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# Biomechanical Analysis of Jumping: The Influence of External Load and Countermovement Depth on Deceleration Strategies and Performance

Leland Adam Barker

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BIOMECHANICAL ANALYSIS OF JUMPING: THE INFLUENCE OF  
EXTERNAL LOAD AND COUNTERMOVEMENT DEPTH ON  
DECELERATION STRATEGIES AND PERFORMANCE

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Of the requirements for the

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Biomechanical Analysis of Jumping: The Influence of External Load and  
Countermovement Depth on Deceleration Strategies and Performance

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## ABSTRACT

Jumping performance has traditionally been measured by jump height alone. In recent years, the reactive strength index (RSI = Jump height / jump time)) has been used as another measure of jump performance. According to RSI, which was developed to assess eccentric force production, jump performance can improve by increasing jump height, decreasing jump time, or both simultaneously. However, it is not clear how force production correlates to RSI variables. If RSI is meant to be a practical measure of eccentric force production, it should correlate strongly to eccentric and amortization force production during jumping. Thus, the purpose of the first study was to determine the relationship between ground reaction force (GRF) variables to jump height, jump time, and the Reactive Strength Index (RSI). Twenty-six Division I male soccer players performed three maximum effort CMJs on a dual-force platform system that measured three-dimensional kinetic data. Vertical GRF (Fz) variables were divided into unloading, eccentric, amortization, and concentric phases and correlated to jump height, RSI (RSI= Jump height/jump time), and jump time (ground contact time from start to takeoff). Significant correlations were observed between jump height and RSI, concentric kinetic energy, peak power, concentric work, and concentric displacement. Significant correlations were observed between RSI and jump time, peak power, unload Fz, eccentric work, eccentric rate of force development (RFD), amortization Fz, amortization time, 2<sup>nd</sup> Fz peak, average concentric Fz, and concentric displacement. Significant correlations were observed between jump time and unload Fz, eccentric work, eccentric RFD, amortization Fz, amortization time, average concentric Fz, and concentric work. In conclusion, jump height correlated to variables derived

from the concentric phase only, while Fz variables from the unloading, eccentric, amortization, and concentric phases correlated highly to RSI and jump time. These observations demonstrate the importance of countermovement Fz characteristics for time-sensitive CMJ performance measures. Further, RSI correlated strongly to Fz variables during eccentric and amortization phases. Researchers and practitioners should include RSI to improve their assessment of jump performance.

The first study observed a strong relationship between jump performance and force production during the eccentric and amortization phases. But, there is limited research on force production during eccentric and amortization phases of the jump squat (JS), which is a countermovement jump performed with external load via barbell. Further, limited research has investigated the influence of countermovement technique on these variables. Therefore, the second and third studies investigated the effect of load and countermovement technique on kinetics during the eccentric and amortization phases of the jump squat. The second and third studies used the same protocol: On day one, participants performed a 3-repetition maximum (RM) back squat. On day two, participants performed JS with 0%, 15%, 30%, 45%, and 60% of estimated 1-RM using three countermovement techniques: preferred (PREF), quarter (QTR), and full (FULL) depths. Participants wore flat athletic shoes, and were outfitted with reflective markers on the lower extremity to collect 3D kinematics. JS were performed on dual force platforms synchronized with the 3D data.

The purpose of the second study was to compare vertical ground reaction forces (Fz) from the eccentric and amortization phases of the JS across loads and countermovement techniques. A convenience sample of 12 healthy, resistance-trained men ( $24.8 \pm 4.04$  yrs,  $86.71$

$\pm 15.59$  kg,  $1.78 \pm 0.79$  m, 3-RM Back Squat:  $123.2 \pm 23.79$  kg) were recruited from the university kinesiology department. Dependent variables included: (1) eccentric rate of force development (RFD1 and RFD2); (2) first Fz peak (Fz1); (3) amortization Fz and time; (4) jump height; (5) RSI; (6) peak and average concentric power; (7) and countermovement depth. Eccentric RFD1 did not change with increasing loads ( $p > 0.05$ ), but eccentric RFD2 decreased with increasing loads ( $p < 0.05$ ). Amortization Fz was not different among the loaded conditions ( $p > 0.05$ ), but was greater with load (15%-60% of 1-RM) than without (0% of 1-RM). Jump height and RSI declined with increasing loads ( $p < 0.05$ ), and power peaked using 15% and 30% of 1-RM. The QTR JS resulted in greater amortization Fz, RSI, peak power, and average power ( $p < 0.05$ ). Based on the second study, it is recommended that QTR techniques be used in conjunction with FULL or PREF techniques throughout a comprehensive training plan purposed for development of stretch-shortening cycle performance.

