0.15 to 1.77 g	N/A	1 g
Markovic and Jaric (2007)	Physically active (n=15)	CMJ	FP	0.70 to 1.30 g	0.7 g	1 g
Nuzzo et al. (2010)	Power trained males (n=14) Untrained males (n=6)	CMJ	FP + 2LPT	10 to 60% MDS	BM (35%) BM (56%)	BM (35%) BM (56%)
Argus et al. (2011)	Elite RU (n=18)	CMJ	LPT	-28 to 60% 1-RM BS	0%	N/A
Markovic et al. (2011)	Physically active males (n=36)	CMJ	FP	-30 to +30% BW	-30% BW	N/A
Vuk et al. (2012)	BB (n=9), Karate players (n=12) and Sedentary males (n=10)	CMJ	FP	0.70 to 1.30 g	0.7 g	0.7 g
Pazin et al. (2012)	BB (n=10), Karate players (n=10), Active males (n=10) and Sedentary males (n=10)	CMJa SJ	FP	0.70 to 1.30 g	1.00 g 0.95 to 1.05 g	1.00 to 1.10 g 0.85 to 1.05 g
Suzovic et al. (2013)	Physically active males (n=13)	CMJ CMJa SJ	FP	-40 to +40% BW	-5 % to 12%	-5 % to 12%
Bobbert (2014)	Simulation	CMJ SJ	Simulation	-60 to +60% BW	-60% -60%	-30% -30%

RU: Rugby Union; BB: Bodybuilder; CMJ: Countermovement Jump; SJ; Squat Jump; CMJa: Countermovement Jump with Arm Swing; FP: Force Platform; LPT: Linear Position Transducer; g: Gravitational Acceleration; MDS: Maximal Dynamic Strength; 1-RM: One Repetition Maximum; BS: Back Squat; BW: Bodyweight; BM: Body Mass; N/A: Not Applicable

2.6 Conclusion

This section of the thesis summarised studies investigating the effects of external loading on system CM and lower limb joint mechanics during countermovement jumping, with a particular emphasis placed on those that have studied power output. It was identified that "power" is often expressed as a "clearly defined, generic neuromuscular or athlete performance characteristic" rather than as an application of the actual mechanical definition (Winter et al., 2016). It appeared that this misapplication has led to considerable inaccuracy and confusion, primarily because it often fails to represent the performance being assessed (Winter et al., 2016). Therefore, the appropriate use of the actual mechanical definition was discussed in the context of jumping performance. This discussion was central to the development of the thesis, as any investigation into the effects of external loading on power output during jumping must be done so within a theoretically valid, Newtonian framework.

This section of the thesis also exposed the presence of two perceived criterion ('gold standard') methods currently used to measure the power output during externally loaded jumping: the force platform method and the combined method. Therefore, the force platform method and the combined method were described for theoretical clarity, and associated contradictions discussed. Further, due to issues associated with the practicality of the aforementioned methods, commonly used pragmatic alternatives were also discussed. This methodological discussion was of particular importance to the development of the thesis, as without considering the way in which power output is calculated, methodological integrity may have been compromised, rendering the discussion and comparison of results inappropriate (Knudson, 2009).

It was also identified that in order to provide a task specific overload, practitioners commonly prescribe externally loaded jumping based on system CM mechanics. Primarily, practitioners appear to focus on the external load that maximises system CM power output, which is also known as the optimal load. Although a number of issues were identified with an optimal loading approach, perhaps the most important issues was the failure to consider the effects of external loading on system CM mechanics cognisant of the underpinning lower limb mechanics. As greater jumping performance has been associated with hip joint peak power output (Aragón-Vargas & Gross, 1997; Marshall & Moran, 2015), it was postulated that prescribing external loads based on system CM mechanics alone may fail to consider the task inherent biomechanics, and limit the transfer of externally loaded jumping to unloaded jumping, as well as other dynamic tasks. Further, it was also identified that conventional methods of external loading may in fact overload knee joint mechanics, meaning that practitioners may be prescribing the position and the magnitude of external loading erroneously.

3. Assessing Agreement between the Force Platform Method and the Combined Method Measurements of Power Output during the Loaded Countermovement Jump

Mundy, P. D., Lake, J. P., Carden, P. J., Smith, N. A., & Lauder, M. A. (2016). Agreement between the force platform method and the combined method measurements of power output during the loaded countermovement jump. *Sports Biomechanics, 15* (1), 23-35.

3.1 Prelude

Section 2.3 of the thesis highlighted two perceived criterion (‘gold standard’) methods were currently used to measure the power output during unloaded and barbell loaded countermovement jumping: the force platform method and the combined method. Therefore, the main aim of this section of the thesis was to establish a ubiquitous criterion method to measure power output, which was imperative to both the development of the thesis and to the overall body of knowledge. The secondary aim of this section of the thesis was to establish the agreement between the force platform method and the combined method to aid the interpretation and application of the results of previous studies. This section of the thesis builds on the work reviewed in section 2.3 and fulfils the requirements of aim 1 or the thesis.

3.2 Introduction

The triple extension of the hips, knees and ankles is integral to the successful execution of a multitude of dynamic athletic tasks (e.g. jumping, sprinting and tackling). During such tasks, the lower extremities are inevitably loaded by the body's own mass, and often by the mass of an opponent. As such, training with external loads is an essential part of physical preparation for many athletes. Barbell-loaded jumping is one of the most commonly used forms of externally loaded jump training. It is postulated that ballistic movements such as barbell-loaded jumping allow the athlete to accelerate the system CM throughout the entire push off phase producing greater velocity and power outputs than traditional non-ballistic movements (Frost et al., 2010). Therefore, the effects of barbell loading on system CM mechanics during countermovement jumping have been extensively investigated.

In particular, there has been a focus on the effects of barbell loading on the maximal production of power output (Cormie et al., 2011b; Jaric & Markovic, 2013). Such studies are typically based on the hypothesis that power output is a performance determining factor in a multitude of dynamic athletic tasks; however, it is important to note that the use of power output during jumping has also been heavily criticised (Knudson, 2009; Winter & Fowler, 2009; Winter & Knudson, 2011). To date, the results of such studies have been used for optimising resistance training programmes (Cormie et al., 2011b; Kawamori & Haff, 2004), assessing and monitoring athletes (Sheppard et al., 2008a), discriminating between levels of competitive playing ability (Baker, 2002; Hansen et al., 2011e), and understanding the design and function of the locomotor system (Jaric & Markovic, 2009, 2013). However, measuring power output during the loaded countermovement jumping remains a contentious issue, with no criterion ('gold standard') method currently accepted within the literature (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004; Hori et al., 2007; Li et al., 2008). Therefore, if the theoretical and practical importance of measuring power output is to be investigated, it must be done so within a theoretically valid, Newtonian framework.

The force platform method (Hori et al., 2007; Li et al., 2008) and the combined method (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004) are the two most commonly used methods within the literature (Jaric & Markovic, 2013), with both argued to be the criterion method for calculating power output. In brief, both methods ostensibly calculate the power output as the product of the force applied to the system CM and the velocity of the system CM. Both methods use force platform vertical ground reaction force data to represent the force applied to the system CM (Newton's third law); however, the velocity used to represent the system CM is different within each method (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004; Hori et al., 2007; Li et al., 2008). Within the force platform method, the velocity of the system CM is calculated by the integration of force platform acceleration data (derived from Newton's second law) (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004; Hori et al., 2007; Li et al., 2008). Conversely, within the combined method, the velocity of the system CM is calculated by the differentiation of displacement data of an Olympic barbell (or an aluminium, plastic or wooden bar alternative during the unloaded countermovement jump), which is collected using various motion capture equipment (e.g. a high-speed digital camera system (Li et al., 2008), a linear position transducer (Cormie et al., 2007a; Cormie et al., 2007b; Hori et al., 2007), two linear position transducers (Cormie et al., 2007a; Cormie et al., 2007b) or an optoelectronic motion capture system (Moir et al., 2012)).

The combined method is underpinned by the assumption that the velocity of the barbell is equivalent to the velocity of the system CM (Cormie et al., 2007b). When this assumption is violated, the combined method is not valid as it results in the calculation of erroneous power output values due to a mismatch of mechanical parameters (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008). Upon comparison, power output calculated by the combined method is often significantly greater than that of the force platform method (Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008), suggesting that the combined method is not theoretically sound. However, statistical tests designed to test for significant differences (t-tests, ANOVA models and effect size) are not appropriate for determining whether two measurement methods are in agreement (McLaughlin, 2013). In context, agreement refers to how much the combined method is likely to differ from the force platform method: if this difference does not cause problems in clinical interpretation, then the two methods can be used interchangeably (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999). To the author's knowledge, agreement between the force platform method and the combined method is yet to be assessed. Further, the influence that load may have on agreement is also yet to be assessed. Therefore, previous studies investigating the effects of loading on power output during the countermovement jump may be confounded by fundamental methodological issues.

The primary aim of the present study was to assess agreement between the force platform method and the combined method measurements of peak power and mean power output during the countermovement jump across a spectrum of loads. The secondary aim of this study was to assess agreement between measurements of the peak and mean force applied to the system CM and the peak and mean velocity of the system CM. It was hypothesised that the agreement between the force platform method and the combined method measurements of peak power, mean power, peak velocity and mean velocity would not be clinically acceptable at any load investigated. Conversely, it was hypothesised that the agreement between the force platform method and the combined method measurements of peak force and mean force would be clinically acceptable at all loads. Further, to enable comparisons with previous studies, it was hypothesised that peak power, mean power, peak velocity and mean velocity would be significantly different at all loads investigated. Conversely, it was hypothesised that peak force and mean force would not be significantly different at any load investigated.

3.3 Methods

3.3.1 Participants

Forty male team sport athletes (M ± SD: age 22.5 ± 2.8 years, height 1.81 ± 0.05 m, BM 89.1 ± 12.4 kg) volunteered to participate in this study at the beginning of their respective preseason training period. All participants had at least two years of structured resistance training experience and were deemed technically proficient in the loaded countermovement jump during a familiarisation session. Following a verbal and written explanation of the procedures and potential risks, the participants provided their written, informed consent. This study was approved in accordance with the University of Chichester's Ethical Policy Framework for research involving the use of human participants.

3.3.2 Testing Procedures

Participants were instructed to report to the laboratory in a fully hydrated state, a minimum of two and a maximum of four hours postprandial, and having abstained from caffeine consumption. Further, participants were instructed to refrain from alcohol consumption and vigorous exercise for at least 48 h prior to data collection. Following a standardised warm-up (submaximal cycling, dynamic stretching and submaximal countermovement jumping), participants performed two single maximal effort countermovement jumps with additional loads of 0, 25, 50, 75 and 100% of BM. Additional loads of 25, 50, 75 and 100% of BM were applied by positioning an Olympic barbell across the posterior aspect of the shoulders. To allow the combined method to be used during the 0% of BM condition, a wooden bar of equal length yet negligible mass (0.7 kg) was placed across the posterior aspect of the shoulders (Cormie et al., 2007b). Participants were instructed to keep constant downward pressure on the Olympic barbell/wooden bar throughout each countermovement jump (Cormie et al., 2007b). All countermovement jumps were performed utilising a standard technique (Cormie et al., 2007b; Hori et al., 2007), but no attempts were made to control the depth of the countermovement (Argus et al., 2011). One-minute rest was provided between each countermovement jump, with four-minute rest provided between each load (Nibali et al., 2013a).

3.3.3 Equipment

All countermovement jumps were performed on two parallel force platforms (Type 9851B, Kistler Instruments Ltd., Hook, UK) embedded in the laboratory floor, each capturing vertical ground reaction force at 1000 Hz. A retro-reflective marker (14 mm) was placed on each end of the Olympic barbell/wooden bar. Three-dimensional retro-reflective marker position data were synchronously captured with vertical ground reaction force at 250 Hz in VICON Nexus (Version 1.7.1; Vicon Motion Systems Ltd., Oxford, UK) using a 10-camera optoelectronic motion capture system (VICON MX T-Series (T40-S), Vicon Motion Systems Ltd., Oxford, UK).

3.3.4 Force Platform Method Calculations

Instantaneous power was calculated as the product of the vertical ground reaction force and the vertical velocity of the system CM. The vertical velocity of the system CM was obtained by the integration of acceleration data (derived from Newton's second law) using the trapezoidal rule (Owen et al., 2014). A quiet standing period of 1 s was recorded prior to the initiation of each respective countermovement jump to ensure an initial velocity of zero. System weight, from which system mass was calculated, was determined by averaging the summed vertical ground reaction force over the 1 s quiet standing period (Owen et al., 2014; Street et al., 2001). The push off phase (commonly referred to as the concentric phase, the propulsion phase) was identified as beginning at the transition from negative (downward) to positive (upward) vertical velocity of the system CM and ending at take-off (identified using a 10 N threshold). Finally, additional precautions taken can be seen in appendix 2.

3.3.5 Combined Method Calculations

As the combined method relies on the assumption that the vertical velocity of the Olympic barbell/wooden bar is equivalent to the vertical velocity of the system CM (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004; Hori et al., 2007), instantaneous power output was calculated as the product of the vertical ground reaction force and the vertical velocity of the Olympic barbell/wooden bar. It is important to note that vertical ground reaction force was down sampled to 250 Hz to match position data, and is therefore different to the vertical ground reaction force used within the force platform method. To reduce error associated with asymmetric lifting technique, the geometric centre of the Olympic barbell/wooden bar was calculated from the respective end points. Vertical velocity was then calculated by differentiating Olympic barbell/wooden bar displacement using the finite difference method. The push off phase was identified as beginning at the transition from negative (downward) to positive (upward) velocity of the Olympic barbell/wooden bar and ending at take-off. Based on a residual analysis, position data were filtered using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 5 Hz (Winter, 2009).

For each method, peak force, peak velocity and peak power were identified as the greatest instantaneous value of the respective signal within the push off phase, whereas mean force mean velocity, and mean power were determined by averaging the respective signal over the push off phase. Both peak and mean values were investigated as they are commonly reported within the literature (Jaric & Markovic, 2013). Further, only vertical components were considered as approximately 97% of the total power output during the push off phase of an unloaded countermovement jump is used for vertical propulsion (Hatze, 1998). The trial with the greatest mean power output calculated by the force platform method was selected from each additional load for further analysis.

3.3.6 Statistical Analysis

Separate analyses were conducted for each dependent variable at each load. Following checks for normality and uniform distribution, the mean of the differences, the standard deviation of the differences and the 95% limits of agreement (LOA: M of the differences ± 1.96 SD) were calculated on base 10 logarithmically transformed data using methods described by Bland and Altman (Altman & Bland, 1983; Bland & Altman, 1986; Bland & Altman, 1999). Clinically unacceptable LOA were determined a priori as a ratio of greater than 0.05, which equates to ± 5% (Hansen, Cronin, & Newton, 2011c). It was inferred that bias was present if the 95% confidence interval (CI) of the mean of the differences did not include the ratio 1.00. To enable comparisons with previous studies, paired t-tests were also used to examine bias (Altman & Bland, 1983). Alpha was set a priori at $\alpha = 0.05$.

3.4 Results

A visual overview of the 95% limits of agreement between the force platform method and the combined method can be seen in appendix 3. The combined method calculations of mean force, peak velocity, mean velocity, peak power and mean power were significantly ($p < 0.0001$) greater than the force platform method calculations at all loads. Conversely, at all loads, there were no significant differences between calculations of peak force.

Bias was present for peak velocity, mean velocity, peak power and mean power at all loads investigated (Table 5 and Table 6). Further, bias was also present for mean force at loads of 0, 25, 50 and 75% of BM (Table 7). In contrast, bias was absent for mean force calculations at 100% of BM, and at all loads for peak force calculations (Table 7). Peak velocity, mean velocity, peak power and mean power LOA were clinically unacceptable at all loads (Table 5 and Table 6), whereas peak force and mean force LOA were clinically acceptable at all loads investigated (Table 7).

Table 5. Group descriptive statistics and 95% ratio limits of agreement for peak power and mean power.

		Force Platform Method		Combined Method		Ratio 95% Limits of Agreement‡						
						Differences						
		Mean	SD	Mean	SD	Mean	[95% CI]	SD	Lower Limit	[95% CI]	Upper Limit	[95% CI]
Peak Power (W)	+0% BM	4132	600	5432	773	1.31*	[1.29 to 1.34]**	0.06	1.17	[1.13 to 1.21]	1.48	[1.43 to 1.53]
	+25% BM	4026	565	4993	705	1.24*	[1.22 to 1.26]**	0.04	1.14	[1.12 to 1.17]	1.34	[1.31 to 1.38]
	+50% BM	4044	573	4759	646	1.18*	[1.16 to 1.19]**	0.05	1.08	[1.05 to 1.10]	1.29	[1.26 to 1.32]
	+75% BM	3967	588	4487	660	1.13*	[1.11 to 1.15]**	0.06	1.00	[0.97 to 1.04]	1.27	[1.23 to 1.32]
	+100% BM	3752	595	4197	648	1.12*	[1.09 to 1.15]**	0.09	0.94	[0.90 to 0.99]	1.33	[1.27 to 1.39]
Mean Power (W)	+0% BM	2198	346	3177	514	1.44*	[1.42 to 1.47]**	0.06	1.28	[1.23 to 1.32]	1.63	[1.58 to 1.69]
	+25% BM	2085	320	2705	395	1.30*	[1.28 to 1.32]**	0.04	1.20	[1.17 to 1.23]	1.41	[1.38 to 1.44]
	+50% BM	2005	297	2446	361	1.22*	[1.20 to 1.24]**	0.05	1.11	[1.08 to 1.14]	1.34	[1.30 to 1.37]
	+75% BM	1900	296	2213	349	1.16*	[1.14 to 1.19]**	0.06	1.03	[0.99 to 1.07]	1.32	[1.27 to 1.36]
	+100% BM	1726	311	1977	377	1.14*	[1.11 to 1.18]**	0.10	0.95	[0.90 to 1.00]	1.38	[1.31 to 1.45]

* Indicates a significant difference ($p < 0.0001$) between the means

** Indicates the presence of bias

‡ A ratio of > 1.00 indicates that the Combined Method gave a higher estimate than the Force Platform Method

SD = Standard Deviation; CI = Confidence Interval; BM = Body Mass.

Table 6. Group descriptive statistics and 95% ratio limits of agreement for peak velocity and mean velocity.

		Force Platform Method		Combined Method		Ratio 95% Limits of Agreement‡													
						Differences					Lower Limit	[95% CI]			Upper Limit	[95% CI]			
		Mean	SD	Mean	SD	Mean	[95% CI]			SD									
Peak Velocity (m/s)	+0% BM	2.63	0.22	3.09	0.38	1.17*	[1.15	to	1.20]**	0.07	1.02	[0.99	to	1.06]	1.34	[1.29	to	1.39]	
	+25% BM	2.30	0.20	2.66	0.27	1.15*	[1.14	to	1.17]**	0.05	1.06	[1.03	to	1.08]	1.26	[1.23	to	1.29]	
	+50% BM	2.06	0.20	2.30	0.23	1.12*	[1.10	to	1.13]**	0.05	1.02	[1.00	to	1.05]	1.22	[1.19	to	1.25]	
	+75% BM	1.85	0.22	2.02	0.21	1.09*	[1.07	to	1.11]**	0.06	0.98	[0.95	to	1.01]	1.22	[1.19	to	1.26]	
	+100% BM	1.61	0.21	1.77	0.20	1.10*	[1.07	to	1.13]**	0.09	0.94	[0.90	to	0.98]	1.30	[1.24	to	1.36]	
Mean Velocity (m/s)	+0% BM	1.50	0.13	2.07	0.25	1.37*	[1.34	to	1.40]**	0.07	1.20	[1.16	to	1.25]	1.56	[1.51	to	1.62]	
	+25% BM	1.31	0.12	1.65	0.17	1.26*	[1.24	to	1.28]**	0.04	1.16	[1.14	to	1.19]	1.37	[1.34	to	1.40]	
	+50% BM	1.14	0.11	1.36	0.14	1.19*	[1.17	to	1.21]**	0.05	1.09	[1.06	to	1.12]	1.31	[1.27	to	1.34]	
	+75% BM	1.00	0.12	1.14	0.13	1.14*	[1.12	to	1.16]**	0.06	1.02	[0.99	to	1.05]	1.28	[1.24	to	1.32]	
	+100% BM	0.84	0.11	0.95	0.12	1.13*	[1.10	to	1.16]**	0.09	0.95	[0.90	to	1.00]	1.34	[1.28	to	1.41]	

* Indicates a significant difference ($p < 0.0001$) between the means

** Indicates the presence of bias

‡ A ratio of > 1.00 indicates that the Combined Method gave a higher estimate than the Force Platform Method

SD = Standard Deviation; CI = Confidence Interval; BM = Body Mass.

Table 7. Group descriptive statistics and 95% ratio limits of agreement for peak force and mean force.