The purpose of the third study was to compare joint kinetics from the eccentric and amortization phases of the JS across loads and countermovement techniques. A convenience sample of 10 healthy, resistance-trained men ( $24 \pm 4.24$  yrs,  $88.35 \pm 16.71$  kg,  $178.15 \pm 7.15$  cm, 3-RM Back Squat:  $119.27 \pm 21.78$  kg) were recruited from the university kinesiology department. Joint kinetics were calculated in the sagittal plane of the hip, knee, and ankle. Dependent variables included: (1) eccentric work of the hip and knee; (2) Eccentric hip to knee work ratio; (3) hip, knee, and ankle moments during amortization; (4) jump height; (5) RSI; (6) countermovement depth; (7) peak power; (8) average concentric power; (9) and peak countermovement kinetic energy. Eccentric joint work was influenced by the interaction of load and technique at the hip ( $p < 0.05$ ), but generally decreased (i.e. greater work) with increasing

loads and greater countermovement depths for both joints. Eccentric hip to knee work ratio revealed more hip contribution to deceleration with increasing loads and countermovement depths, and knee dominant deceleration during the QTR JS. Amortization hip moment was significantly less using QTR compared to PREF or FULL ( $p < 0.05$ ), but there was no main effect of technique on ankle or knee amortization moments ( $p > 0.05$ ). Performance variables followed similar results of the second study. The QTR JS elicited greater RSI, peak and average concentric power, and less countermovement kinetic energy. Countermovement kinetic energy peaked using 15% of 1-RM with a FULL JS, indicating that increasing loads does not ensure an increase in downward kinetic energy despite verbal instruction to lower the weight as quickly as possible.

In conclusion, the eccentric and amortization phases may have been previously undervalued for jump performance because they do not correlate to jump height. However, RSI has a strong relationship with eccentric and amortization force production, as intended. The presented studies further our understanding of force production in these phases when load and countermovement depth changes. The QTR JS elicits greater power output and RSI values, and is knee dominant during deceleration. The FULL JS elicits peak deceleration demands using 15% and 30% of 1-RM, accompanied by increasing contributions from the hip. It appears advisable to view the QTR and FULL JS as separate exercises with complementary stresses that could be combined in a comprehensive jump training program. Further, because the highest load did not result in greater deceleration demands (i.e. peak countermovement kinetic energy), coaches should consider defining, monitoring, and cueing specific countermovement strategies when organizing training programs.



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## INTRODUCTION

Jumping is a fundamental movement used regularly in sport. Horizontal and vertical jumping can be performed with an approach such as in the long jump, high jump, and varying cases in basketball, volleyball, and other sports. Vertical jumping without an approach includes the squat jump, drop jump, and countermovement jump. Many varieties are used in training and sport, but the countermovement jump (CMJ) is one fundamental jump technique that can be studied effectively due to its simplicity. The CMJ requires the subject to begin standing, perform a downward countermovement, and jump vertically as high as possible. For sport testing, the CMJ serves as a simple jumping task allowing for time-efficient, reliable, and valid assessment of lower body power that is strongly correlated to sprint acceleration and sport performance (Barnes et al., 2007; Cronin & Hansen, 2005; Rodriguez-Rosell, Mora-Custodio, Franco-Marquez, Yanez-Garcia, & Gonzalez-Badillo, 2017).

Due to the countermovement, CMJ height tends to be greater than during a squat jump. This observation is due to a few interrelated factors: (1) more time for the muscle to build an active state at concentric initiation; (2) greater elastic energy contributions from elastic components at concentric initiation; (3) greater neural input due to increased muscle spindle firing; and (4) the pre-stretch during the countermovement encourages optimal interaction between contractile elements (Bobbert, Gerritsen, Litjens, & VanSoest, 1996). However, the primary factor causing greater CMJ height than the squat jump is (1) the extra time to build an active muscle state. Extra time allows more work to be performed in the early concentric phase

compared to the squat jump (Bobbert et al., 1996). However, jump height is not the only measure of jump performance.