		Force Platform Method		Combined Method		Ratio 95% Limits of Agreement‡												
						Differences					Lower Limit	[95% CI]			Upper Limit	[95% CI]		
		Mean	SD	Mean	SD	Mean	[95% CI]			SD								
Peak Force (N)	+0% BM	2000	330	1999	330	1.00	[1.00	to	1.00]	0.00	1.00	[1.00	to	1.00]	1.00	[1.00	to	1.00]
	+25% BM	2122	308	2124	309	1.00	[1.00	to	1.00]	0.00	1.00	[1.00	to	1.00]	1.00	[1.00	to	1.01]
	+50% BM	2292	294	2292	293	1.00	[1.00	to	1.00]	0.00	1.00	[0.99	to	1.00]	1.00	[1.00	to	1.01]
	+75% BM	2467	326	2464	327	1.00	[1.00	to	1.00]	0.00	0.99	[0.99	to	0.99]	1.01	[1.01	to	1.01]
	+100% BM	2650	374	2649	374	1.00	[1.00	to	1.00]	0.00	1.00	[1.00	to	1.00]	1.00	[1.00	to	1.00]
Mean Force (N)	+0% BM	1593	252	1616	258	1.01*	[1.01	to	1.02]**	0.01	1.00	[1.00	to	1.01]	1.03	[1.02	to	1.03]
	+25% BM	1721	259	1738	261	1.01*	[1.01	to	1.01]**	0.00	1.00	[1.00	to	1.00]	1.02	[1.02	to	1.02]
	+50% BM	1878	264	1891	267	1.01*	[1.01	to	1.01]**	0.00	1.00	[1.00	to	1.00]	1.01	[1.01	to	1.02]
	+75% BM	2016	290	2029	295	1.01*	[1.01	to	1.01]**	0.00	1.00	[0.99	to	1.00]	1.02	[1.01	to	1.02]
	+100% BM	2152	314	2168	322	1.01*	[1.00	to	1.01]	0.01	0.99	[0.99	to	1.00]	1.02	[1.02	to	1.02]

* Indicates a significant difference ($p < 0.0001$) between the means

** Indicates the presence of bias

‡ A ratio of > 1.00 indicates that the Combined Method gave a higher estimate than the Force Platform Method

SD = Standard Deviation; CI = Confidence Interval; BM = Body Mass.

3.5 Discussion

To the best of the author's knowledge, no criterion method for measuring power output during the loaded countermovement jumping has been accepted within the literature (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004; Hori et al., 2007; Li et al., 2008). Therefore, the primary aim of the present study was to assess agreement between the two most commonly reported criterion methods: the force platform method (Hori et al., 2007; Li et al., 2008). and the combined method (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004). It was hypothesised that the agreement between the force platform method and the combined method measurements of peak power and mean power output would not be clinically acceptable at any load investigated. It was found that peak power and mean power output were limited by the presence of bias and clinically unacceptable LOA at all loads investigated. Therefore, depending on which method is deemed to be the criterion method, previous studies must be interpreted with caution, as fundamental methodological issues may confound the results. Consequently, standardisation within the literature is of paramount importance if power output is to be meaningfully investigated (Cronin & Sleivert, 2005; Li et al., 2008).

There is a strong argument for the force platform method to be considered the criterion method for measuring power output during the loaded countermovement jump. The force platform method is derived from Newton's second law, whereby the motion of the CM is fully determined by the system's mass, the forces applied to the system CM and the initial velocity of the system CM (Cavagna, 1975). Therefore, the possible sources of error originate from the force platform electronics, the analog-to-digital conversion and the data processing (Kibele, 1998). Recently, Owen et al. (2014) presented excellent guidelines for calculating peak power output during the unloaded countermovement jump, which produced errors of less than 1% ($p < 0.05$). Further, the possible sources of error when integrating force platform data have been extensively documented, and necessary precautions for minimising error within vertical ground reaction force and velocity data presented (Kibele, 1998; Street et al., 2001; Vanrenterghem et al., 2001). In spite of this, the combined method is the most commonly reported method within the literature (Jaric & Markovic, 2013).

It has been suggested that the combined method overcomes the disadvantages of the force platform method: it uses accurate force platform vertical ground reaction force data to represent the force applied to the system CM, but ostensibly requires less 'data manipulation' to calculate the velocity of the system CM, thus decreasing the risk of accumulating error (Cormie et al., 2007b; Dugan et al., 2004). In terms of 'data manipulation' the force platform method requires acceleration to be integrated with respect to time, whereas the combined method requires displacement to be differentiated with respect to time. Upon comparison, these two types of 'data manipulation' yield a different outcome with regards to noise: integration suppresses noise in the velocity signal, whereas differentiation amplifies noise in the velocity signal. As such, the combined method requires a further 'data manipulation' known as filtering, which introduces potential error due to over smoothing or under smoothing of the true signal (Winter, 2009). Conversely, filtering of countermovement jump vertical ground reaction force data is not required (Street et al., 2001), meaning the combined method in fact appears to increase the risk of accumulating error. Moreover, there appears to be no consensus on the equipment used to collect displacement data, with various motion capture equipment reported within the literature (e.g. a high-speed digital camera system

(Li et al., 2008), a linear position transducer (Cormie et al., 2007a; Cormie et al., 2007b; Hori et al., 2007), two linear position transducers (Cormie et al., 2007a; Cormie et al., 2007b) or an optoelectronic motion capture system (Moir et al., 2012)). Therefore, paradoxically, not only is the combined method less accessible to sport scientists and strength and conditioning coaches, but the combined method does not logically improve the measurement of power output during the unloaded or loaded countermovement jump.

For the calculation of power output to be meaningful, the calculation must be made using the correct theoretical, Newtonian framework (Lake et al., 2012b; Li et al., 2008); that is, power output must be calculated as the product of the force applied to the system CM and the velocity of the system CM. Therefore, the secondary aim of this study was to assess agreement between measurements of the force applied to the system CM and the velocity of the system CM. It was hypothesised that the agreement between the force platform method and the combined method measurements of peak force and mean force would be clinically acceptable at all loads investigated. Further, to enable comparisons with previous studies, it was hypothesised that peak force and mean force would not be significantly different at any load investigated. In line with previous studies (Cormie et al., 2007b; Hori et al., 2007), the present study found no significant differences between calculations of peak force. Conversely, the combined method measurements of mean force were significantly greater than the force platform method measurements at all loads. This may be explained by the different sampling frequencies and phase identification methods used between the force platform method and the combined method, which were kept constant by Cormie et al. (2007b). However, despite the statistical significance, mean force LOA were clinically acceptable at all loads investigated. As such, the methods could be used interchangeably within practice for calculating mean force despite the methodological differences. At the 0% of BM condition where the mean force LOA were widest, 95% of the combined method observations were between 0% and 3% greater than the force platform method. Practically speaking, using the present studies group mean as an example, this equates to 0 and 47 N, respectively. Therefore, it is unlikely that the differences in vertical ground reaction force used within each method explains the presence of bias and clinically unacceptable LOA reported for peak power and mean power output. Further, these findings highlight the limitation of using statistical tests designed to test for significant differences when determining agreement (McLaughlin, 2013).

The clinically unacceptable peak power and mean power output LOA are likely explained by the velocity used to represent the system CM in each method. A concern with the combined method is the underpinning assumption that the velocity of the Olympic barbell/ wooden bar is equivalent to the velocity of the system CM (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008). When this assumption is violated, it results in the calculation of erroneous power output values due to a mismatch of mechanical parameters (Lake et al., 2012b; Li et al., 2008). In the present study, as hypothesised, comparison of the theoretically sound force platform method peak velocity and mean velocity to the combined method peak velocity and mean velocity revealed the presence of bias and clinically unacceptable LOA at all loads. Therefore, the presence of bias and clinically unacceptable LOA reported for peak power and mean power output are most likely explained by the erroneous assumption that the velocity of Olympic barbell/wooden bar is equivalent to the velocity of the system CM (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008).

It is important to note that although still clinically unacceptable, the peak power and mean power output LOA improved as load increased. At the 0% of BM condition where the mean power output LOA were widest, 95% of the combined method observations were between 28 and 63% greater than the force platform method. Practically speaking, using the present studies group mean as an example, this equates to 615 and 1384 W, respectively. Conversely, at the 100% of BM condition where the LOA were narrowest, 95% of the combined method observations were between −5% and 38% of the force platform method, which equates to −86 and 655 W. This suggests that the assumption underpinning the combined method depends on the loads investigated. A possible explanation is that as load increases, the position of the system CM moves upwards to the superior position of the Olympic barbell, making the Olympic barbell a better representation of the system CM. Further considerations are the depth of the countermovement (Argus et al., 2011; Bobbert, 2014) and the forward inclination of the trunk (Lees et al., 2004; Swinton et al., 2012), both of which may decrease as load increases. With a decrease in either, the Olympic barbell may become more likely to move in a vertical and linear path with the system CM (Chiu et al., 2004), consequently improving agreement. However, controlling the depth of the countermovement (Argus et al., 2011) or the forward inclination of the trunk (Lees et al., 2004) may limit the work done during the unloaded and loaded countermovement jump. Thus, in line with previous studies (Cormie et al., 2007b; Hori et al., 2007; Li et al., 2008), the present study did not stringently control for either to ensure ecological validity. Therefore, further investigation of both system and segmental kinematic data may be warranted to explain the true aetiology of this clinically unacceptable agreement (Lake et al., 2012b).

In conclusion, the force platform method and the combined method cannot be used interchangeably within practice for measuring peak and mean power output during the loaded countermovement jump between loads of 0 and 100% of BM. A growing body of research, the present study included, suggests that this may be because the velocity of the Olympic barbell is not equivalent to the velocity of the system CM (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008), which is a key assumption underpinning the combined method (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004). Therefore, previous studies using the combined method should be interpreted with caution, particularly when comparisons are made between loads. Further, as agreement was influenced by load, comparisons between previous studies using the force platform method and the combined method should also be made with caution. As such, the author discourages researchers and practitioners against using the combined method for measuring power output during the unloaded and loaded countermovement jump. However, it is important to note that the aim of the present study was not to discredit the work of previous authors by pointing out methodological flaws. The intention was to provide steps towards a standardised method of measuring power output. Therefore, it is proposed that the force platform method be used as the criterion method for measuring power output during the unloaded and loaded countermovement jump.

4. The Effects of Barbell Load on Countermovement Vertical Jump Power and Net Impulse

Mundy, P. D., Smith, N. A., Lauder, M. A., & Lake, J. P. (2016). The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sports Sciences,* 1-7.

4.1 Prelude

Section 3 of the thesis demonstrated that the combined method artificially inflates power output during unloaded and barbell loaded countermovement jumping. Further, sections 2.4 and 2.5 of the thesis highlighted that power output is commonly reported in the absence of the underpinning force, temporal and spatial components. As such, the effects of barbell load on power output during countermovement jumping may not be fully understood, and perhaps even overemphasised. Therefore, the aim of this section of the thesis was to examine the effects of barbell load on power output during countermovement jumping within a theoretically valid, Newtonian framework. This section of the thesis builds on the work reviewed in sections 2.3 and 2.4, the work conducted in section 3, and fulfils the requirements of aim 2 of the thesis.

4.2 Introduction

Mechanical work must be performed to accelerate and/or raise the CM of the body during dynamic athletic tasks (Cavagna, 1975). Hence, the rate of mechanical work, defined as mechanical power output (referred to as power output hereafter), is commonly hypothesised to be one of the main performance determining factors in a multitude of time-constrained dynamic athletic tasks, particularly those requiring one movement sequence to produce a high velocity at take-off or impact (Cormie et al., 2011b; Kawamori & Haff, 2004). Previously, it has been suggested that athletes who produce greater power output during unloaded (no external loading applied) and externally loaded jumping perform better in dynamic athletic tasks such as jumping (Dowling & Vamos, 1993), sprinting (Cunningham et al., 2013), and weightlifting (Hori et al., 2008). Therefore, to optimise periodic testing and training prescription, research has focused on the relationship between external loading and countermovement jump power output.

An Olympic barbell loaded with weight plates placed across the posterior aspect of the shoulders is the most commonly investigated form of external loading during countermovement jumping. The effects of barbell loading on countermovement jump power output are well reported, with the majority of studies demonstrating a systematic linear decline in power output as barbell load increases (Jaric & Markovic, 2013). However, the majority of studies have used a combination of force platform vertical ground reaction force data and barbell-derived velocity data (also referred to within the literature as the combined method) to measure countermovement jump power output (Jaric & Markovic, 2013), which Mundy et al. (2016a) demonstrated artificially inflates both peak and average power output, particularly with lighter barbell loads. As such, the effect of barbell load on countermovement jump peak and average power output may not be fully understood, and perhaps even overemphasised (e.g., training with an “optimal load” (Cormie & Flanagan, 2008; Cronin & Sleivert, 2005).

Despite the perceived importance of countermovement jump power output in the strength and conditioning community, the misuse of this mechanical variable has been heavily criticised (Knudson, 2009; Winter et al., 2016; Winter & Fowler, 2009). In brief, "power" is often expressed as a "clearly defined, generic neuromuscular or athlete performance characteristic" rather than as an application of the actual mechanical definition (Winter et al., 2016). As such, this leads to considerable inaccuracy and confusion, primarily because it often fails to represent the performance being assessed (Winter et al., 2016). Conversely, as the impulse–momentum relationship is precise and mathematically irrefutable and not only describes requirements for preface but also importantly explains prerequisites for performance, strength and conditioning coaches should perhaps focus on examining net impulse and its underpinning components of net force and time (Knudson, 2009; Winter et al., 2016; Winter & Fowler, 2009).

Although previous studies have investigated the effects of load on net impulse during countermovement jumping (Vaverka et al., 2013), a comprehensive comparison of the load–power and load–impulse relationships is yet to be reported. Further, the majority of studies investigating such relationships have not interpreted them cognisant of the underpinning force, temporal, and spatial components (Crewther et al., 2005; McMaster et al., 2014). As such, the interactions between the re-requisites for performance derived using the work–energy (force and displacement) and the impulse– momentum (force and time) relationships remain unclear, meaning external loads may be inappropriately prescribed. To demonstrate this complexity, power output may be different between 2 loads due to an increase in the force applied, an increase the displacement of the CM, a decrease in time, or a combination of all 3 – all of which have very different implications for the strength and conditioning coach. Elucidating such information may provide a greater understanding of the effects of barbell load on system CM mechanics during countermovement jump, which may reduce the misuse of power output. Further, this may also help us to better understand the nature of the acute mechanical stimulus and its contributions to adaption (Crewther et al., 2005), as well as how such relationships can contribute to periodic testing. Therefore, the primary aim of this study was to investigate the effects of barbell load on countermovement jump power output and net impulse. The secondary aim of this study was to investigate the effect barbell load has on the underpinning force, temporal, and spatial components during countermovement jumping.

4.3 Methods

4.3.1 Participants

Based on an a priori power analysis (effect size f = 0.25; $\alpha = 0.05$; $\beta = 0.80$), 24 male athletes (average ± SD: age: 23.1 ± 3.4 years; height: 1.83 ± 0.05 m; body mass (BM): 91.3 ± 10.5 kg) volunteered to participate during their respective preseason training period. All participants had at least 2 years of structured resistance training experience and were currently participating in a structured strength and conditioning programme as part of their respective sport (Rugby Football Union). Further, all participants were deemed technically proficient in the barbell loaded countermovement jump by a certified strength and conditioning specialist during a familiarisation session. Following a verbal and written explanation of the procedures and potential risks, the participants provided their written, informed consent. This study was approved in accordance with the University's Ethical Policy Framework for research involving the use of human participants.

4.3.2 Testing Procedures

Participants were instructed to report to the laboratory fully hydrated, a minimum of 2 and a maximum of 4 h postprandial, having abstained from caffeine consumption. Further, participants were instructed to refrain from alcohol consumption and vigorous exercise for at least 48 h before testing. Upon arrival, participants were led through a standardised, progressive dynamic warm-up, which included 2 sets of 6 repetitions of unloaded countermovement jumping at submaximal efforts of 50% and 75%. The athletes then performed 2 single maximal effort countermovement jumps under 5 experimental conditions in a randomised, counterbalanced order: unloaded, and with additional loads of 25%, 50%, 75%, and 100% of BM. It is important to note that external loads were prescribed relative to BM due to the strength-independent optimum loading behaviour observed in maximum countermovement jumping (readers are referred to Jaric & Markovic, 2013). Additional loads of 25%, 50%, 75%, and 100% of BM were applied by positioning an Olympic barbell across the posterior aspect of the shoulders, whereas a wooden bar of negligible mass (mass: 0.7 kg) was used during the unloaded condition. After a 1 s quiet standing period, all CMJ were performed utilising a standard technique (Hori et al., 2007), but no attempts were made to control the depth of the countermovement (Argus et al., 2011). To control for attentional focus, no verbal encouragement was provided throughout the testing, with participants simply instructed to jump as high as possible at the beginning of each trial. A 1-min rest was provided between each countermovement jump, with 4-min rest provided between each load (Nibali et al., 2013a).

4.3.3 Equipment

All countermovement jumps were performed on 2 parallel force platforms (Type 9851B, Kistler Instruments Ltd., Hook, UK) embedded in the laboratory floor, each sampling vertical ground reaction force at 1000 Hz. Both force platforms were mounted according to the manufacturer's specifications, with cables and connections checked for integrity before data collection.

4.3.4 Data Processing

Before processing, the 1-s quiet standing period was inspected to ensure that the assumptions of 0 initial velocity and position were satisfied (Cavagna, 1975). System weight was obtained by averaging the summed vertical ground reaction force over the 1-s quiet standing period (Owen et al., 2014). System mass was obtained by dividing system weight by gravitational acceleration. Net vertical ground reaction force was calculated by subtracting system weight from the vertical ground reaction force time curve. Net vertical ground reaction force was then integrated with respect to time to obtain the net impulse applied to the system CM. The vertical acceleration of the system CM was derived from Newton's 2nd Law (net vertical ground reaction force divided by mass), and then integrated with respect to time to obtain the vertical velocity of the system CM (referred to as velocity hereafter). Velocity was integrated with respect to time to obtain the vertical displacement of the system CM (referred to as countermovement displacement hereafter). Power output was calculated as the product of vertical ground reaction force and velocity (Mundy et al., 2016a), and then integrated with respect to time to obtain the work performed on the system CM. All integrals were solved for using the trapezoidal rule (Owen et al., 2014). The push-off phase began at the transition from negative to positive velocity (first positive velocity value) and ended at take-off (10 N threshold). Peak values were identified as the greatest instantaneous value of the respective signal within the push-off phase, whereas average values were determined by averaging the respective signal over the push-off phase. Jump height was calculated using the velocity at take-off (Hatze, 1998). Within session reliability was deemed acceptable for all dependent variables, with coefficients of variation at a 95% confidence level of less than 5%. The criteria of 5% was chosen to reflect the reliability previously observed within the literature (Hansen et al., 2011c). A total of 2 trials were chosen to minimise fatigue, but in order to identify optimal performance, the trial with the greatest take-off velocity was selected from each additional load for further analysis.

4.3.5 Statistical Analysis

Descriptive statistics (mean and standard deviations) were calculated for all the dependent variables. The normality of the distribution for each dependent variable was confirmed using Z-scores for skewness and kurtosis. The effect of load on each dependent variable was analysed using a 1-way repeated measures analysis of variance. Greenhouse–Geisser adjustments of the degrees of freedom were applied if the Mauchly test of sphericity was violated. Significant main effects were analysed using Bonferroni-adjusted, post hoc tests. The magnitude of the difference between each condition was also expressed as a standardised average difference (Cohen's d effect size = [average 1 – average 2]/pooled standard deviation). Cohen's d effect sizes were interpreted according to Hopkins, Marshall, Batterham, and Hanin (2009): >0.20 (small), 0.60 (moderate), 1.20 (large), 2.0 (very large), and 4.0 (extremely large). An a priori alpha level was set to $P < 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS Version 20, SPSS Inc., Chicago, IL, USA).

4.4 Results

4.4.1 Power Output and Net Impulse

Table 8 presents the means and standard deviations of peak power output, average power output, and net impulse. The effects of barbell load, including individual variation, on peak power output, average power output, and net impulse can be seen in Figures 5–7, respectively. Further, Figure 8 presents the differences in the individual's optimal load and the group's optimal load. Peak power and average power output were maximised during the unloaded condition, which were significantly greater than the 25% (d = 0.38 and 0.55), 50% (d = 0.44 and 0.97), 75% (d = 0.49 and 1.40), and 100% (d = 1.10 and 2.00) of BM conditions. Conversely, net impulse was maximised with 75% of BM, which was significantly greater than the unloaded (d = 0.93) and 100% (d = 0.58) of BM conditions.

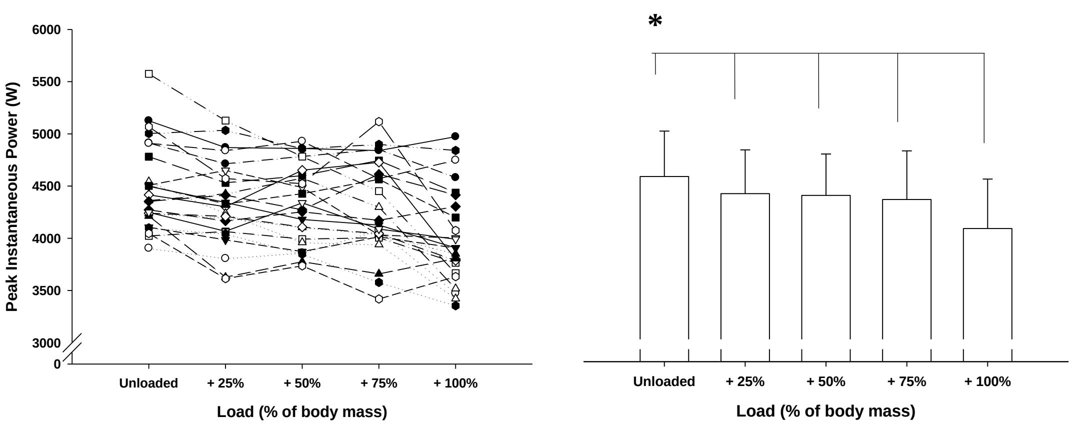


Figure 5. The effects of barbell load on peak power, including individual variation. * Denotes a significant ($p < 0.05$) difference. Each symbol represents a different individual.

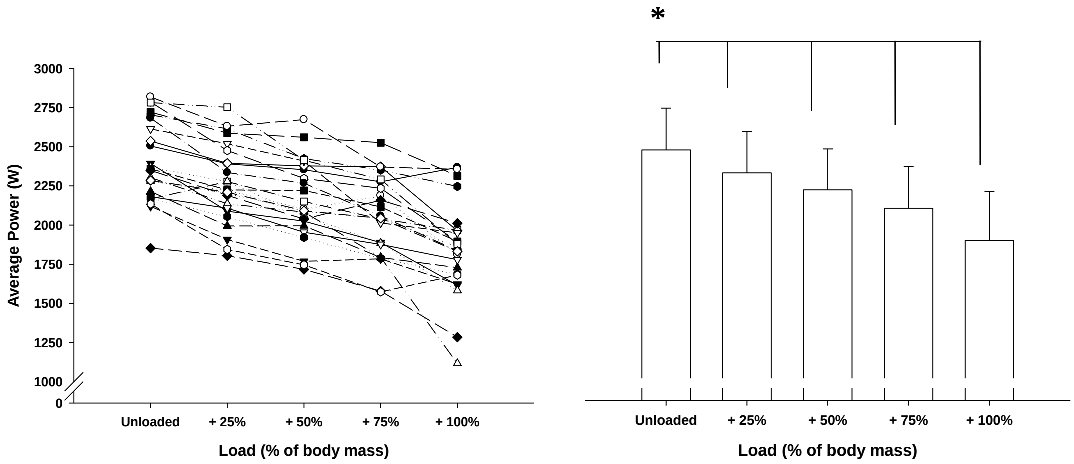


Figure 6. The effects of barbell load on average power, including individual variation. * Denotes a significant ($p < 0.05$) difference. Each symbol represents a different individual.

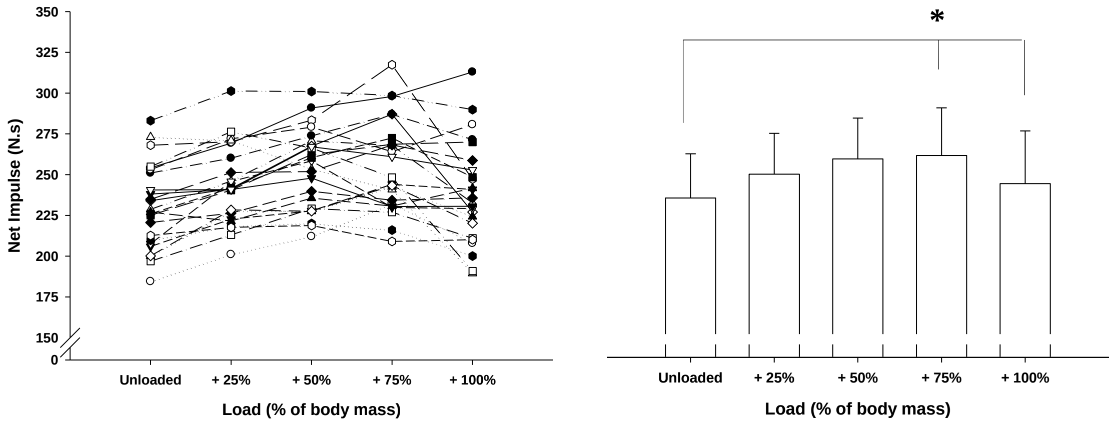


Figure 7. The effects of barbell load on net impulse, including individual variation. * Denotes a significant ($p < 0.05$) difference. Each symbol represents a different individual.

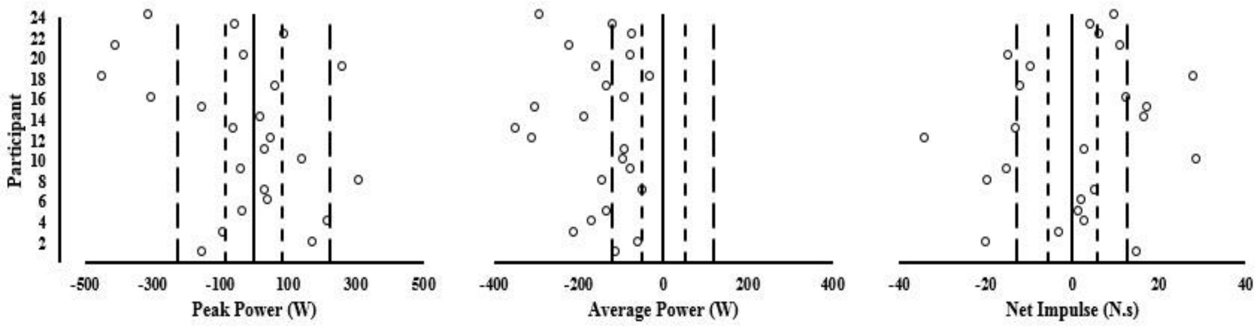


Figure 8. The-intra-individual differences in the optimal load. As average power output was maximised during the unloaded condition for all participants, the negative difference represents the difference between the individual's optimal load, and the individual's output at the second highest load. For peak power output and net impulse, a positive difference shows how much greater the externally loaded condition which maximised the individual's output is than the individual's output in the unloaded condition (the groups optimal load), whereas a negative difference shows much greater the individual's output in the unloaded condition is than the individual's output at the second highest load. The wider limits represent the coefficient of variation, whereas the narrower limits represent the smallest worthwhile change. Values within these limits are not deemed practically meaningful.

Table 8. The effects of barbell load on power and net impulse.

	Load				
	Unloaded	+25% of BM	+50% of BM	+75% of BM	+100% of BM
Peak Power (W)	4498 ± 418[†‡§¶]	4340 ± 403[¶]	4324 ± 381[¶]	4286 ± 448[¶]	4019 ± 455
Average Power (W)	2401 ± 256[†‡§¶]	2260 ± 253[‡§¶]	2156 ± 251[§¶]	2043 ± 256[¶]	1845 ± 301
Net Impulse (Ns)	230 ± 26	244 ± 24[*]	253 ± 24[*†]	255 ± 28[*¶]	238 ± 31

* Significantly greater than 0%: † Significantly greater than 25%: ‡ Significantly greater than 50%: § Significantly greater than 75%: ¶ Significantly greater than 100%

4.4.2 Force, Temporal, And Spatial Components

Table 9 presents the means and standard deviations of average force, net average force, average velocity, work, phase duration, countermovement displacement, and jump height. Average net force (d = 0.57, 1.03, 1.55, and 2.09), average velocity (d = 1.60, 3.17, 4.16, and 5.44), and jump height (d = 1.64, 3.00, 3.80, and 5.33) were maximised during the unloaded condition, and decreased significantly with load. Conversely, average force (d = 0.51, 1.11, 1.63, and 2.04), work (d = 0.53, 1.02, 1.37, and 1.40), and push-off phase duration (d = 0.77, 1.47, 1.89, and 1.93) increased significantly with load. Finally, countermovement displacement was maximised under the 25% of BM condition, which was significantly greater than the unloaded (d = 0.30), 75% (d = 0.40), and 100% (d = 0.38) of BM conditions.

Table 9. The effects of barbell load on the underpinning force, temporal, and spatial components.

	Load				
	Unloaded	+25% of BM	+50% of BM	+75% of BM	+100% of BM
Average Force (N)	1704 ± 231	1826 ± 250*	1981 ± 266*†	2115 ± 274*†‡	2251 ± 305*†‡§
Net Average Force (N)	804 ± 162†‡§¶	714 ± 154‡§¶	647 ± 144§¶	568 ± 143¶	472 ± 155
Average Velocity (m/s)	1.55 ± 0.13†‡§¶	1.35 ± 0.12‡§¶	1.17 ± 0.11§¶	1.03 ± 0.12¶	0.87 ± 0.12
Work (J)	709 ± 146	793 ± 171*	870 ±171*†	956 ± 215*†‡	1003 ± 273*†‡§
Phase Duration (s)	0.30 ± 0.06	0.35 ± 0.07*	0.41 ± 0.09*†	0.47 ± 0.12*†‡	0.57 ± 0.22*†‡§
Countermovement Displacement (m)	-0.35 ± 0.10	-0.38 ± 0.10*§¶	-0.37 ± 0.11	-0.34 ± 0.10	-0.34 ± 0.11
Jump Height (m)	0.34 ± 0.06†‡§¶	0.25 ± 0.05‡§¶	0.19 ± 0.04§¶	0.15 ± 0.04¶	0.10 ± 0.03

* Significantly greater than 0%: † Significantly greater than 25%: ‡ Significantly greater than 50%: § Significantly greater than 75%: ¶ Significantly greater than 100%

4.5 Discussion

The primary aim of this study was to investigate the effect of barbell load on countermovement jump power output and net impulse. Within the present study, unloaded peak power output was significantly greater than with additional barbell loads of 25% (d = 0.38), 50% (d = 0.44), 75% (d = 0.49), and 100% (d = 1.10) of BM. Conversely, there were no significant differences between peak power output at the 25%, 50%, and 75% of BM conditions. The effects observed are generally consistent with those previously reported within the literature, regardless of the method used (Jaric & Markovic, 2013); however, for peak power output, the decreases were generally small and not of practical importance. Therefore, focus on the identification a single load that maximises countermovement jump peak power output is perhaps overstated and practitioners should prescribe external loading parameters based on individual training needs, as well as the external loads encountered within the individual's sport (Cormie & Flanagan, 2008; Cronin & Sleivert, 2005). Further, it is important to note that there was a large intra-individual variation in the load that maximised peak power output, with 12 participants maximising power output during the unloaded condition, 3 at 25% of BM, 3 at 50% of BM, 5 at 75% of BM, and 1 at 100% of BM. However, as demonstrated within Figure 8, the majority of these differences were either smaller than the coefficient of variation or the smallest worthwhile change. As such, for a number of individuals, the optimal load for countermovement jump peak power output is unlikely to be practically meaningful.

From a mechanistic perspective, average power output is a performance determining factor, whereas considering the sampling frequency used in this study, peak power output represents a 1 ms period corresponding to less than 1% of the push-off phase duration (Lake, Mundy, & Comfort, 2014). Although a number of studies have examined the effects of barbell load on countermovement jump average power output (Cormie et al., 2011b; Lake et al., 2014; Moir et al., 2012; Nibali et al., 2013b; Swinton et al., 2012), only Swinton et al. (2012) and Lake et al. (2014) used the force platform method. The results of the present study were in line with those of Swinton et al. (2012), with average power output significantly lower at each load than at all preceding loads. When compared to the unloaded condition, moderate to large decreases were observed (d = 0.55, 0.97, 1.40, and 2.00). Conversely, Lake et al. (2014) reported that average power output was maximised with 38.8 ± 34% of a 1 repetition maximum back squat. This may have been a result of the load that maximised average power output being identified on an individual by-individual basis and then averaged, which may be misleading. However, within the present study, when the "optimal load" was identified on an individual-by-individual basis, average power output was still maximised during the unloaded condition for all 24 athletes. As such, it is likely explained by the use of different loading spectrums, the training status of the participants, or the way in which the phase was calculated (Lake, Lauder, Smith, & Shorter, 2012a). Therefore, researchers and practitioners must be aware of such methodological differences when interpreting and comparing the results of different studies.

As intra-individual variation cannot explain the moderate to large decreases observed in average power output, it may be prudent to explain this at a system level using mechanical theory. As external load increases, the mechanical work required to jump the same height increases. However, mechanical work is anatomically constrained (because countermovement displacement is limited by human anatomy), and therefore a greater magnitude of force must be applied. Therefore, as expected, within the present study, as barbell load increased, moderate to large increases in mechanical work were observed (d = 0.53–1.40). This was underpinned by small to very large increases in average force (d = 0.51–2.04) over an approximately constant countermovement displacement (d = 0.31–0. 40). However, this was not enough to compensate for the large to extremely large decreases in average velocity (d = 1.60–5.44), which was underpinned by increases in push off phase duration (d = 0.77–1.93). Therefore, the decreases observed in power output may be explained by the increased time required to perform mechanical work, as well as the inability to apply the greater magnitude of force required to perform greater mechanical work over an anatomically constrained push-off phase. Conversely, this may be more appropriately explained mechanically at the joint level, whereby the position of the external load restricted trunk inclination by increasing the moment arm (Lees et al., 2004), limiting hip joint extensor work (Vanrenterghem et al., 2008). As changing the type and position of the external load may limit the restriction of trunk inclination and, therefore, maximise both system CM (Swinton et al., 2012) and joint mechanics, further research is warranted. Such research may help improve the efficacy of prescribing loading parameters (type of load, position of load, and magnitude of load) for jump training during the physical preparation of athletes.

As concerns have previously been raised about the misuse of power output as a mechanical variable during countermovement jumping (Knudson, 2009; Winter et al., 2016; Winter & Fowler, 2009), it may be prudent to highlight the effect barbell load has on alternative mechanical parameters. The prescription of training loads for countermovement jumping based on the barbell load that maximises net push-off impulse remains a relatively novel idea (Crewther et al., 2005; Lake et al., 2014). This may be important for sports where athletes are repeatedly loaded by an opponent or have to accelerate through prolonged contact. However, it is important to emphasise that the work–energy and impulse–momentum theorems are essentially just spatial and temporal descriptions of the same change. Therefore, practitioners should choose which theorem to prescribe external loads based on the spatial and temporal restrictions of the respective sport and athlete.

In the present study, net impulse was maximised at 75% of BM, although this was only significantly greater than the unloaded (d = 0.93) and 100% (d = 0.58) of BM conditions. This small, linear increase in net impulse between the unloaded and the 75% of BM condition is in line with previous research. When externally loaded with a weighted vest equivalent to 10%, 20%, and 30% of BM, Vaverka et al. (2013) reported a significant linear increase in push-off net impulse. Similar findings have also been reported for "eccentric impulse", "concentric impulse", and "total impulse" (combined eccentric and concentric impulse) (Harris et al., 2008a; Jidovtseff, Quievre, Harris, & Cronin, 2014). The small, linear increase in net impulse between the unloaded and the 75% of BM condition can be explained using the impulse–momentum theorem. In brief, net impulse, the product of net force and time, is equal to the change in momentum, the product of mass, and change in velocity (because mass is constant during each countermovement jump). Within the present study, as barbell load increased, the system mass increased. Conversely, the average velocity of the system CM, which represents change in velocity of the system CM as its velocity is zero at the beginning of the push-off phase, decreased significantly (d = 1.60–5.44). However, the decrease in average velocity (13%, 25%, 34%, and 44% decrease) was not proportional to the increase in system mass (25%, 50%, 75%, and 100% increase). Therefore, the momentum of the system CM increased.

However, as momentum is simply the quantity of motion of the system CM, the underpinning net force and time components of net impulse must be discussed if it is to be applied appropriately within the physical preparation of athletes from different sports.

The average force applied to the system CM increased significantly as barbell load increased ($d = 0.51–2.04$), whereas average net force applied to the system CM decreased significantly ($d = 0.57–2.09$). Therefore, it appears that as barbell load increased, a greater proportion of the average force applied was to overcome the increased inertia of the system (represented by the increased mass), as opposed to accelerating it. However, the linear decline in the average net force was offset by the significant linear increase in the duration of its application, that is, push-off phase duration ($d = 0.77–1.93$). Therefore, net impulse initially increased linearly (e.g., unloaded to 75% of BM); however, thereafter, the increase in push-off phase duration was no longer enough to compensate for the decreasing magnitude of the net force, causing a decrease in net impulse.

Based on the findings of the present study, jump training with barbell loads of 50–75% of BM during specific phases of a periodised strength and conditioning programme may help improve the ability to accelerate through contact or when externally loaded by an opponent during sport specific events (e.g., tackling, rucking, mauling). However, as previously alluded to, net impulse may be maximised by either increasing the magnitude of the net force applied or the duration for which the application occurs. Therefore, it is important to note that due to the time constraints of most sporting activities, optimising the rate of force development may also be an important consideration for load prescription (Knudson, 2009; Lake et al., 2014; McLellan et al., 2011b). However, to the author's knowledge, there is no ubiquitously accepted method of calculating rate of force development (Hansen et al., 2011d), with the reliability of commonly used methods not acceptable within practice (Hansen et al., 2011a; Mizuguchi et al., 2015). As such, if the rate of force development is to be used in conjunction with net impulse to prescribe jump training loads, the way in which it is calculated must first be improved, and then standardised (Knudson, 2009; McLellan et al., 2011b; Sheppard et al., 2008a).

The results of this study are important to practitioners who prescribe or may prescribe loaded countermovement jumping. It was demonstrated that additional barbell loads relative to BM significantly influence system CM mechanics during countermovement jumping. When optimising external load prescription for a periodised strength and conditioning programme, barbell loads are often prescribed based on the load that maximises either peak power or average power output. Within the present study, both peak power and average power output were maximised during the unloaded condition; however, load did not typically have a large effect. As such, further work investigating the type and position of positive external loading on both system CM and lower extremity joint mechanics may help improve the efficacy of prescribing loading parameters (type of load, position of load, and magnitude of load) for countermovement jump training during the physical preparation of athletes. As concerns have previously been raised about the misuse of power output, the relatively novel identification of loading parameters based on push-off net impulse was investigated (Lake et al., 2014), as this may help develop the ability to accelerate through prolonged contact or when loaded by an opponent during sport specific events (e.g., tackling, rucking, mauling). It was found that load only had a small effect on net impulse, which was maximised at 75% of BM. As such, a greater consideration of how the underpinning time and force components interact is required when prescribing loads.

5. The Effects of External Load Positioning (Straight Barbell vs. Hexagonal Barbell) on Countermovement Jump System Centre of Mass and Lower Limb Joint Mechanics

5.1 Introduction

Section 4 (Mundy et al., 2016b) of the thesis demonstrated that when using a theoretically valid method, both peak power and average power output were maximised during unloaded conditions, with moderate, negative effect sizes observed with increases in barbell loading. Interestingly, peak power output was confounded by intra-individual variation, with changes between barbell loads often smaller than the coefficient of variation, making them not practically meaningful, of which had not previously been considered within the body of knowledge. Further, decreases observed in average power output were likely explained by the increased time required to perform mechanical work, as well as the inability to apply the greater magnitude of force required to perform greater mechanical work over an anatomically constrained push off phase. These findings were of particular importance for the progression of this thesis and to the body of knowledge, as the majority of previous studies had either used the combined method (section 2.4), which artificially inflates power output during lighter conditions (section 3, (Mundy et al., 2016a)), or had not explained changes in power output cognisant of the underpinning force, temporal, and spatial components (sections 2.2 and 2.4).

Despite the contributions made to the body of knowledge within section 4 (Mundy et al., 2016b) of the thesis, it was noted in sections 2.2 and 2.4 that although system CM information may provide important global information, it does not necessarily provide information about lower limb joint mechanics (Jandacka et al., 2014; Kipp et al., 2011; Moir et al., 2012). Rather than explaining increases in power output using the system level, we can perhaps more appropriately explain them at the joint level. For example, the hip joint extensors work maximally only when there is an opportunity to extend the trunk from a forward inclined position (Lees et al., 2004; Vanrenterghem et al., 2008). However, when an external load is positioned across the shoulders, trunk inclination is restricted to prevent the moment arm of the external resistance becoming too large, minimising resistive torque and shear forces experienced at the lumbar spine (Fry et al., 2003; Swinton et al., 2012). Conversely, when the position of the external load is changed the range of motion at the hip may not be limited to the same degree, if at all (Lees et al., 2004). This has considerable implications for practitioners, as manipulating both the magnitude and the position of the external load may change the focus from the hip extensors to the knee extensors. As such, a failure to consider such information may limit the effectiveness of a given physical preparation programme. However, as highlighted in sections 2.4 and 2.5 of the thesis, to the author’s knowledge, there is a dearth of information available regarding the effects of external load, as well as the effects of the position of the external load, on lower limb joint mechanics during the countermovement jump.

From a practitioner’s perspective, understanding which biomechanical factors to change is just as important as understanding which factors determine (limit) athletic performance (Bobbert & Van Soest, 1994). This was particularly important to the thesis as novel contributions to the body of knowledge should not only enhance theoretical understanding, but also practical outcomes. Recently, Marshall and Moran (2015) identified issues associated with prescribing training parameters based on cross-sectional data. Based on a novel pre-to-post design, it was implied that not all factors identified in a cross-sectional analysis may be critical to jump height improvement, and that cross-sectional analyses alone may not provide an insight into all of the potential factors to train to enhance jump height. Interestingly, despite some of the issues previously presented pertaining to system CM peak power output, it was identified as one of the largest associations with post training increases in jump height. Moreover, based on the joint level data, it was suggested that exercises prescribed to improve jump height should aim to enhance push-off power output at all lower limb joints, with a particular emphasis on enhancing hip joint peak power output. Therefore, the primary aim of this section of the thesis was to investigate how changing the position and magnitude of the external load affects both system CM and lower limb joint mechanics during loaded countermovement jumping in well trained athletes, with a particular emphasis on joint peak power output. This section of the thesis builds on the work reviewed in sections 2.4 and 2.5, the work conducted in sections 3 and 4, and fulfils the requirements of aim 3.

5.2 Methods

5.2.1 Participants

Based on an *a priori* power analysis (effect size f = 0.4; $\alpha = 0.05$; $\beta = 0.80$), eight well trained male athletes (mean ± SD: age: 24 ± 5 yrs; height: 1.83 ± 0.06 m; body mass: 89 ± 9 kg) volunteered to participate in this study during their respective off-season training period. All participants had at least two years of structured resistance training experience, had a 1-RM back squat above 1.8 x body mass, and were currently participating in a structured strength and conditioning program as part of their respective sport (Rugby Football Union and Football). Following a verbal and written explanation of the procedures and potential risks, the participants provided their written, informed consent. This study was approved in accordance with the University of Chichester's Ethical Policy Framework for research involving the use of human participants.

5.2.2 Testing Procedure

Participants were instructed to report to the laboratory in a hydrated state, a minimum of two and a maximum of four hours postprandial, and having abstained from caffeine consumption. Further, participants were instructed to refrain from alcohol consumption and vigorous exercise for at least 48 hours before testing. Upon arrival, participants were led through a standardised, progressive dynamic warm-up, which included unloaded submaximal and maximal effort countermovement jumps. Participants then performed unloaded and externally loaded maximal effort countermovement jumps in a randomised, counterbalanced order. The unloaded jumps were performed with a wooden bar of negligible mass (mass: 0.7 kg) placed across the posterior aspect of the shoulders. The externally loaded jumps were performed with both a straight barbell and a hexagonal barbell with external loads of 20%, 40%, 60%, 80% and 100% of body mass (Figure 9). All jumps were performed utilising a standard countermovement technique, but no attempts were made to control the depth of the countermovement (Argus et al., 2011). Prior to testing, all participants attended technique sessions, supervised by a certified strength and conditioning specialist, whereby they were deemed technically proficient.

Further, all testing sessions were supervised by the same certified strength and conditioning specialist to ensure consistency and participant safety. Two jumps were performed at each condition, with the jump that resulted in the greatest jump height selected for further analysis. One minutes rest was provided between each jump, with up to four minutes rest provided between each condition (Nibali et al., 2013a).

Figure 9. A participant performing both straight barbell (left) and hexagonal barbell (right) countermovement jumps with 100% of body mass.

5.2.3 Equipment

Jumps were performed with a separate force platform (Type 9851B, Kistler Instruments Ltd., Hook, UK) under each foot, in a capture area defined by a 10-camera optoelectronic motion capture system (VICON MX T-Series (T40-S), Vicon Motion Systems Ltd., Oxford, UK). Marker position and ground reaction force data were captured at 250 Hz and 1000 Hz, respectively. Prior to testing, retro-reflective markers (12 mm) were placed bilaterally over anatomical landmarks including the iliac crest, posterior and anterior superior iliac spines, greater trochanter, medial and lateral femoral condyles, medial and lateral malleoli, the posterior aspect of the calcaneus, and the heads of the first and the fifth metatarsals. In addition, markers were placed bilaterally on the acromion process, as well as on the sacrum, the sternum, the xiphoid process, and the spinous process of the 7th cervical and 8th thoracic vertebras. Anatomical landmark palpation and marker placement were completed by the lead investigator, using guidelines described by Van Sint Jan and Della Croce (2005). Finally, semi-rigid, thermoplastic clusters mounted with three non-collinear markers were affixed with double-sided tape to the lateral thighs and shanks. Once instrumented, a static calibration trial was collected, whereby the participants assumed the anatomical reference position (Cappozzo, Catani, Croce, & Leardini, 1995).

5.2.4 Data Analysis

Synchronised marker position and ground reaction force signals were processed using Visual 3D software (Version 5; C-Motion, Rockville, MD, USA). Segment masses were defined using standard regression equations (Dempster, 1955). Segment moments of inertia were defined using geometric primitives (Hanavan, 1964). More specifically, the feet, shanks, and thighs were modelled as a frustum of right-circular cones, whereas the trunk and pelvis were modelled as cylinders. Based on a residual analysis and a qualitative evaluation of the data, both marker position and ground reaction force data were filtered using a fourth-order Butterworth filter with a cut-off frequency of 12 Hz (Winter, 2009). Joint angles for the hip, knee and ankle were calculated using an x (flexion/extension), y (abduction/adduction), z (internal/external rotation) Cardan rotation sequence, and were referenced to the coordinate systems embedded in the distal segment. Joint angular velocities were calculated relative to the laboratory global coordinate system by differentiating the rotation matrix using finite differences (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2014). Net joint moments (expressed in the respective proximal local coordinate systems) were calculated using a Newton–Euler inverse dynamics technique (Robertson et al., 2014). Joint power outputs were calculated as the product of the proximal net joint moment and the segments joint angular velocity. Net joint moments and joints power outputs were scaled to body mass. Finally, system CM mechanics were calculated using the methods described in section 4 of the thesis (Mundy et al., 2016b).

5.2.5 Statistical Analysis

The effects of joint (hip x knee x ankle), external load (20% x 40% x 60% x 80% x 100% of body mass), and position (straight barbell x hexagonal barbell) on peak angular velocity, relative peak net moment, and relative peak power output were analysed using a series of 3x5x2 mixed analyses of variance. The effects of external load (20% x 40% x 60% x 80% x 100% of body mass) and position (straight barbell x hexagonal barbell) on joint angle at joint reversal, relative peak power output, relative average power output, relative average push-off force, push-off phase time and system CM displacement were analysed using a series of 5x2 repeated measures analyses of variance. Normality of distribution was confirmed using Z-scores for skew and kurtosis. The absence of outliers was confirmed with boxplots. Homogeneity of variance was assessed by Levene's test for equality of variances. Greenhouse-Geisser adjustments of the degrees of freedom were applied if the Mauchly test of sphericity was violated. Where appropriate, Bonferroni corrections were made for multiple comparisons. Partial eta squared was used to help interpret the magnitude of interaction and main effects. An a priori alpha level was set to

$p < 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS Version 20, SPSS Inc., Chicago, IL, USA).

5.3 Results

5.3.1 Jump Height

Mean ± SD jump heights across external loading conditions and positions are shown in Table 1210. For jump height there was no interaction between external loading condition and position. However, jump height was explained independently by position ($p < 0.001$, $ŋ^2_p = 0.689$) and external load ($p < 0.001$, $ŋ^2_p = 0.969$). Post hoc testing revealed that jump height was significantly greater in the hexagonal barbell than the straight barbell, and that jump height decreased significantly with external load.

5.3.2 Relative System Power Output

Mean ± SD relative system power outputs across external loading condition and position are shown in Table 10 and Figure 10, respectively. For relative system average power output there was no interaction between external loading condition and position. However, relative system average power output was explained independently by position ($p < 0.001$, $ŋ^2_p = 0.813$) and external load ($p < 0.001$, $ŋ^2_p = 0.537$). Post hoc testing revealed that relative system power output was significantly greater in the hexagonal barbell than the straight barbell, and 40% of body mass was significantly greater than 80% and 100% of body mass.

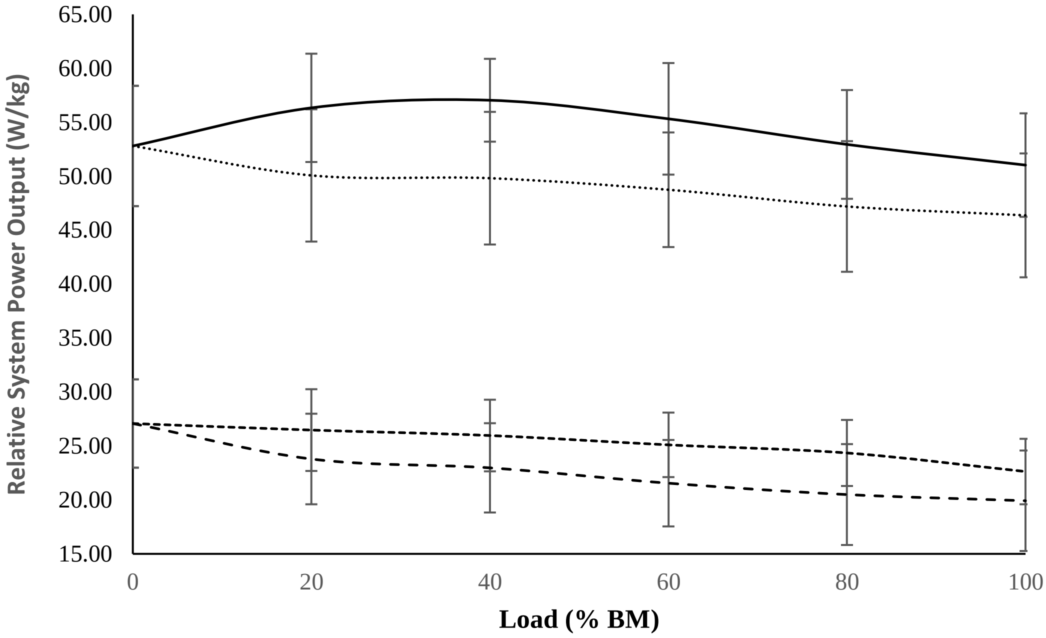


Figure 10. Mean ± SD relative system power outputs across external loading condition and position. The top two lines represent relative peak power output, whereas the bottom two lines represent relative average power output. For both relative peak power output and relative average power output, the hexagonal barbell was greater than the straight barbell.

For relative system peak power output there was no interaction between external loading condition and position. However, relative system peak power output was explained independently by position ($p < 0.001$, $\eta^2_p = 0.906$) and external load ($p < 0.001$, $\eta^2_p = 0.674$). Post hoc testing revealed that relative system peak power output was significantly greater in the hexagonal barbell than the straight barbell, and 20% and 40% of body mass were significantly greater than 100% of body mass.

Table 10. Mean ± SD jump height (m) and relative system power output (W/kg) across external loading condition and position.

Position	Load (% of BM)	Variable		
		Jump Height	Peak Power	Average Power
CMJ	Unloaded	0.37 ± 0.06	52.80 ± 5.57	27.09 ± 4.09
BB	20%	0.28 ± 0.05	50.07 ± 6.13	23.79 ± 4.20
	40%	0.22 ± 0.04	49.81 ± 6.15	22.97 ± 4.14
	60%	0.18 ± 0.03	48.74 ± 5.31	21.55 ± 4.01
	80%	0.13 ± 0.03	47.19 ± 6.05	20.49 ± 4.67
	100%	0.10 ± 0.02	46.37 ± 5.74	19.92 ± 4.66
HB	20%	0.30 ± 0.05	56.34 ± 5.57	26.47 ± 3.79
	40%	0.25 ± 0.04	57.04 ± 3.84	25.97 ± 3.32
	60%	0.20 ± 0.03	55.32 ± 5.17	25.10 ± 2.99
	80%	0.16 ± 0.03	52.94 ± 5.04	24.35 ± 3.06
	100%	0.12 ± 0.03	51.03 ± 4.80	22.63 ± 3.03

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.3.3 Underpinning Force, Temporal and Spatial Components

Mean ± SD average force, push-off duration and system CM displacement across loading condition and position are shown in Table 11. The two-way interaction for position and external load for relative average force was significant ($p = 0.011$, $\eta^2_p = 0.361$). Post hoc testing revealed that relative average force was significantly greater in the hexagonal barbell than the straight barbell at 20%, 40%, 60% and 80% of body mass, but not at 100% of body mass.

The effect of external load for the straight barbell was significant ($p < 0.001$, $\eta^2_p = 0.904$). Post hoc testing for external load revealed that relative average force was significantly greater at 100% of body mass than at 20%, 40%, 60% and 80% of body mass. Further, 40%, 60% and 80% of body mass were significantly greater than 20% of body mass, and 80% of body mass was significantly greater than 40% of body mass.

The effect of external load for the hexagonal barbell was significant ($p < 0.001$, $\eta^2_p = 0.928$). Post hoc testing for external load revealed that relative average force was significantly greater at 100% of body mass than at 20%, 40%, 60% and 80% of body mass. Further, 40%, 60% and 80% of body mass were significantly greater than 20% of body mass, and 60% and 80% of body mass were significantly greater than 40% of body mass.

For push-off duration there was no interaction between external loading conditions and positions. However, push-off duration was explained independently by position ($p = 0.025$, $\eta^2_p = 0.535$) and external load ($p < 0.001$, $\eta^2_p = 0.692$). Post hoc testing for position revealed that push-off duration was significantly greater in the straight barbell than the hexagonal barbell. Further, post hoc testing for external load revealed that push-off duration was significantly greater at 60% and 80% of body mass than at 20% and 40% of body mass, as well as significantly greater at 100% of body mass than at 40% of body mass.

For system CM displacement there was no interaction between external loading condition and position. However, system CM displacement was explained independently by external load ($p = 0.43$, $\eta^2_p = 0.288$). However, post hoc testing for external load did not reveal any significant differences for system CM displacement.

Table 11. Mean ± SD average force (N/kg), push-off duration (s) and system CM displacement (m) across external loading condition and position.

Position	Load (% of BM)	Variable		
		Average Force	Push-off Duration	CM Displacement
CMJ	Unloaded			
BB	20%	18.46 ± 1.28	0.424 ± 0.043	-0.46 ± 0.06
	40%	20.56 ± 1.64	0.444 ± 0.078	-0.45 ± 0.08
	60%	21.37 ± 1.53	0.530 ± 0.097	-0.45 ± 0.08
	80%	22.83 ± 1.78	0.584 ± 0.142	-0.44 ± 0.09
	100%	24.79 ± 2.18	0.599 ± 0.196	-0.39 ± 0.06
HB	20%	20.07 ± 1.30	0.361 ± 0.043	-0.39 ± 0.07
	40%	21.47 ± 1.33	0.404 ± 0.057	-0.39 ± 0.06
	60%	22.83 ± 1.21	0.444 ± 0.056	-0.42 ± 0.06
	80%	24.26 ± 1.35	0.483 ± 0.0541	-0.40 ± 0.05
	100%	25.42 ± 1.60	0.541 ± 0.106	-0.38 ± 0.07

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.3.4 Joint Angle at Joint Reversal

Mean ± SD hip, knee and ankle joint angles at joint reversal across external loading condition and position are shown in Table 12. For knee angle at joint reversal there was no interaction between external loading condition and position. However, knee angle at joint reversal was explained independently by external load ($p < 0.001$, $\eta^2_p = 0.462$) and position ($p = 0.021$, $\eta^2_p = 0.558$). Post hoc testing for external load revealed that knee angle at joint reversal was significantly greater at 40% and 60% of body mass than at

100% of body mass. Further, post hoc testing for position revealed that knee angle at joint reversal in the straight barbell was significantly greater than the hexagonal barbell.

Table 12. Mean ± SD hip, knee and ankle joint angles (°) at joint reversal across external loading condition and position.

Position	Load (% of BM)	Joint		
		Hip	Knee	Ankle
CMJ	Unloaded	94 ± 11	90 ± 14	22 ± 6
BB	20%	98 ± 7	96 ± 10	21 ± 5
	40%	93 ± 7	94 ± 14	21 ± 5
	60%	93 ± 9	95 ± 12	20 ± 5
	80%	91 ± 10	91 ± 14	20 ± 5
	100%	89 ± 10	89 ± 14	20 ± 6
HB	20%	94 ± 9	82 ± 11	20 ± 6
	40%	92 ± 9	79 ± 12	19 ± 5
	60%	91 ± 9	79 ± 11	19 ± 5
	80%	90 ± 9	77 ± 9	18 ± 5
	100%	88 ± 13	76 ± 12	18 ± 4

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.3.5 Joint Peak Angular Velocity

Mean ± SD hip, knee and ankle joint peak angular velocities across external loading condition and position during the push-off phase are shown in Table 13. For joint peak angular velocity there was no interaction between joint, external loading condition and position. However, joint angular velocities depended on the combined effects of external load and joint ($p < 0.001$, $ŋ^2_p = 0.268$) and position and joint ($p = 0.005$, $ŋ^2_p = 0.287$). The effects of position on hip, knee and ankle joint angular velocities did not depend on external load, but could not be explained independently of joint. More specifically, post hoc testing revealed that joint angular velocities in the hexagonal barbell were significantly greater than the straight barbell at 20, 40%, 60%, 80% and 100% of body mass. Further, ankle and knee joint angular velocities were significantly greater than hip joint angular velocities at 40%, 60%, 80%, and 100% of body mass. However, at 20% of body mass, only knee joint angular velocities were significantly greater than the hip joint angular velocities.

The effects of external load on hip, knee and ankle joint angular velocities did not depend on position, but could not be explained independently of joint. More specifically, post hoc testing revealed that for the straight barbell, knee joint angular velocities were significantly greater at 20% and 40% of body mass than at 60%, 80% and 100% of body mass, and 60% of body mass was significantly greater than 100% of body mass. Hip joint angular velocities were significantly greater at 20%, 40% and 60% of body mass than at 100% of body mass, 20% and 40% of body mass were significantly greater than 80% of body mass, and 20% of body mass was greater than 60% of body mass. For the hexagonal barbell, knee joint angular velocity was significantly greater at 20% of body mass than at

40%, 60%, 80% and 100% of body mass, 40%, 60% and 80% were significantly greater than 100% of body mass, and 40% of body mass was significantly greater than 80% of body mass. Hip joint angular velocity was significantly greater at 20% of body mass than at 40%, 60%, 80% and 100% of body mass, and 40%, 60% and 80% of body mass were significantly greater than 100% of body mass.

Table 13. Mean ± SD hip, knee and ankle joint peak angular velocities (ω) across external loading condition and position during the push-off phase.

Position	Load (% of BM)	Joint		
		Hip	Knee	Ankle
CMJ	Unloaded	544 ± 76	785 ± 104	664 ± 204
BB	20%	468 ± 63	710 ± 107	624 ± 171
	40%	433 ± 65	682 ± 94	604 ± 149
	60%	393 ± 52	627 ± 85	577 ± 128
	80%	354 ± 70	584 ± 102	573 ± 125
	100%	335 ± 60	549 ± 85	546 ± 112
HB	20%	521 ± 56	709 ± 93	630 ± 197
	40%	470 ± 69	678 ± 82	635 ± 167
	60%	444 ± 68	644 ± 88	615 ± 140
	80%	411 ± 43	610 ± 83	603 ± 126
	100%	367 ± 36	563 ± 67	567 ± 114

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.3.6 Joint Peak Net Moment

Mean ± SD normalised hip, knee and ankle joint peak net moments across external loading condition and position during the push-off phase are shown in Table 14. For joint peak angular velocity there was no interaction between joint, external loading condition and position. However, joint net moments were explained independently by external load ($p < 0.001$, $ŋ^2_p = 0.584$) and joint ($p < 0.001$, $ŋ^2_p = 0.766$). Post hoc testing for external load revealed that joint net moments were significantly greater at 100% of body mass than at 20%, 40% and 60% of body mass. Further, 40%, 60% and 80% of body mass were significantly greater than 20% of body mass, and 60% and 80% of body mass were significantly greater than 40% of body mass. Post hoc testing for joint revealed that hip joint net moments were significantly greater than knee and ankle joint net moments.

Table 14. Mean ± SD normalised hip, knee and ankle joint peak net moments ($Nm.kg^{-1}$) across external loading condition and position during the push-off phase.

Position	Load (% of BM)	Joint		
		Hip	Knee	Ankle
CMJ	Unloaded	2.24 ± 0.28	1.55 ± 0.36	1.39 ± 0.20
BB	20%	2.27 ± 0.35	1.57 ± 0.33	1.43 ± 0.21
	40%	2.49 ± 0.36	1.73 ± 0.27	1.59 ± 0.23
	60%	2.55 ± 0.44	1.78 ± 0.17	1.71 ± 0.27
	80%	2.69 ± 0.44	1.79 ± 0.26	1.85 ± 0.28
	100%	2.61 ± 0.40	1.98 ± 0.28	1.93 ± 0.27
HB	20%	2.37 ± 0.15	1.54 ± 0.36	1.59 ± 0.24
	40%	2.50 ± 0.23	1.66 ± 0.19	1.71 ± 0.24
	60%	2.61 ± 0.20	1.80 ± 0.22	1.81 ± 0.30
	80%	2.68 ± 0.12	1.75 ± 0.19	1.93 ± 0.24
	100%	2.73 ± 0.36	1.97 ± 0.27	1.96 ± 0.30

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.3.7 Joint Peak Power Output

Mean ± SD normalised hip, knee and ankle joint peak power outputs across external loading condition and position during the push-off phase are shown in Table 15. For joint peak power output there was no interaction between joint, external loading condition and position. However, joint power outputs depended on the combined effects of external load and joint ($p < 0.001$, $\eta^2_p = 0.383$) and position and joint ($p = 0.005$, $\eta^2_p = 0.391$). The effects of position on hip, knee and ankle joint power output did not depend on external load, but could not be explained independently of joint. More specifically, post hoc testing revealed that joint power outputs in the hexagonal barbell were significantly greater than the straight barbell at 40%, 60%, 80% and 100% of BM. However, at 20% of BM, only hip and ankle joint power outputs in the hexagonal barbell were significantly greater than the straight barbell. Ankle joint power outputs was significantly greater than hip joint power outputs at 80 and 100% of BM. Knee joint power output was also significantly greater than hip joint power output at 100% of BM.

The effects of external load on hip, knee and ankle joint power output did not depend on position, but could not be explained independently of joint. More specifically, post hoc testing revealed that for the straight barbell, ankle joint power output was significantly greater at 60%, 80% and 100% of BM than at 20% of BM, and 80% of BM was significantly greater than 40%. Hip joint power output was significantly greater at 20, 40 and 60% of BM than at 100% of BM, and 20% of BM was significantly greater than 80% of BM. Ankle and knee joint power outputs were significantly greater than hip joint power output at 60%, 80%, and 100% of BM. However, at 40% of BM, only the ankle was greater than the hip. For the hexagonal barbell, ankle joint power output was significantly greater at 60%, 80% and 100% of BM than at 20% and 40% of BM. Further, ankle and knee joint power outputs were significantly greater than hip joint power output at 100% of BM, and the ankle was significantly greater than the hip at 80% of BM.

Table 15. Mean ± SD normalised hip, knee, and ankle joint peak power outputs ($W.kg^{-1}$) across loading condition and position during the push-off phase

Position	Load (% of BM)	Joint		
		Hip	Knee	Ankle
CMJ	Unloaded	6.84 ± 1.60	9.45 ± 1.94	8.06 ± 3.15
BB	20%	6.39 ± 1.92	8.68 ± 1.88	8.22 ± 3.46
	40%	5.96 ± 1.68	8.99 ± 2.76	8.48 ± 3.04
	60%	5.88 ± 1.30	8.70 ± 2.63	8.93 ± 3.06
	80%	5.51 ± 1.75	8.81 ± 2.80	9.36 ± 3.09
	100%	5.06 ± 1.01	8.59 ± 2.33	9.63 ± 3.10
HB	20%	7.56 ± 2.11	8.05 ± 2.19	8.73 ± 3.45
	40%	7.83 ± 2.73	8.96 ± 1.94	9.14 ± 3.12
	60%	7.18 ± 2.44	8.69 ± 1.82	9.68 ± 3.37
	80%	7.56 ± 2.27	8.58 ± 1.49	10.14 ± 3.19
	100%	6.29 ± 2.31	9.38 ± 2.33	9.99 ± 3.21

CMJ: countermovement jump; BM: body mass; BB: barbell; HB: hexagonal barbell.

5.4 Discussion

The primary aim of this section of the thesis was to investigate how changing the position and magnitude of the external load affects both system CM and lower limb joint mechanics during loaded countermovement jumping in well trained athletes, with a particular emphasis on joint peak power output. Within this section of the thesis, it was demonstrated that greater system CM and lower limb joint peak power output can be achieved by changing the position of the external load from the shoulders to arms' length by using a hexagonal barbell. However, the effects at the system CM level differed from those at the joint level. In brief, it appears that the system CM peak power output can be used as a teleological measure for hip joint peak power output in well trained athletes regardless of the load position, but not the ankle joint or the knee joint. These differences demonstrate the limitations in the contemporary use of system CM information to inform both position and magnitude of external load selection during the physical preparation of athletes.

When aiming to improve unloaded countermovement jumping performance, Marshall and Moran (2015) recommended that practitioners should prescribe the magnitude of the external load based on the external load that enhances power output at all of the lower limb joints, with a particular emphasis on enhancing hip joint peak power output. Within this section of the thesis, when using the hexagonal barbell, lower limb joint peak power outputs were significantly greater than those produced using the straight barbell at every load except 20% of body mass, where only hip and ankle joint peak power outputs were significantly greater when using the straight barbell. These findings may be explained by differences in joint range of motion. When using the straight barbell, the knee joint angle at joint reversal was significantly greater than the hexagonal barbell. Conversely, the position of the external load did not affect hip and ankle joint ranges of motion. Therefore, due to the proximal to distal sequencing of joint peak moment production observed during jumping, a more effective hip extension may have allowed a more optimal energy transfer between joints (Bobbert & Van Soest, 1994), resulting in a greater system CM output.

Interestingly, no main effect for external load position on lower limb joint peak moments were identified, nor did the percentage contribution of the hip, knee and ankle change (Hip: 42%, Knee: 30% and Ankle: 28% ± 1%). In contrast, when using the hexagonal barbell, lower limb joint peak angular velocities were significantly greater for all joints when compared to the straight barbell at all external loads. Although this may be explained by more effective kinematics (e.g. proximal to distal sequencing), it may also be explained by the absolute load being positioned closer to the system CM so that the relative resistance is less, allowing for significantly greater angular velocities at all external loads investigated. Therefore, in order to maximise the transfer of externally loaded jumping to unloaded countermovement jumping, practitioners should consider changing the position of the external load to arms' length using a hexagonal barbell.

In order to optimise the prescription of the hexagonal barbell during externally loaded jumping, the effects of the magnitude of external load must also be considered. Historically, the magnitude of the external load is often prescribed based on the external load that maximises either system CM peak power or average power output, which as previously stated is commonly referred to as the optimal load (Soriano, Jimenez-Reyes, Rhea, & Marin, 2015). Unsurprisingly, when using the straight barbell, the findings of this section of the thesis were in line with other investigations using well trained athletes (Swinton et al., 2012), including section 4 (Mundy et al., 2016b) of this thesis, whereby a systematic linear decline in system power output was observed as external load increased. Conversely, when using the hexagonal barbell, only average power output declined, whereas peak power output appeared quadratic, and was maximised with 40% of body mass (Figure 10). Generally, these findings are in line with similar investigations using well trained (Swinton et al., 2012) and elite (Turner et al., 2015) athletes. However, at the system CM level, differences between the optimal load and other loading conditions do not appear to be practically meaningful across a range of external loads in both straight barbell (section 4, (Mundy et al., 2016b)) and hexagonal barbell (Turner et al., 2015) loaded countermovement jumps. Further, and perhaps more importantly, both Moir et al. (2012) and Jandacka et al. (2014) have demonstrated that the optimal load for the system CM is generally not equal to the optimal load for the lower limb joints.

Within this section of the thesis, regardless of the position of the external load, system CM peak power output and hip joint peak power output were maximised at the same external load and followed the same trend, but the knee joint and ankle joint peak power outputs did not. Conversely, Moir et al. (2012) reported that system CM peak power output was maximised at the same load as the knee joint and ankle joint, but not the hip join, whereas Jandacka et al. (2014) reported that system CM, hip, knee and ankle joint peak power outputs were all maximised at different loads. However, Moir et al. (2012) used the combined method to calculate system CM power output, which in section 3 (Mundy et al., 2016a) of the thesis was shown to artificially inflate power output at lower external loads, whereas Jandacka et al. (2014) investigated the concentric only squat jump, and did not normalise power to body mass in a heterogeneous population. Therefore, when prescribing external loads based upon previous recommendations, practitioners appear to be able to prescribe the position and magnitude of the external load based on system CM data. However, practitioners should also be aware that these external loads do not maximise system CM average power output, or peak power output at the knee or ankle joint, so this method of prescription may be limited when transfer to other sporting tasks is of interest. Further, the range of external loads investigated was narrow in comparison to previous studies. For example 100% of body mass only represents approximately 55% of the average participant's 1-RM back squat. Therefore, if practitioners are to improve the physical preparation of athletes, further investigation may be warranted.

Although this section of the thesis provides novel insights into how changing the position of the external load affects both system CM and lower limb joint mechanics during loaded countermovement jumping, the result should be interpreted with caution. Within this section of the thesis, hip joint peak moments were significantly greater than both knee joint and ankle joint peak moments. This suggests that participants were hip dominant jumpers (Hip: 42%, Knee: 30% and Ankle: 28%), a strategy of which was maintained despite the position and magnitude of external load. The findings of this section of the thesis are in line with Vanezis and Lees (2005), who demonstrated that athletes that performed better in the unloaded countermovement jump used a hip dominant (Hip: 43%, Knee: 29% and Ankle: 28%), as opposed to a knee dominant strategy (Hip: 41%, Knee: 31% and Ankle: 28%). Further, the findings of this section of the thesis also agree with Cushion, Goodwin, and Cleather (2016), who reported that participants maintain their dominant strategy with external load. Thus, populations which demonstrate a knee dominant strategy may respond differently to changes in both the position and magnitude of external load. Further, the maximum dynamic output hypothesis (Jaric & Markovic, 2009) suggests that the effects of external load are population specific, whereas the strength-independent behaviour hypothesis (Jaric & Markovic, 2013) suggests they are not. As such, extrapolating the results of the present section of the thesis to other populations may result in erroneous prescription, and should be done so with caution. Further, despite being appropriately powered based on an *a priori* power analysis, practitioners should also apply a degree of caution when interpreting findings towards the broader population. However, it is important to note that all aforementioned hypotheses are based solely on system CM mechanics, and do not consider the effects on lower limb joint mechanics (Aragón-Vargas & Gross, 1997). Therefore, further investigations regarding the position and magnitude of external load may be required in different populations.

It is important to note that the results presented within the present section of the thesis provide only a cross-sectional, discrete parameter perspective of changes in system CM and lower limb joint mechanics. Marshall and Moran (2015) identified that a number factors commonly associated with performance from a cross-sectional perspective are not associated with actual changes in performance. As such, a reliance on cross-sectional studies alone to identify factors to enhance ability will likely result in sub-optimal improvements in performance. Based on Marshall and Moran (2015) recommendations of aiming to maximise power output at all of the lower limb joints, with a particular emphasis on enhancing hip joint peak power output, it may be prudent to suggest that the findings of the present section of the thesis may be used to facilitate improvements in countermovement jump height. However, randomised controlled trials are still required to establish both efficacy and effectiveness of externally loaded jump training for improving various dynamic athletic tasks, particularly in different populations.

6. The Effects of Training Status and External Loading (Weighted Vest) on Countermovement Jump System Centre of Mass and Lower Limb Joint Mechanics

6.1 Introduction

Section 5 of this thesis demonstrated that in well trained athletes, greater system CM and lower limb joint peak power outputs can be achieved by changing the position of the external load from the shoulders to arms' length by using a hexagonal barbell. It was suggested that although this may be explained by more effective kinematics (e.g. proximal to distal sequencing), it may also be explained by the absolute load being positioned closer to the system CM so that the relative resistance is less, allowing for significantly greater joint angular velocities at all loads investigated. It was also identified that system CM and hip joint peak power output were maximised at 40% of body mass and followed the same quadratic load relationship, whereas the ankle joint and knee joint peak power were produced at other external loads. As such, in order to overload the hip extensors and maximise the transfer of training to unloaded jumping, it is suggested that practitioners prescribe the hexagonal barbell over the straight barbell. Further, it was also suggested that external loads of around 40% of body mass may also be favourable, although it is likely that periodising across loads still remains the best approach.

Although the hexagonal barbell may facilitate a more favourable method of overloading the system CM and hip extensors, the hexagonal barbell itself is not without constraints. The primary constraint observed during section 5 of the thesis was the restricted range of motion due to the position of the external load (e.g. the weight plates made contact with the ground if the athlete flexed too much, influencing the optimisation of the movement). Further, the magnitude of loading cannot be lower than 20 kg, nor can it be applied to other forms of jumping or locomotion. An alternative, pragmatic way of changing the position of the external load is through evenly distributing the external load across the trunk via a weighted vest.

As highlighted in section 2.5 of the thesis, there is a dearth of information regarding the effects of the weighted vest on both the system CM (Driss et al., 2001) and lower limb joint mechanics (Feeney, Stanhope, Kaminski, Machi, & Jaric, 2016) during jumping. Interestingly, it appears that only resistance trained 'strength-power' athletes demonstrate an external load associated increase in system CM power output (Driss et al., 2001). It may be postulated that by increasing the mass of the trunk segment, strength-power trained athletes may be able to effectively overload the hip extensors, and therefore system CM output, as they are able to effectively coordinate the increased external load, whereas recreational or untrained athletes cannot. Therefore, the primary aim of this section of the thesis was to investigate the effects of training status and external (weighted vest) loading on system CM and lower limb joint mechanics during countermovement jumping. This section of the thesis builds on the work reviewed in section 2.5, the work conducted in sections 3, 4, and 5, and fulfils the requirements of aim 4 of the thesis. Within this section of the thesis, it is important to note that the weighted vest is constrained via the magnitude of the external load which can be applied, meaning that only the lower third of the external loading spectrum investigated in sections 3, 4, and 5 could be investigated. However, as recreational and untrained athletes are strength limited, and have previously shown a decline in both lower limb joint and system CM output with increased external load, this constrained external loading spectrum is unlikely to be of practical significance when comparing the effects of training status.

6.2 Method

6.2.1 Participants

Based on an *a priori* power analysis (effect size f = 0.4; α = 0.05; β = 0.80), eight well trained male athletes (mean ± SD: age: 22 ± 2 yrs; height: 1.85 ± 0.05 m; body mass: 87 ± 9 kg) and eight recreational male athletes (mean ± SD: age: 23 ± 3 yrs; height: 1.81 ± 0.08 m; body mass: 78 ± 11 kg) volunteered to participate in this study during their respective off-season training period. All trained participants had at least two years of structured resistance training experience, had a 1-RM back squat above 1.8 x body mass, and were currently participating in a structured strength and conditioning program as part of their respective sport (Rugby Football Union and Football). All recreational athletes had less than six months of structured resistance training experience, had a 1-RM back squat below 1.5 x body mass, and were not currently participating in a structured strength and conditioning program as part of their respective sport (Rugby Football Union and Football). Following a verbal and written explanation of the procedures and potential risks, the participants provided their written, informed consent. This study was approved in accordance with the University of Chichester's Ethical Policy Framework for research involving the use of human participants.

6.2.2 Testing Procedure

Participants were instructed to report to the laboratory in a fully hydrated state, a minimum of two and a maximum of four hours postprandial, and having abstained from caffeine consumption. Further, participants were instructed to refrain from alcohol consumption and vigorous exercise for at least 48 hours before testing. Upon arrival, participants were led through a standardised, progressive dynamic warm-up, which included unloaded submaximal and maximal effort countermovement jumps. Participants then performed unloaded and externally loaded maximal effort countermovement jumps in a randomised, counterbalanced order. The unloaded jumps were performed with a wooden bar of negligible mass (mass: 0.7 kg) across the posterior aspect of the shoulders. The externally loaded jumps were performed using a weighted vest with loads of 10%, 20% and 30% of body mass. All jumps were performed utilising a standard countermovement technique, but no attempts were made to control the depth of the countermovement (Argus et al., 2011). Prior to testing, all participants attended technique sessions, supervised by a certified strength and conditioning specialist, whereby they were deemed technically proficient. Further, all testing sessions were supervised by the same certified strength and conditioning specialist to ensure consistency and participant safety. Two jumps were performed at each condition, with the jump that resulted in the greatest jump height selected for further analysis. One minutes rest was provided between each jump, with up to four minutes rest provided between each condition (Nibali et al., 2013a).

6.2.3 Equipment

Jumps were performed with a separate force platform (Type 9851B, Kistler Instruments Ltd., Hook, UK) under each foot, in a capture area defined by a 10-camera optoelectronic motion capture system (VICON MX T-Series (T40-S), Vicon Motion Systems Ltd., Oxford, UK). Marker position and ground reaction force data were captured at 250 Hz and 1000 Hz, respectively. Prior to testing, retro-reflective markers (12 mm) were placed bilaterally over anatomical landmarks including the iliac crest, posterior and anterior superior iliac spines, greater trochanter, medial and lateral femoral condyles, medial and lateral malleoli, the posterior aspect of the calcaneus, and the heads of the first and the fifth metatarsals. In addition, markers were placed bilaterally on the acromion process, as well as on the sacrum, the sternum, the xiphoid process, and the spinous process of the 7^{th} cervical and 8^{th} thoracic vertebras. Anatomical landmark palpation and marker placement were completed by the lead investigator, using guidelines described by Van Sint Jan and Della Croce (2005). Finally, semi-rigid, thermoplastic clusters mounted with three non-collinear markers were affixed with double-sided tape to the lateral thighs and shanks. Once instrumented, a static calibration trial was collected, whereby the participants assumed the anatomical reference position (Cappozzo et al., 1995).

6.2.4 Data Analysis

Synchronised marker position and ground reaction force signals were processed using Visual 3D software (Version 5; C-Motion, Rockville, MD, USA). Segment masses were defined using standard regression equations (Dempster, 1955). Segment moments of inertia were defined using geometric primitives (Hanavan, 1964). More specifically, the feet, shanks, and thighs were modelled as a frustum of right-circular cones, whereas the trunk and pelvis were modelled as cylinders. Based on a residual analysis and a qualitative evaluation of the data, both marker position and ground reaction force data were filtered using a fourth-order Butterworth filter with a cut-off frequency of 12 Hz (Winter, 2009). Joint angles for the hip, knee and ankle were calculated using an x (flexion/extension), y (abduction/adduction), z (internal/external rotation) Cardan rotation sequence, and were referenced to the coordinate systems embedded in the distal segment. Joint angular velocities were calculated relative to the laboratory global coordinate system by differentiating the rotation matrix using finite differences (Robertson et al., 2014). Net joint moments (expressed in the respective proximal local coordinate systems) were calculated using a Newton–Euler inverse dynamics technique (Robertson et al., 2014). Joint power outputs were calculated as the product of the proximal net joint moment and the segments joint angular velocity. Net joint moments and joints power outputs were scaled to body mass. Finally, system CM mechanics were calculated using the methods described in section 4 of the thesis (Mundy et al., 2016b).

6.2.5 Statistical Analysis

The effects of joint (hip x knee x ankle), external load (unloaded x 10% x 20% x 30% of body mass) and training status (trained x untrained) on peak angular velocity, relative peak net moment, and relative peak power output were analysed using a series of 3x4x2 mixed analyses of variance. The effects of external load (unloaded x 10% x 20% x 30% of body mass) and training status (trained x untrained) on joint angle at joint reversal, relative peak power output, relative average power output, relative average push-off force, push-off phase time and system CM displacement were analysed using a series of 4x2 repeated measures analyses of variance. Normality of distribution was confirmed using Z-scores for skew and kurtosis. The absence of outliers was confirmed with boxplots. Homgeneity of variance was assessed by Levene's test for equality of variances. Greenhouse-Geisser adjustments of the degrees of freedom were applied if the Mauchly test of sphericity was violated. Where appropriate, Bonferroni corrections were made for multiple comparisons. Partial eta squared was used to help interpret the magnitude of interaction and main effects. An a priori alpha level was set to $p < 0.05$. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS Version 20, SPSS Inc., Chicago, IL, USA).

6.3 Results

Mean ± SD normalised system CM mechanics across external loading condition and training statuses during the push-off phase are shown in. Table 16.

6.3.1 Jump Height

The two-way interaction between external load and training status for jump height was not significant ($p = 0.260$, $\eta^2_p = 0.090$). However, the main effect of external load was significant ($p < 0.001$, $\eta^2_p = 0.887$), with post hoc test revealing a significant decline in jump height with external load. Further, the main effect of training status was significant ($p = 0.013$, $\eta^2_p = 0.367$), with post hoc test revealing that strength power trained athletes produced significantly greater jump heights than the recreational athletes.

6.3.2 Relative System Power Output

The two-way interaction between external load and training status for relative system CM peak power output was not significant ($p = 0.951$, $\eta^2_p = 0.000$). However, the main effect of training status was significant ($p = 0.003$, $\eta^2_p = 0.482$), with post hoc testing revealing that strength power trained athletes produced significantly greater relative system CM peak power output than the recreational athletes.

The two-way interaction between external load and training status for relative system CM average power output was not significant ($p = 0.635$, $\eta^2_p = 0.039$). However, the main effect of external load was significant ($p < 0.001$, $\eta^2_p = 0.336$), with post hoc testing revealing that relative system CM average power output was significantly greater during the unloaded condition than the 20% and 30% of body mass conditions.

6.3.3 Underpinning Force, Temporal and Spatial Components

The two-way interaction between external load and training status for relative system CM average force was not significant ($p = 0.810$, $\eta^2_p = 0.004$). However, the main effect of external load was significant ($p < 0.001$, $\eta^2_p = 0.839$), with post hoc testing revealing that relative system CM average force increased significantly with external load. The two-way interaction between external load and training status for push-off phase duration was not significant ($p = 0.827$, $\eta^2_p = 0.021$). However, the main effect of external load was significant ($p < 0.001$, $\eta^2_p = 0.713$), with post hoc testing revealing a significant increase in push-off phase duration with external load. The two-way interaction between external load and training status for system CM depth was not significant ($p = 0.644$, $\eta^2_p = 0.039$), nor were the main effects of external load ($p = 0.578$, $\eta^2_p = 0.045$) or training status ($p = 0.913$, $\eta^2_p = 0.001$).

Table 16. Mean ± SD normalised system CM mechanics across external loading conditions and training statuses during the push-off phase.

		Load (% of BM)			
Variable	Status	Unloaded	10%	20%	30%
Jump Height	Trained	0.35 ± 0.04	0.30 ± 0.04	0.26 ± 0.04	0.24 ± 0.04
(m)	Recreational	0.29 ± 0.05	0.24 ± 0.02	0.22 ± 0.02	0.19 ± 0.02
Peak Power Output	Trained	51.92 ± 4.79	52.60 ± 6.09	51.18 ± 6.38	51.40 ± 6.24
($W.kg^{-1}$)	Recreational	43.90 ± 4.64	43.01 ± 2.59	43.41 ± 3.59	42.84 ± 3.59
Average Power Output	Trained	26.05 ± 3.22	24.43 ± 3.09	23.79 ± 3.50	23.58 ± 3.73
($W.kg^{-1}$)	Recreational	23.06 ± 3.16	22.27 ± 2.63	21.82 ± 3.15	21.65 ± 3.31
Average Force	Trained	18.27 ± 1.31	18.74 ± 1.08	19.26 ± 1.19	20.03 ± 1.44
($N.kg^{-1}$)	Recreational	17.43 ± 1.31	17.86 ± 1.15	18.46 ± 1.40	19.28 ± 1.41
Push-Off Duration	Trained	0.315 ± 0.045	0.345 ± 0.030	0.369 ± 0.042	0.394 ± 0.056
(s)	Recreational	0.318 ± 0.051	0.352 ± 0.054	0.381 ± 0.069	0.392 ± 0.070
CM Depth	Trained	-0.38 ± 0.07	-0.37 ± 0.04	-0.38 ± 0.3	-0.37 ± 0.2
(m)	Recreational	-0.37 ± 0.07	-0.39 ± 0.07	-0.39 ± 0.08	-0.37 ± 0.07

BM: body mass; CM: centre of mass.

6.3.4 Joint Angle at Joint Reversal

Mean ± SD hip, knee and ankle joint angles at joint reversal across external loading condition and training statuses are shown in Table 17. The two-way interaction between external load and training status for hip joint angle at joint reversal was not significant ($p = 0.312$, $\eta^2_p = 0.073$). However, the main effect of external load was significant ($p = 0.003$, $\eta^2_p = 0.480$), with post hoc testing revealing that hip joint angle at joint reversal during the unloaded condition was significantly greater at 30% of body mass. Conversely, the interaction ($p = 0.240$, $\eta^2_p = 0.094$) and main effects of external load ($p = 0.259$, $\eta^2_p = 0.090$) and training status ($p = 0.531$, $\eta^2_p = 0.029$) on knee joint angle were not significant. Further, the interaction ($p = 0.237$, $\eta^2_p = 0.098$) and main effects of external load ($p = 0.668$, $\eta^2_p = 0.013$) and training status ($p = 0.220$, $\eta^2_p = 0.105$) on ankle joint angle were not significant.

Table 17. Mean ± SD hip, knee and ankle joint angles (°) at joint reversal across external loading conditions and training statuses.

Status	Load (% of BM)	Joint		
		Hip	Knee	Ankle
Trained	Unloaded	101 ± 14	87 ± 12	20 ± 5
	10%	98 ± 8	83 ± 10	19 ± 6
	20%	92 ± 15	79 ± 10	19 ± 5
	30%	89 ± 20	77 ± 11	19 ± 4
Recreational	Unloaded	99 ± 8	89 ± 14	21 ± 5
	10%	95 ± 7	91 ± 9	22 ± 5
	20%	95 ± 8	90 ± 11	22 ± 5
	30%	91 ± 9	90 ± 8	23 ± 5

BM: body mass.

6.3.5 Joint Peak Angular Velocity

Mean ± SD hip, knee and ankle joint peak angular velocities across external loading conditions and training statuses during the push-off phase are shown in Table 18. The three-way interaction between joint, external load and training status for joint angular velocity was not significant ($p = 0.850$, $ŋ^2_p = 0.021$). The two-way interaction between joint and external load for joint angular velocity was significant ($p < 0.001$, $ŋ^2_p = 0.176$), whereas the two-way interactions between external load and training status ($p = 0.112$, $ŋ^2_p = 0.046$) and joint and training status ($p = 0.750$, $ŋ^2_p = 0.014$) were not.

The effects of training status could be explained independently of load, but not joint Post hoc testing revealed that at all four external loads, ankle and knee angular velocities were significantly greater than hip angular velocities. Further, post hoc testing also revealed that at all four external loads, strength power trained athletes angular velocities were significantly greater than recreationally trained angular velocities. The effects of external load could be explained independently of joint, but not training status. Post hoc testing revealed that the effects of external load on the hip ($p < 0.001$, $\eta^2_p = 0.705$), knee ($p < 0.001$, $\eta^2_p = 0.679$), and ankle ($p = 0.015$, $\eta^2_p = 0.218$) joint angular velocities were significant. Further, post hoc testing revealed that the strength power trained athletes produced significantly greater hip joint angular velocities ($p = 0.034$, $\eta^2_p = 0.283$), but not knee ($p = 0.074$, $\eta^2_p = 0.210$) or ankle ($p = 0.312$, $\eta^2_p = 0.073$) joint angular velocities.

Table 18. Mean ± SD hip, knee and ankle joint peak angular velocity (ω) across external loading conditions and training statuses.

Status	Load (% of BM)	Joint		
		Hip	Knee	Ankle
Trained	Unloaded	621 ± 178	870 ± 104	764 ± 122
	10%	545 ± 116	825 ± 83	735 ± 117
	20%	512 ± 86	771 ± 104	726 ± 92
	30%	482 ± 101	739 ± 126	704 ± 74
Recreational	Unloaded	514 ± 69	766 ± 65	706 ±111
	10%	457 ± 40	736 ± 41	680 ± 84
	20%	430 ± 46	725 ± 39	678 ± 85
	30%	396 ± 49	679 ± 51	676 ± 62

BM: body mass.

6.3.6 Joint Peak Net Moment

Mean ± SD normalised hip, knee and ankle joint peak net moments across external loading conditions and training statuses during the push-off phase are shown in Table 19. The three-way interaction between joint, external load and training status for joint net moment was not significant ($p = 0.458$, $\eta^2_p = 0.044$). Further, the two-way interaction between joint and external load ($p = 0.133$, $\eta^2_p = 0.074$), external load and training status ($p = 0.640$, $\eta^2_p = 0.013$), and joint and training status ($p = 0.194$, $\eta^2_p = 0.075$) for joint net moments were not significant. Moreover, the main effects of external load ($p = 0.422$, $\eta^2_p = 0.022$) and training status ($p = 0.710$, $\eta^2_p = 0.003$) for joint net moments were not significant. However, the main effect of joint was significant ($p < 0.001$, $\eta^2_p = 0.456$), with post hoc testing revealing that the hip joint moment was significantly greater than knee and ankle joint moments.

Table 19. Mean ± SD normalised hip, knee and ankle joint peak net moment ($Nm.kg^{-1}$) across external loading conditions and training statuses.

Status	Load (% of BM)	Joint		
		Hip	Knee	Ankle
Trained	Unloaded	2.03 ± 0.25	1.47 ± 0.39	1.51 ± 0.11
	10%	2.06 ± 0.23	1.35 ± 0.32	1.66 ± 0.13
	20%	1.90 ± 0.40	1.38 ± 0.28	1.73 ± 0.13
	30%	1.92 ± 0.39	1.42 ± 0.48	1.74 ± 0.16
Recreational	Unloaded	1.88 ± 0.31	1.55 ± 0.43	1.50 ± 0.15
	10%	1.96 ± 0.24	1.60 ± 0.31	1.53 ± 0.13
	20%	2.01 ± 0.23	1.54 ± 0.34	1.62 ± 0.15
	30%	1.92 ± 0.28	1.72 ± 0.24	1.64 ± 0.16

BM: body mass.

6.3.7 Joint Peak Power Output

Mean ± SD normalised hip, knee and ankle joint peak power outputs across external loading conditions and training statuses during the push-off phase are shown in Table 20. The three-way interaction between joint, external load and training status for joint power output was not significant ($p = 0.897$, $\eta^2_p = 0.017$). Further, the two-way interaction between external load and training status for joint power output was not significant ($p = 0.300$, $\eta^2_p = 0.029$). However, the two-way interactions between joint and external load

($p < 0.001$, $\eta^2_p = 0.221$) and joint and training status were significant ($p < 0.001$, $\eta^2_p = 0.279$). Post hoc analysis revealed that ankle and hip joint power outputs were greater than knee joint power outputs at all loads investigated, but the ankle joint power outputs were also greater than hip joint power outputs at 20% and 30% of body mass. Further, post hoc analysis also revealed that the strength power trained athletes produced significantly greater hip joint power outputs at all external loads investigated, but not ankle or knee joint power outputs.

Table 20. Mean ± SD normalised hip, knee and ankle joint peak power output ($W.kg^{-1}$) across external loading conditions and training statuses.

Status	Load (% of BM)	Joint		
		Hip	Knee	Ankle
Trained	Unloaded	11.77 ± 2.24	4.37 ± 1.58	10.26 ± 1.73
	10%	10.81 ± 1.66	3.76 ± 1.67	10.59 ± 1.92
	20%	10.44 ± 1.94	3.65 ± 1.83	10.57 ± 1.73
	30%	9.07 ± 1.60	4.67 ± 2.19	10.38 ± 1.74
Recreational	Unloaded	7.77 ± 1.81	4.00 ± 1.63	10.75 ± 1.87
	10%	7.18 ± 0.94	3.80 ± 1.46	10.45 ± 1.91
	20%	7.26 ± 1.27	3.66 ± 1.24	10.94 ± 1.71
	30%	6.46 ± 1.06	4.88 ± 1.76	11.12 ± 1.65

BM: body mass.

6.4 Discussion

Previously, it has been demonstrated that strength-power trained athletes produce greater power outputs than sedentary controls during jumping tasks (Driss et al., 2001). Further, it has also been demonstrated that strength-power trained athletes maximise system CM power output during externally loaded conditions, whereas sedentary controls maximise power output during unloaded conditions (Driss et al., 2001). As such, it has previously been postulated that that the effects of the magnitude of the external load depend on the strength of the individual, as well as training history (e.g Maximum Dynamic Output hypothesis). Therefore, the primary aim of this section of the thesis was to investigate the effects of training status and external (weighted vest) loading on system CM and lower limb joint mechanics during countermovement jumping.

Within this section of the thesis, strength-power trained athletes produced significantly greater jump heights and system CM peak power outputs than the recreationally trained athletes, but not significantly greater system CM average power outputs. The differences observed, or the lack of differences thereof, could not be explained at the system level as there were no statistically significant differences between training statuses in relative system CM average force, push-off phase duration, or system CM displacement. As such, this demonstrates the complex interaction of the force, temporal and spatial components underpinning the effects of external loading on jumping system CM mechanics. Further, both strength-power trained and recreationally trained athletes maximised both peak and average system CM power output during the unloaded condition, with the unloaded condition producing significantly greater system CM average power outputs than the 20% and 30% of body mass conditions.

The findings of this section of the thesis contradict those of Driss et al. (2001) who reported that both system CM peak and average power outputs were significantly greater in the strength-power trained athletes. Further, Driss et al. (2001) reported that system CM average power output was significantly greater during externally loaded conditions, whereas system CM peak power output was not. However, Driss et al. (2001) compared elite jumping athletes' performance in concentric only jumps to sedentary controls, and prescribed absolute external loads as opposed to relative to body mass. As such, a logical explanation for these contradictions is that although a difference in strength level existed, the difference in strength level was either not of a great enough magnitude, or that the strength-power trained group were also unable to rapidly optimise control under the given external loading conditions (Bobbert, 2014). This may demonstrate a limitation of using strength level as a discriminator in training status.

Due to the limitations of system CM mechanical data identified in sections 4 (Mundy et al., 2016b) and 5 of the thesis, it may be prudent to consider the effects of training status and external load on lower limb joint mechanics. Within this section of the thesis, a particularly novel contribution to the body of knowledge was that regardless of the magnitude of the external load, strength-power trained athletes produced significantly greater hip joint peak power outputs than their recreationally trained counterparts. Greater peak hip joint power output may be due to fibre type composition, as well as coordination strategies (Aragón-Vargas & Gross, 1997). As there is little we can do to address a natural fibre type predisposition, this highlights the importance of training modalities that improve the hip muscles ability to combine high joint peak net moments with relatively high joint peak angular velocities (Aragón-Vargas & Gross, 1997). As such, the findings of this section of the thesis support the hypothesis that practitioners should consider prescribing both exercises, as well as the magnitude of external loading, that maximise hip joint peak power output.

Interestingly, both strength-power trained and recreationally trained athletes utilised a hip dominant jumping strategy (hip joint was significantly greater than knee joint), of which they maintained regardless of the magnitude of the external load. These findings are in line with the findings of section 5 of the thesis, which demonstrated that regardless of the position or magnitude of the external load, strength-power trained athletes maintained their jumping strategy. However, based on the work of Vanezis and Lees (2005), it is perhaps surprising that the recreational athletes produced a hip dominant, as opposed to knee dominant jumping strategy. As alluded to earlier within this section of the thesis, perhaps the difference in strength level was either not of a great enough magnitude, which again may question the use of strength level to determine training status, particularly in jumping tasks which require optimisation (Bobbert, 2014).

A surprising contribution of this section of the thesis was that there were no significant differences in joint net peak moments between strength-power trained and recreationally trained athletes. As such, the differences observed in hip joint peak power output may be explained by the ability of strength-power trained athletes to produce significantly greater angular velocities, regardless of the magnitude of the external load. As there were no differences in joint angles at joint reversal, these differences may be due to differences in fibre type composition, as well as coordination strategies, between the strength-power trained athletes and the recreational controls (Aragón-Vargas & Gross, 1997). It is logical to suggest that better coordination strategies would allow the hip joint muscles to act at a more advantages range of the force-velocity curve (Aragón-Vargas & Gross, 1997). For example, a lower muscle-fibre shortening velocity at the same joint angular velocity would allow the muscle to generate greater force (Aragón-Vargas & Gross, 1997; Bobbert et al., 1986). This highlights the importance of training modalities that improve the muscles ability to combine high joint peak net moments with relatively high joint peak angular velocities (Aragón-Vargas & Gross, 1997).

From a practical perspective, it is interesting that there were no effects of the magnitude of external load on hip joint peak net moments or peak power outputs. However, these findings were in line with section 5 of the thesis, whereby it was demonstrated that hip joint peak power output was not significantly affected by the magnitude of the external load. Further, these findings are in line with those of Jandacka et al. (2014), who reported that the hip joint power outputs are constant with external load in concentric only jumps. Conversely, these findings contradict those of Feeney et al. (2016), who reported an external load associated increase in knee joint power output during the countermovement jump, whereas as the contribution of the hip joint and ankle joint power output revealed no significant trend. This may be explained by the use of the arm swing in a low training status sample group (recreationally active, non-athletes). Further, these findings also contradict the mechanical changes observed in other exercises, such as the weightlifting clean (Kipp et al., 2011), although this may be explained by the magnitude of the external load, as well as the position of the external load. As such, comparisons of externally loaded jumping to other resistance training exercises, as well as other forms of locomotion, may help further elucidate the mechanical demands impose on both the system and lower limb joint mechanics, and help make steps towards optimising the physical preparation of athletes.

Within this section of the thesis, the primary novel contribution to the body of knowledge was that regardless of the magnitude of the external load, strength-power trained athletes produced significantly greater hip joint peak power outputs than their recreationally trained counterparts. This was explained by the strength-power trained athletes' ability to produce significantly greater angular velocities, which in turn was likely underpinned by differences in fibre type composition, as well as coordination strategies. This has considerable implications for the physical preparation of athletes, as it supports the hypothesis that hip joint mechanics underpin successful performance within jumping tasks regardless of the magnitude of external load. As such practitioners should perhaps focusing on prescribing exercises, as well as the magnitude of external load based on hip joint mechanics output as this may maximise the transfer of training effect. However, within this section of the thesis, there was no effect of the magnitude of external load on lower limb joint power outputs during weighted vest jumping, and as such further investigation is required.

7. General Discussion

The primary aim of this thesis was to investigate the effects of changing the position of the external load and training status on system CM and lower limb joint mechanics during countermovement jumping, with a particular emphasis on power output. Although considerable research has been conducted investigating system CM power output, section 2 of the thesis highlighted a number of methodological issues, as well as a common omission of key mechanical theory, with limited research investigating lower limb joint output. As such, this section of the thesis demonstrates how addressing the aforementioned aims through the implementation of four separate, progressive, and thematically related studies has moved the scientific field forward, as well as provides a translation message for practitioners.

7.1 Methodological Concerns

Section 2.2 of the thesis highlighted that two perceived criterion ('gold standard') methods for measuring power output existed within the strength and conditioning literature: the force platform method and the combined method. Further, section 2.3 revealed that the majority of studies had used the combined method to investigate the effects of applying external loads on human jumping mechanics. As it had previously been suggested that the combined method was based on erroneous mechanical principles (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008), this raised serious concerns from a practitioner's perspective when interpreting the strength and conditioning literature. Due to the contradictory narratives surrounding the validity of the combined method, it was imperative that section 3 (Mundy et al., 2016a) of the thesis established the agreement between the force platform method and the combined method. Establishing agreement identified whether or not the methods were interchangeable, regardless of which method was the perceived criterion within the strength and conditioning literature. Further, it was also imperative that section 3 of the thesis consequently established a true criterion method by interpreting any differences in agreement within a correct theoretical, Newtonian framework, as this had previously been absent within the strength and conditioning literature, and was therefore crucial to both the development of the thesis and to the overall body of knowledge.

The results of section 3 (Mundy et al., 2016a) of the thesis confirmed that the methods were not interchangeable within practice, and that the velocity of the barbell was not equivalent to the velocity of the system CM (Hori et al., 2007; Lake et al., 2012b; Li et al., 2008), which is a key assumption underpinning the combined method (Cormie et al., 2007a; Cormie et al., 2007b; Dugan et al., 2004). As such, a large portion of the current body of knowledge is confounded by fundamental methodological issues. Going forward, practitioners must interpret any study using the combined method with caution, particularly where comparisons are made between external loads. Furthermore, as the combined method artificially inflated power output during lighter external loading conditions, it is likely that the effects of external loading on power output during countermovement jumping are not fully understood, and perhaps even overemphasised. As such, practitioners must question whether or not the optimal load is produced during unloaded conditions or if this is simply an artefact of the common use of the combined method.

7.2 The Optimal Load

When using a theoretically valid method, it was identified in section 4 (Mundy et al., 2016b) of the thesis that average power output was maximised during the unloaded condition, with moderate to large decreases observed as barbell load increased. From a mechanistic perspective, decreases observed in average power output were likely explained by the increased time required to perform mechanical work, as well as the inability to apply the greater magnitude of force required to perform greater mechanical work over an anatomically constrained push-off phase. This load associated decline in average power output was also observed in both sections 5 and 6 of the thesis, regardless of the position of the external load or the training status of the participants. Therefore, at the system level, this may support the argument that due to the evolutionary design of the locomotor system, the external load that maximises average power output during countermovement jumping is the individual's own body mass, regardless of the strength of the lower limb muscles (i.e., strength-independent behaviour) (Jaric & Markovic, 2013).

This strength-independent behaviour hypothesis was also supported in sections 4 (Mundy et al., 2016b) and 6 of the thesis when investigating peak power output; however, only moderate decreases were observed. A particularly novel contribution of section 4 (Mundy et al., 2016b) of the thesis was that it identified that peak power output was confounded by intra-individual variation, whereas average power output was not. These findings support the assertions that if practitioners are interested in extrapolating the effects of external loading on power output and the optimal load from group level data, it may be prudent to focus on the external load that maximises average power output as opposed to peak power output. Not only can this clearly be observed within the intra-individual variation plots presented in section 4 (Mundy et al., 2016b) of the thesis, but when the two external loads which produced the highest peak power output were compared at an intra-individual level, the differences were largely within the coefficient of variation, whereas for average power output they were not. Interestingly, in section 5 of the thesis, system CM peak power output was maximised at 40% of body mass when using the hexagonal barbell. However, the 40% of body mass condition was not significantly or meaningfully greater than other external loading conditions. Therefore, as with average power output, when an optimal load is prescribed based on peak power output, the effects may be overstated, and are unlikely to be practically meaningful.

For practitioners, this raises a philosophical question regarding the prescription of the optimal load based on system level data during the physical preparation of athletes. If the locomotor system is designed to maximise power output during unloaded conditions, then identifying and prescribing the optimal load may be erroneous as unloaded jumping will unlikely provide a progressive overload sufficient for adaptation. As such, based solely on system CM mechanics, it is suggested that practitioners periodise across a spectrum of external loads encountered within the athletes sport to improve both the force and velocity capabilities of the athlete as part of a comprehensive physical preparation programme. However, it is important to note that despite the poor prescriptive information provided, profiling and monitoring system CM mechanics over various external loads may still be meaningful, as section 6 supported the contemporary notion that system CM power output distinguishes between levels of ability.

Although the previously discussed system CM mechanics data has provided important global information for practitioners, it has not necessarily provided information about lower limb joint mechanics (Aragón-Vargas & Gross, 1997; Jandacka et al., 2014; Kipp et al., 2011; Moir et al., 2012). As specificity of training is a function of the task-inherent biomechanics, not simply the external movement characteristics, it was also important to consider how changing the position and magnitude of external load effected lower limb joint mechanics. Such information may be used to help practitioners to provide greater descriptive information to be considered during the physical preparation of athletes (Kipp et al., 2011).

In section 5 of the thesis, lower limb joint peak power outputs when using the hexagonal barbell were significantly greater than those produced using the straight barbell at every load except 20% of body mass, where only hip joint and ankle joint peak power outputs were significantly greater. Further, hip joint peak power output was maximised at 40% of body mass when using the hexagonal barbell, whereas when using the straight barbell hip joint peak power output declined with external load. Although this may be explained by more effective kinematics (e.g. proximal to distal sequencing, decreased relative resistance, greater trunk inclination etc), it may also be explained by the absolute load being positioned closer to the system CM so that the relative resistance is less, allowing for significantly greater angular velocities at every external load investigated. However, it is important to note that although hip joint peak power output in the hexagonal barbell was maximised at 40% of body mass, this was not significantly or meaningfully greater than other external loading conditions, which provides further support against the prescriptive ability of the optimal load. Therefore, in order to maximise the transfer of externally loaded jumping to unloaded countermovement jumping, practitioners should not only periodise across a spectrum of external loads, but they should also change the position of the external load to arm's length using a hexagonal barbell to overload the hip joint extensors.

A particularly novel contribution to the body of knowledge was that changing the position and magnitude of the external load to overload the hip joint extensors was also further supported in section 6 of the thesis, which identified that regardless of the magnitude of the external load, strength-power trained athletes produced significantly greater hip joint peak power outputs than their recreationally trained counterparts. This was explained by the strength-power trained athletes' ability to produce significantly greater angular velocities, which in turn was likely underpinned by differences in fibre type composition, as well as coordination strategies. However, regardless of training status, there was no effect of the magnitude of external load on lower limb joint peak power outputs, further supporting the notion that the optimal load has limited prescriptive ability.

7.3 Limitations

A key limitation of this thesis was the focus on the push-off phase. It is acknowledged that a pre-stretch (eccentric breaking phase) may enhance the maximum work output that muscles can produce during the push-off phase (Schenau et al., 1997a, 1997b). As such, the position and the magnitude of the external load may influence the time available for force development, storage, and reutilization of elastic energy, potentiation of the contractile machinery, and the associated reflexes (Schenau et al., 1997a, 1997b). Thus, manipulating the pre-stretch is likely an important consideration during the physical preparation of athletes, and must be considered when prescribing externally loaded jumping. However, to the author's knowledge, there is a dearth of information available, and as such future work should aim to establish the effects of the position and magnitude of loading on the pre-stretch, with consideration of both the system CM and lower limb joint mechanics.

A further limitation of this thesis was the focus on countermovement jumping. For example, previous comparisons to weightlifting derivatives (Cushion et al., 2016; MacKenzie, Lavers, & Wallace, 2014) have revealed important information regarding the specificity of exercise prescription. However, a more holistic appreciation of the mechanical changes, including muscle activation and muscle-tendon unit mechanical properties, may help optimise exercise and external load prescription during the physical preparation of athletes. For example, Bobbert and van Ingen Schenau (1988) and Bobbert and Van Soest (1994) previously argued that jumping performance depends largely on the precise timing of muscle action, with ideal timings differing from one athlete to another depending on strength (Aragón-Vargas & Gross, 1997). As such, it is the author's opinion that practitioners must be cognisant of the total mechanical changes, as this ensures the desired overload is prescribed. This is of particular importance during the rehabilitation of athletes, as unknowingly overloading joints, muscles, or tendons may place athletes at risk. Therefore, future work should aim to establish and compare the effects of the position and magnitude of loading to other commonly prescribed exercises, but provide a more holistic overview of the mechanical changes.

A key consideration going forward, which is currently a limitation of the thesis, as well as the present body of knowledge, is appropriate consideration of key spatiotemporal information when investigating the effects of external load on jumping mechanics. Within this thesis, data sampled from smooth one dimensional fields were analysed discretely by extracting zero dimensional summary metrics from the push-off phase before conducting classic hypothesis testing (Pataky, 2010; Pataky, Vanrenterghem, & Robinson, 2016). Although the zero dimensional summary metrics were identified a priori as the only metrics of empirical interest, which may reduce regional focus bias and other potential sources of false positives (Pataky, Robinson, & Vanrenterghem, 2013; Pataky et al., 2016), they still offer a somewhat incomplete impression of the field wide changes associated with the effects of external load on jumping mechanics (Pataky, 2010). Previously, several techniques have been proposed which may be relevant; however, a comprehensive discussion of these techniques is outside the scope of this thesis As such, readers are referred to the appendix of Pataky, Vanrenterghem, and Robinson (2015). Going forward, practitioners should consider using these techniques to consider the entire temporal domain, as this may allow a more complete impression of the field wide changes (e.g. when do key aspects of technique occur/change) associated with the effects of external load on jumping mechanics.

Finally, despite the novel contributions made to the body of knowledge by this thesis, and those made by cross-sectional investigations in general, changes in athletic performance must be established through randomised, controlled trials. Particular emphasis should be placed on novel pre-to-post analyses of mechanical changes interpreted cognisant of the key underpinning mechanical theory, investigating how manipulating the position and magnitude of external loading changes athletic performance.

7.4 Conclusion

In conclusion, this thesis has not only made significant steps towards providing a standardised method of measuring power output during unloaded and externally loaded jumping, but it has also offered a revealing insight into the effects of training status, as well as the effects of changing the position and magnitude of the external load on system CM and lower limb joint mechanics during countermovement jumping. It is the author's recommendation that practitioners should measure power output during unloaded and externally loaded jumping using the force platform method, and that practitioners should interpret the previous literature cognisant of the fatal limitations of the combined method. Further, as hip joint peak power output distinguished between levels of performance, it is recommended that practitioners prescribe hexagonal barbell jumping to overload the hip joint extensors. However, it is important to reiterate that as the optimal load appeared to be insignificant, practitioners should periodise across a spectrum of external loads, particularly those encountered within the athlete's sport to improve both the force and velocity capabilities of the athlete as part of a comprehensive physical preparation programme.

Appendix 1: Ethical Approval

Research and Employer Engagement Office
The University of Chichester
Bishop Otter Campus
Chichester
PO19 6PE

To whom it may concern,

Re. Ethical Review Application – ***Mechanisms underpinning differences in the load that maximises mechanical power output*** **– Peter Mundy**

This is to confirm that an Ethical Review Application for the above was received and approved as a Category A application in line with the University of Chichester Ethical Policy Framework on 2 August 2012.

Kind regards

A. Walsh

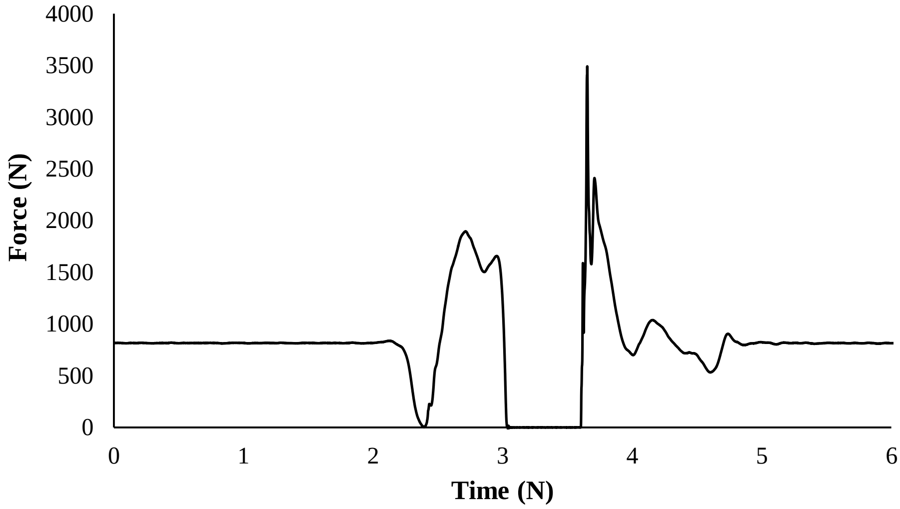
Dr Antony Walsh
Postgraduate Research Coordinator
Research and Employer Engagement Office (REEO)

a.walsh@chi.ac.uk

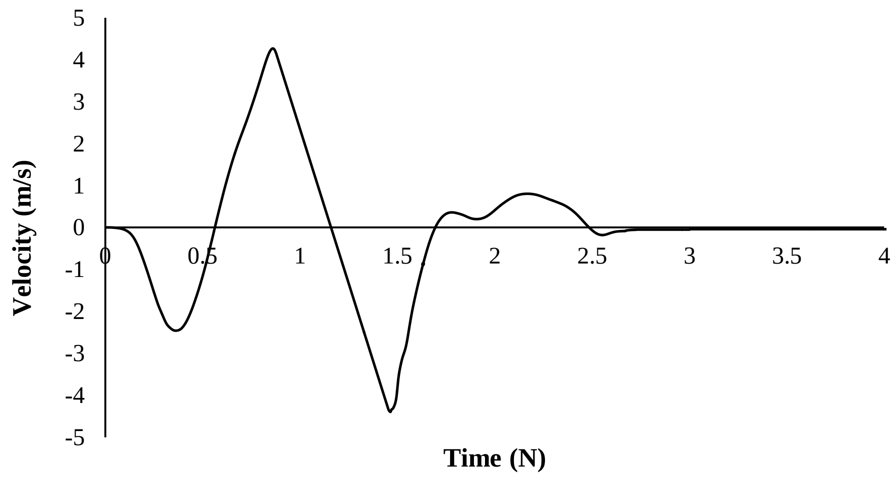
Appendix 2: Additional Precautions

Additional precautions taken when measuring countermovement jump performance by means of a force platform.

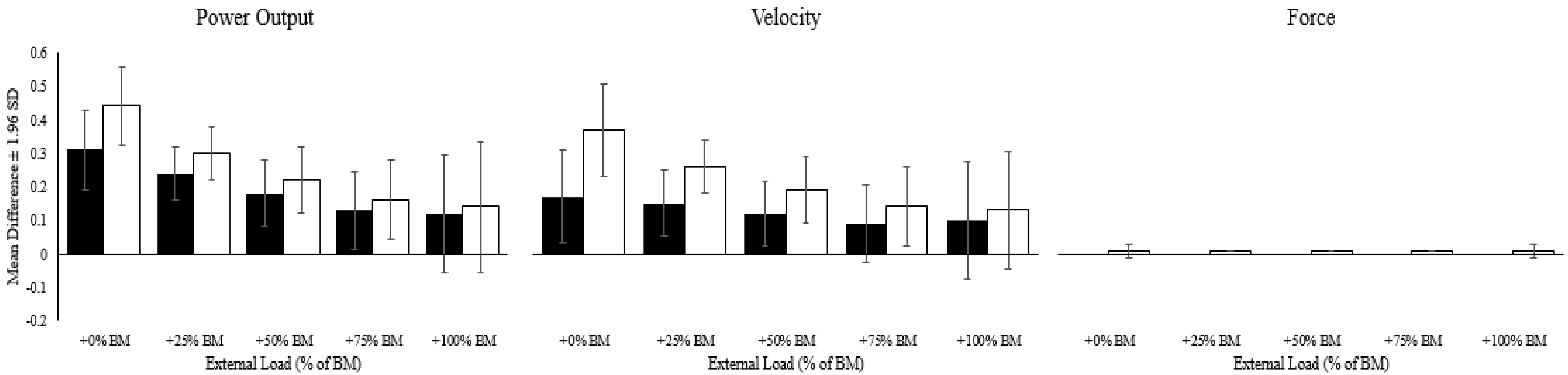
- Force platforms were manufacturer calibrated.
- Trials were screened for a minimum of a 1 s quiet standing period.



- Trials were screened for drift, with velocity at the end of the trial confirmed as zero.



Appendix 3: Overview of 95% Limits of Agreement



Overview of 95% limits of agreement between the force platform method and the combined method. Black shaded boxes represent peak values, whereas white shaded boxes represent average values. Bias is shown as the height of the blocks, whereas 95% limits of agreement are shown by the vertical bars.

List of References

Altman, D. G., & Bland, J. M. (1983). Measurement in medicine: The analysis of method comparison studies. *The Statistician, 32*, 307-317.

Aragón-Vargas, L. F., & Gross, M. M. (1997). Kinesiological factors in vertical jump performance: Differences among individuals. *Journal of Applied Biomechanics, 13*(1), 24-44.

Argus, C. K., Gill, N. D., & Keogh, J. W. (2012). Characterization of the differences in strength and power between different levels of competition in rugby union athletes. *Journal of Strength and Conditioning Research, 26*(10), 2698-2704.

Argus, C. K., Gill, N. D., Keogh, J. W., & Hopkins, W. G. (2011). Assessing lower-body peak power in elite rugby-union players. *Journal of Strength and Conditioning Research, 25*(6), 1616-1621.

Baker, D. (2001). Acute and long-term power responses to power training: Observations on the training of an elite power athlete. *Strength & Conditioning Journal, 23*(1), 47-56.

Baker, D. (2002). Differences in strength and power among junior-high, senior-high, college-aged, and elite professional rugby league players. *Journal of Strength and Conditioning Research, 16*(4), 581-585.

Baker, D., & Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *Journal of Strength and Conditioning Research, 13*(3), 230-235.

Baker, D., Nance, S., & Moore, M. (2001). The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *Journal of Strength and Conditioning Research, 15*(1), 92-97.

Bevan, H. R., Bunce, P. J., Owen, N. J., Bennett, M. A., Cook, C. J., Cunningham, D. J., . . . Kilduff, L. P. (2010). Optimal loading for the development of peak power output in professional rugby players. *Journal of Strength and Conditioning Research, 24*(1), 43-47.

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet, 1*(8476), 307-310.

Bland, J. M., & Altman, D. G. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research, 8*(2), 135-160.

Bobbert, M. F. (2014). Effect of unloading and loading on power in simulated countermovement and squat jumps. *Medicine & Science in Sports & Exercise, 46*(6), 1176-1184.

Bobbert, M. F., Gerritsen, K. G., Litjens, M. C., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? *Medicine & Science in Sports & Exercise, 28*(11), 1402-1412.

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1986). A model of the human triceps surae muscle-tendon complex applied to jumping. *Journal of Biomechanics, 19*(11), 887-898.

Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics, 21*(3), 249-262.

Bobbert, M. F., & Van Soest, A. J. (1994). Effects of muscle strengthening on vertical jump height: A simulation study. *Medicine & Science in Sports & Exercise, 26*(8), 1012-1020.

Bosco, C., Luhtanen, P., & Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology, 50*(2), 273-282.

Bourque, S., & Sleivert, G. (2003). Determinants of load at peak power during maximal effort squat jumps in endurance and power trained athletes. University of New Brunswick, Fredericton.

Caia, J., Doyle, T. L., & Benson, A. C. (2013). A cross-sectional lower-body power profile of elite and subelite australian football players. *Journal of Strength and Conditioning Research, 27*(10), 2836-2841.

Cappozzo, A., Catani, F., Croce, U. D., & Leardini, A. (1995). Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clinical Biomechanics, 10*(4), 171-178.

Cavagna, G. A. (1975). Force platforms as ergometers. *Journal of Applied Physiology, 39*(1), 174-179.

Cavagna, G. A., Zamboni, A., Faraggiana, T., & Margaria, R. (1972). Jumping on the moon: Power output at different gravity values. *Aerospace Medicine, 43*(4), 408-414.

Chiu, L., Schilling, B., Fry, A., & Weiss, L. (2004). Measurement of resistance exercise force expression. *Journal of Applied Biomechanics, 20* (2), 204-212.

Chiu, L. Z., & Salem, G. J. (2010). Pelvic kinematic method for determining vertical jump height. *Journal of Applied Biomechanics, 26*(4), 508-511.

Chiu, L. Z., Schilling, B. K., Fry, A. C., & Salem, G. J. (2008). The influence of deformation on barbell mechanics during the clean pull. *Sports Biomechanics, 7*(2), 260-273.

Cormie, P., Deane, R., & McBride, J. M. (2007a). Methodological concerns for determining power output in the jump squat. *Journal of Strength and Conditioning Research, 21*(2), 424-430.

Cormie, P., & Flanagan, S. P. (2008). Does an optimal load exist for power training? *Strength & Conditioning Journal, 30*(2), 67-69.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2007b). Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics, 23*(2), 103-118.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics, 24*(2), 112-120.

Cormie, P., McCaulley, G. O., & McBride, J. M. (2007c). Power versus strength-power jump squat training: Influence on the load-power relationship. *Medicine and Science in Sports and Exercise, 39*(6), 996-1003.

Cormie, P., McCaulley, G. O., Triplett, N. T., & McBride, J. M. (2007d). Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports and Exercise, 39*(2), 340-349.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise, 42*(8), 1582-1598.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine and Science in Sports and Exercise, 42*(8), 1566-1581.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011a). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports Medicine, 41*(1), 17-38.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011b). Developing maximal neuromuscular power: Part 2 - training considerations for improving maximal power production. *Sports Medicine, 41*(2), 125-146.

Crewther, B., Cronin, J., & Keogh, J. (2005). Possible stimuli for strength and power adaptation: Acute mechanical responses. *Sports Medicine, 35*(11), 967-989.

Crewther, B. T., Kilduff, L. P., Cunningham, D. J., Cook, C., Owen, N., & Yang, G. Z. (2011). Validating two systems for estimating force and power. *International Journal of Sports Medicine, 32*(04), 254-258.

Cronin, J., & Sleivert, G. (2005). Challenges in understanding the influence of maximal power training on improving athletic performance. *Sports Medicine, 35*(3), 213-234.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of Strength and Conditioning Research, 19*(2), 349-357.

Cronin, J. B., Hing, R. D., & McNair, P. J. (2004). Reliability and validity of a linear position transducer for measuring jump performance. *Journal of Strength and Conditioning Research, 18*(3), 590-593.

Cunningham, D. J., West, D. J., Owen, N. J., Shearer, D. A., Finn, C. V., Bracken, R. M., . . . Kilduff, L. P. (2013). Strength and power predictors of sprinting performance in professional rugby players. *The Journal of Sports Medicine and Physical Fitness, 53*(2), 105-111.

Cushion, E. J., Goodwin, J. E., & Cleather, D. J. (2016). Relative intensity influences the degree of correspondence of jump squats and push jerks to countermovement jumps. *Journal of Strength and Conditioning Research, 30*(5), 1255-1264.

Davies, C. T., & Young, K. (1984). Effects of external loading on short term power output in children and young male adults. *European Journal of Applied Physiology and Occupational Physiology*, *52*(3), 351-354.

Dayne, A. M., McBride, J. M., Nuzzo, J. L., Triplett, N. T., Skinner, J., & Burr, A. (2011). Power output in the jump squat in adolescent male athletes. *Journal of Strength and Conditioning Research*, *25*(3), 585-589.

Dempster, W. (1955). Space requirements of the seated operator: Geometrical, kinematic, and mecahncial aspects of the body with special referece to the limbs. WADC-TR-55-159, Wright Patterson Air Force Base, Ohio: Wright Air Development Center

Dowling, J., & Vamos, L. (1993). Identification of kinetic and temporal factors related to vertical jump performance. *Journal of Applied Biomechanics, 9*, 95-110.

Driss, T., Vandewalle, H., Quievre, J., Miller, C., & Monod, H. (2001). Effects of external loading on power output in a squat jump on a force platform: A comparison between strength and power athletes and sedentary individuals. *Journal of Sports Sciences, 19*(2), 99-105.

Dugan, E. L., Doyle, T. L., Humphries, B., Hasson, C. J., & Newton, R. U. (2004). Determining the optimal load for jump squats: A review of methods and calculations. *Journal of Strength and Conditioning Research, 18*(3), 668-674.

Feeney, D., Stanhope, S. J., Kaminski, T. W., Machi, A., & Jaric, S. (2016). Loaded vertical jumping: Force-velocity relationship, work, and power. *Journal of Applied Biomechanics, 32*(2), 120-127.

Fradkin, A. J., Zazryn, T. R., & Smoliga, J. M. (2010). Effects of warming-up on physical performance: A systematic review with meta-analysis. *Journal of Strength and Conditioning Research, 24*(1), 140-148.

Frost, D. M., Cronin, J., & Newton, R. U. (2010). A biomechanical evaluation of resistance: Fundamental concepts for training and sports performance. *Sports Medicine*, *40*(4), 303-326.

Fry, A. C., Smith, J. C., & Schilling, B. K. (2003). Effect of knee position on hip and knee torques during the barbell squat. *Journal of Strength and Conditioning research, 17*(4), 629-633.

Gant, N., Ali, A., & Foskett, A. (2010). The influence of caffeine and carbohydrate coingestion on simulated soccer performance. *International Journal of Sport Nutrition and Exerccise Metabolism, 20*(3), 191-197.

Gard, S. A., Miff, S. C., & Kuo, A. D. (2004). Comparison of kinematic and kinetic methods for computing the vertical motion of the body center of mass during walking. *Human Movement Science, 22*(6), 597-610.

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

Garhammer, J., & Newton, H. (2013). Applied video analysis for coaches: Weightlifting examples. *International Journal of Sports Science & Coaching, 8*(3), 581-594.

Gonzalez-Badillo, J. J., & Marques, M. C. (2010). Relationship between kinematic factors and countermovement jump height in trained track and field athletes. *Journal of Strength and Conditioning Research, 24*(12), 3443-3447.

Gullstrand, L., Halvorsen, K., Tinmark, F., Eriksson, M., & Nilsson, J. (2009). Measurements of vertical displacement in running, a methodological comparison. *Gait and Posture*, *30*(1), 71-75.

Haff, G. G., & Nimphius, S. (2012). Training principles for power. *Strength & Conditioning Journal, 34*(6), 2-12.

Hanavan, E. (1964). A mathmatical model for the human body. AMRL-TR-64-102, AD-608-463. Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011a). The reliability of linear position transducer and force plate measurement of explosive force-time variables during a loaded jump squat in elite athletes. *Journal of Strength and Conditioning Research*, *25*(5), 1447-1456.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011b). The reliability of linear position transducer, force plate and combined measurement of explosive power-time variables during a loaded jump squat in elite athletes. *Sports Biomechanics, 10*(1), 46-58.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011c). The reliability of linear position transducer, force plate and combined measurement of explosive power-time variables during a loaded jump squat in elite athletes. *Sports Biomechanics*, *10*(1), 46-58.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011d). Three methods of calculating force-time variables in the rebound jump squat. *Journal of Strength and Conditioning Research, 25*(3), 867-871.

Hansen, K. T., Cronin, J. B., Pickering, S. L., & Douglas, L. (2011e). Do force-time and power-time measures in a loaded jump squat differentiate between speed performance and playing level in elite and elite junior rugby union players? *Journal of Strength and Conditioning Research, 25*(9), 2382-2391.

Harris, N., Cronin, J., Taylor, K., Boris, J., & Sheppard, J. (2010). Understanding position transducer technology for strength and conditioning practitioners. *Strength & Conditioning Journal, 32*(4), 66-79.

Harris, N. K., Cronin, J. B., & Hopkins, W. G. (2007). Power outputs of a machine squat-jump across a spectrum of loads. *Journal of Strength and Conditioning Research, 21*(4), 1260-1264.

Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008a). Relationship between sprint times and the strength/power outputs of a machine squat jump. *Journal of Strength and Conditioning Research, 22*(3), 691-698.

Harris, N. K., Cronin, J. B., Hopkins, W. G., & Hansen, K. T. (2008b). Squat jump training at maximal power loads vs. Heavy loads: Effect on sprint ability. *Journal of Strength and Conditioning Research, 22*(6), 1742-1749.

Hatze, H. (1998). Validity and reliability of methods for testing vertical jumping performance. . *Journal of applied biomechanics, 14*(2), 127-140.

Hill, A. V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B, Containing papers of a Biological character. Royal Society, 126,* 136-195.

Hill, A. V. (1953). The mechanics of active muscle. *Proceedings of the Royal Society of London. Series B, Containing papers of a Biological character. Royal Society, 141*(902), 104-117.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3-13.

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2007). Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *Journal of Strength and Conditioning Research, 21*(2), 314-320.

Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R., & Nosaka, K. (2008). Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *Journal of Strength and Conditioning Research, 22*(2), 412-418.

Hori, N., Newton, R. U., Nosaka, K., & McGuigan, M. R. (2006). Comparison of different methods of determining power output in weightlifting exercises. *Strength & Conditioning Journal, 28*(2), 34-40.

Jandacka, D., Uchytil, J., Farana, R., Zahradnik, D., & Hamill, J. (2014). Lower extremity power during the squat jump with various barbell loads. *Sports Biomechanics, 13*(1), 75-86.

Jaric, S., & Markovic, G. (2009). Leg muscles design: The maximum dynamic output hypothesis. *Medicine and Science in Sports and Exercise, 41*(4), 780-787.

Jaric, S., & Markovic, G. (2013). Body mass maximizes power output in human jumping: A strength-independent optimum loading behavior. *European Journal of Applied Physiology, 113*(12), 2913-2923.

Jidovtseff, B., Quievre, J., Harris, N. K., & Cronin, J. B. (2014). Influence of jumping strategy on kinetic and kinematic variables. *Journal of Sports Medicine and Physical Fitness, 54*(2), 129-138.

Judelson, D. A., Maresh, C. M., Anderson, J. M., Armstrong, L. E., Casa, D. J., Kraemer, W. J., & Volek, J. S. (2007). Hydration and muscular performance: Does fluid balance affect strength, power and high-intensity endurance? *Sports Medicine, 37*(10), 907-921.

Kawamori, N., Crum, A. J., Blumert, P. A., Kulik, J. R., Childers, J. T., Wood, J. A., . . . Haff, G. G. (2005). Influence of different relative intensities on power output during the hang power clean: Identification of the optimal load. *Journal of Strength and Conditioning Research, 19*(3), 698-708.

Kawamori, N., & Haff, G. G. (2004). The optimal training load for the development of muscular power. *Journal of Strength and Conditioning Research, 18*(3), 675-684.

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of countermovement jumps: A methodological study. *Journal of Applied Biomechanics, 14*(1), 105-117.

Kipp, K., Harris, C., & Sabick, M. B. (2011). Lower extremity biomechanics during weightlifting exercise vary across joint and load. *Journal of Strength and Conditioning Research, 25*(5), 1229-1234.

Knudson, D. V. (2009). Correcting the use of the term "power" in the strength and conditioning literature. *Journal of Strength and Conditioning Research, 23*(6), 1902-1908.

Lake, J., Lauder, M., Smith, N., & Shorter, K. (2012a). A comparison of ballistic and nonballistic lower-body resistance exercise and the methods used to identify their positive lifting phases. *Journal of Applied Biomechanics, 28*(4), 431-437.

Lake, J. P., & Lauder, M. A. (2012). Kettlebell swing training improves maximal and explosive strength. *Journal of Strength and Conditioning Research, 26*(8), 2228-2233.

Lake, J. P., Lauder, M. A., & Smith, N. A. (2012b). Barbell kinematics should not be used to estimate power output applied to the barbell-and-body system center of mass during lower-body resistance exercise. *Journal of Strength and Conditioning Research, 26*(5), 1302-1307.

Lake, J. P., Mundy, P. D., & Comfort, P. (2014). Power and impulse applied during push press exercise. *Journal of Strength and Conditioning Research, 28*(9), 2552-2559.

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). The maximal and submaximal vertical jump: Implications for strength and conditioning. *Journal of Strength and Conditioning Research, 18*(4), 787-791.

Leontijevic, B., Pazin, N., Bozic, P. R., Kukolj, M., Ugarkovic, D., & Jaric, S. (2012). Effects of loading on maximum vertical jumps: Selective effects of weight and inertia. *Journal of Electromyography and Kinesiology 22*(2), 286-293.

Li, L., Olson, M. W., & Winchester, J. B. (2008). A proposed method for determining peak power in the jump squat exercise. *Journal of Strength and Conditioning Research, 22*(2), 326-331.

Lyttle, A. D., Wilson, G. J., & Ostrowski, K. J. (1996). Enhancing performance: Maximal power versus combined weights and plyometrics training. *Journal of Strength & Conditioning Research, 10*(3), 173-179.

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat. *Journal of Sports Sciences, 32*(16), 1576-1585.

Maffiuletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., & Duchateau, J. (2016). Rate of force development: Physiological and methodological considerations. *European journal of Applied Physiology, 116*(6), 1091-1116.

Major, J. A., Sands, W. A., McNeal, J. R., Paine, D. D., & Kipp, R. (1998). Design, construction, and validation of a portable one-dimensional force platform. *The Journal of Strength & Conditioning Research, 12*(1), 37-41.

Markovic, G., & Jaric, S. (2007). Positive and negative loading and mechanical output in maximum vertical jumping. *Medicine and Science in Sports and Exercise, 39*(10), 1757-1764.

Markovic, G., Vuk, S., & Jaric, S. (2011). Effects of jump training with negative versus positive loading on jumping mechanics. *International Journal of Sports Medicine, 32*(5), 365-372.

Markovic, S., Mirkov, D. M., Nedeljkovic, A., & Jaric, S. (2014). Body size and countermovement depth confound relationship between muscle power output and jumping performance. *Human Movement Science, 33*, 203-210.

Marshall, B. M., & Moran, K. A. (2015). Biomechanical factors associated with jump height: A comparison of cross-sectional and pre-to-posttraining change findings. *Journal of Strength and Conditioning Research, 29*(12), 3292-3299.

McBride, J. M., Haines, T. L., & Kirby, T. J. (2011). Effect of loading on peak power of the bar, body, and system during power cleans, squats, and jump squats. *Journal of Sports Sciences, 29*(11), 1215-1221.

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

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

McGuigan, M. R., Cormack, S. J., & Gill, N. D. (2013). Strength and power profiling of athletes: Selecting tests and how to use the information for program design. *Strength & Conditioning Journal, 35*(6), 7-14.

McLaughlin, P. (2013). Testing agreement between a new method and the gold standard- how do we test? *Journal of Biomechanics, 46*(16), 2757-2760.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011a). Markers of postmatch fatigue in professional rugby league players. *Journal of Strength and Conditioning Research, 25*(4), 1030-1039.

McLellan, C. P., Lovell, D. I., & Gass, G. C. (2011b). The role of rate of force development on vertical jump performance. *Journal of Strength and Conditioning Research, 25*(2), 379-385.

McMaster, D. T., Gill, N., Cronin, J., & McGuigan, M. (2014). A brief review of strength and ballistic assessment methodologies in sport. *Sports Medicine, 44*(5), 603-623.

Mizuguchi, S., Sands, W. A., Wassinger, C. A., Lamont, H. S., & Stone, M. H. (2015). A new approach to determining net impulse and identification of its characteristics in countermovement jumping: Reliability and validity. *Sports Biomechanics, 14*(2), 258-272.

Moir, G. L., Gollie, J. M., Davis, S. E., Guers, J. J., & Witmer, C. A. (2012). The effects of load on system and lower-body joint kinetics during jump squats. *Sports Biomechanics, 11*(4), 492-506.

Mundy, P. D., Lake, J. P., Carden, P. J., Smith, N. A., & Lauder, M. A. (2016a). Agreement between the force platform method and the combined method measurements of power output during the loaded countermovement jump. *Sports Biomechanics*, *15*(1), 23-35.

Mundy, P. D., Smith, N. A., Lauder, M. A., & Lake, J. P. (2016b). The effects of barbell load on countermovement vertical jump power and net impulse. *Journal of Sports Sciences*, 1-7.

Newton, R. U., & Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength & Conditioning Journal*, 20-31.

Newton, R. U., Rogers, R. A., Volek, J. S., Hakkinen, K., & Kraemer, W. J. (2006). Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *Journal of Strength and Conditioning Research, 20*(4), 955-961.

Nibali, M. L., Chapman, D. W., Robergs, R. A., & Drinkwater, E. J. (2013a). Influence of rest interval duration on muscular power production in the lower-body power profile. *Journal of Strength and Conditioning Research, 27*(10), 2723-2729.

Nibali, M. L., Chapman, D. W., Robergs, R. A., & Drinkwater, E. J. (2013b). A rationale for assessing the lower-body power profile in team sport athletes. *Journal of Strength and Conditioning Research*, *27*(2), 388-397.

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

Nuzzo, J. L., McBride, J. M., Dayne, A. M., Israetel, M. A., Dumke, C. L., & Triplett, N. T. (2010). Testing of the maximal dynamic output hypothesis in trained and untrained subjects. *Journal of Strength and Conditioning Research*, *24*(5), 1269-1276.

Owen, N. J., Watkins, J., Kilduff, L. P., Bevan, H. R., & Bennett, M. A. (2014). Development of a criterion method to determine peak mechanical power output in a countermovement jump. *Journal of Strength and Conditioning Research, 28*(6), 1552-1558.

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics*, *43*(10), 1976-1982.

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics, 46*(14), 2394-2401.

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. One-dimensional, parametric vs. Non-parametric, and confidence interval vs. Hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics, 48*(7), 1277-1285.

Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2016). The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and emg trajectories. *Journal of Biomechanics, 49*(9), 1468-1476.

Patterson, C., Raschner, C., & Platzer, H. P. (2009). Power variables and bilateral force differences during unloaded and loaded squat jumps in high performance alpine ski racers. *Journal of Strength and Conditioning Research, 23*(3), 779-787.

Pazin, N., Berjan, B., Nedeljkovic, A., Markovic, G., & Jaric, S. (2012). Power output in vertical jumps: Does optimum loading depend on activity profiles? *European Journal of Applied Physiology*.

Ranavolo, A., Don, R., Cacchio, A., Serrao, M., Paoloni, M., Mangone, M., & Santilli, V. (2008). Comparison between kinematic and kinetic methods for computing the vertical displacement of the center of mass during human hopping at different frequencies. *Journal of Applied Biomechanics, 24*(3), 271-279.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2014). Research methods in biomechanics (Second Edition ed.). Champaign, IL.: Human Kinetics.

Rodgers, M. M., & Cavanagh, P. R. (1984). Glossary of biomechanical terms, concepts, and units. *Physical Therapy, 64*(12), 1886-1902.

Samozino, P., Morin, J. B., Hintzy, F., & Belli, A. (2008). A simple method for measuring force, velocity and power output during squat jump. *Journal of Biomechanics, 41*(14), 2940-2945.

Schenau, G. J. v. I., Bobbert, M. F., & Haan, A. d. (1997a). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics, 13*(4), 389-415.

Schenau, G. J. v. I., Bobbert, M. F., & Haan, A. d. (1997b). Mechanics and energetics of the stretch-shortening cycle: A stimulating discussion. *Journal of Applied Biomechanics, 13*(4), 484-496.

Sheppard, J. M., Cormack, S., Taylor, K. L., McGuigan, M. R., & Newton, R. U. (2008a). Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *Journal of Strength and Conditioning Research, 22*(4), 1320-1326.

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008b). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *Journal of Strength and Conditioning Research, 22*(3), 758-765.

Sheppard, J. M., Nolan, E., & Newton, R. U. (2012). Changes in strength and power qualities over two years in volleyball players transitioning from junior to senior national team. *Journal of Strength and Conditioning Research, 26*(1), 152-157.

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

Smilios, I., Sotiropoulos, K., Christou, M., Douda, H., Spaias, A., & Tokmakidis, S. P. (2013). Maximum power training load determination and its effects on load-power relationship, maximum strength, and vertical jump performance. *Journal of Strength and Conditioning Research, 27*(5), 1223-1233.

Soriano, M. A., Jimenez-Reyes, P., Rhea, M. R., & Marin, P. J. (2015). The optimal load for maximal power production during lower-body resistance exercises: A meta-analysis. *Sports Medicine, 45*(8), 1191-1205.

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength and Conditioning Research, 17*(1), 140-147.

Street, G., McMillan, S., Board, W., Rasmussen, M., & Heneghan, M. J. (2001). Sources of error in determining countermovement jump height with the impulse method. *Journal of Applied Biomechanics, 17*(1), 43-54.

Suzovic, D., Markovic, G., Pasic, M., & Jaric, S. (2013). Optimum load in various vertical jumps support the maximum dynamic output hypothesis. *International Journal of Sports Medicine, 13*, 13.

Swinton, P. A., Stewart, A. D., Lloyd, R., Agouris, I., & Keogh, J. W. (2012). Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *Journal of Strength and Conditioning Research, 26*(4), 906-913.

Teo, W., Newton, M. J., & McGuigan, M. R. (2011). Circadian rhythms in exercise performance: Implications for hormonal and muscular adaptation. *Journal of Sports Science & Medicine, 10*(4), 600-606.

Thomas, G. A., Kraemer, W. J., Spiering, B. A., Volek, J. S., Anderson, J. M., & Maresh, C. M. (2007). Maximal power at different percentages of one repetition maximum: Influence of resistance and gender. *Journal of Strength and Conditioning Research, 21*(2), 336-342.

Thomasson, M. L., & Comfort, P. (2012). Occurrence of fatigue during sets of static squat jumps performed at a variety of loads. *Journal of Strength and Conditioning Research, 26*(3), 677-683.

Turner, A. P., Unholz, C. N., Potts, N., & Coleman, S. G. (2012). Peak power, force, and velocity during jump squats in professional rugby players. *Journal of Strength and Conditioning Research, 26*(6), 1594-1600.

Turner, T. S., Tobin, D. P., & Delahunt, E. (2015). Optimal loading range for the development of peak power output in the hexagonal barbell jump squat. *Journal of Strength and Conditioning Research, 29*(6), 1627-1632.

Van Sint Jan, S., & Della Croce, U. (2005). Identifying the location of human skeletal landmarks: Why standardized definitions are necessary--a proposal. *Clinical Biomechanics*, *20*(6), 659-660.

Vanezis, A., & Lees, A. (2005). A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics, 48*(11-14), 1594-1603.

Vanrenterghem, J., De Clercq, D., & Van Cleven, P. (2001). Necessary precautions in measuring correct vertical jumping height by means of force plate measurements. *Ergonomics, 44*(8), 814-818.

Vanrenterghem, J., Lees, A., & Clercq, D. D. (2008). Effect of forward trunk inclination on joint power output in vertical jumping. *Journal of Strength and Conditioning Research, 22*(3), 708-714.

Vaverka, F., Jakubsova, Z., Jandacka, D., Zahradnik, D., Farana, R., Uchytil, J., . . . Vodicar, J. (2013). The influence of an additional load on time and force changes in the ground reaction force during the countermovement vertical jump. *Journal of Human Kinetics, 38*, 191-200.

Vuk, S., Markovic, G., & Jaric, S. (2012). External loading and maximum dynamic output in vertical jumping: The role of training history. *Human Movement Science, 31*(1), 139-151.

Wilson, G. J., Newton, R. U., Murphy, A. J., & Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise, 25*(11), 1279-1286.

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (Fourth ed.). Hoboken, New Jersey: John Wiley & Sons, Inc.

Winter, E. M., Abt, G., Brookes, F. B., Challis, J. H., Fowler, N. E., Knudson, D. V., . . . Yeadon, M. R. (2016). Misuse of "power" and other mechanical terms in sport and exercise science research. *Journal of Strength and Conditioning Research, 30*(1), 292-300.

Winter, E. M., & Fowler, N. (2009). Exercise defined and quantified according to the systeme international d'unites. *Journal of Sports Sciences, 27*(5), 447-460.

Winter, E. M., & Knudson, D. V. (2011). Terms and nomenclature. *Journal of Sports Sciences, 29*(10), 999-1000.

Wood, G. A. (1982). Data smoothing and differentiation procedures in biomechanics. *Exercise and Sport Sciences Reviews, 10*, 308-362.

Wright, G. A., Pustina, A. A., Mikat, R. P., & Kernozek, T. W. (2012). Predicting lower body power from vertical jump prediction equations for loaded jump squats at different intensities in men and women. *Journal of Strength and Conditioning Research, 26*(3), 648-655.

Wulf, G. (2013). Attentional focus and motor learning: A review of 15 years. *International Review of Sport and Exercise Psychology, 6*(1), 77-104.

Wulf, G., Zachry, T., Granados, C., & Dufek, J. S. (2007). Increases in jump-and-reach height through an external focus of attention. *International Journal of Sports Science & Coaching, 2*(3), 275-284.

Young, W. B., Newton, R. U., Doyle, T. L., Chapman, D., Cormack, S., Stewart, G., & Dawson, B. (2005). Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite australian rules football: A case study. *Journal of Science and Medicine in Sport, 8*(3), 333-345.