The Reactive Strength Index (RSI) was developed to assess eccentric force production and plyometric performance for the drop jump when a landing is followed by an immediate jump (Flanagan & Comyns, 2008). RSI is calculated by normalizing jump height to jump time (ground contact time during plyometric exercises involving a landing and immediate jump), but this index could also be calculated in the CMJ. Jump height could be normalized to jump time during the CMJ by defining jump time from countermovement initiation to takeoff. Using RSI, jump performance could be improved by increasing jump height, decreasing jump time, or both. There is research reporting significant correlations between jump height and peak power ( $r = 0.928$ ) and force ( $r = 0.519$ ) (Dowling & Vamos, 1993), but it is not clear what GRF variables correlate to RSI or jump time alone. Therefore, the purpose of the first study was to identify the relationship between GRFs and jump height, RSI, and jump time. Our results suggest RSI is an effective measure of eccentric force production due to strong correlations with unloading, eccentric, and amortization GRFs that were not correlated to jump height. These findings guided the second and third studies, which investigated the influence of external loading and countermovement depths on eccentric and amortization phases.

Strength and conditioning professionals often seek to improve their athletes' jump performance. One exercise, the jump squat (JS), is a CMJ using a barbell for external loading. The jump squat has been well-studied as an exercise to improve lower body power and jumping performance (Baker, Nance, & Moore, 2001; Cormie, McBride, & McCaulley, 2008; Cormie, McCaulley, & McBride, 2007; Jandacka, Uchytel, Farana, Zahradnik, & Hamill, 2014; McBride,



Triplett-McBride, Davie, & Newton, 2002; Moir, Gollie, Davis, Guers, & Witmer, 2012). Strength and power training has been reported to improve the eccentric phase of the CMJ (Cormie, McGuigan, & Newton, 2010), but there is limited research on the GRFS and joint kinetics during the eccentric and amortization phases of the jump squat. Further, a recent study reported favorable results for participants training bench press with multiple countermovement depths compared to full depth only (Clark, Humphries, Hohmann, & Bryant, 2011). Thus, countermovement depth and load are likely to influence kinetics during the eccentric and amortization phases. Therefore, the second and third study investigated the JS during eccentric and amortization phases to determine if there are specific phases, loads, or techniques that could be targeted to improve jump performance. A range of loads (0-60% of 1-RM) and countermovement techniques (preferred depth, quarter depth, full depth) were used while measuring GRFs and 3D kinematics. The second study investigated kinetics of the center of mass (COM) system using GRFs alone; the third study investigated kinetics of lower extremity joints using 3D kinematics and GRFs to calculate inverse dynamics.

The results and recommendations of this dissertation can be used by athletes and strength and conditioning professionals to improve awareness and planning of training programs. By understanding the eccentric and amortization kinetics from COM and joint perspectives, a variety of loads and techniques may be selected to train sport specific deceleration and jumping abilities.

# RELATIONSHIPS BETWEEN COUNTERMOVEMENT JUMP GROUND REACTION FORCES AND JUMP HEIGHT, REACTIVE STRENGTH INDEX, AND JUMP TIME

## Significance of the Chapter

The purpose of this chapter is to provide the foundation for the dissertation by analyzing countermovement jump (CMJ) performance (i.e. no external loading, preferred countermovement depth). Dependent variables were correlated to CMJ performance. Dependent variables were selected from four phases of the CMJ: unloading, eccentric, amortization, and concentric. Correlations are reported between each dependent variable and three measures of jump performance: jump height, jump time (duration from start to takeoff), and the Reactive Strength Index ( $RSI = \text{jump height} / \text{jump time}$ ). The dependent variables producing the strongest correlations to jump performance guided the research questions of the second and third studies investigating the influence of load and countermovement technique on system and joint kinetics during CMJs.

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## Abstract

The purpose of this study was to determine the relationship between ground reaction force (GRF) variables to jump height, jump time, and the Reactive Strength Index (RSI). Twenty-six Division I male soccer players performed three maximum effort CMJs on a dual-force platform system that measured three-dimensional kinetic data. The trial producing peak jump height was used for analysis. Vertical GRF (Fz) variables were divided into unloading, eccentric, amortization, and concentric phases and correlated to jump height, RSI (RSI= Jump height/jump time), and jump time (ground contact time from start to takeoff). Significant correlations were observed between jump height and RSI, concentric kinetic energy, peak power, concentric work, and concentric displacement. Significant correlations were observed between RSI and jump time, peak power, unload Fz, eccentric work, eccentric rate of force development (RFD), amortization Fz, amortization time, 2<sup>nd</sup> Fz peak, average concentric Fz, and concentric displacement. Significant correlations were observed between jump time and unload Fz, eccentric work, eccentric RFD, amortization Fz, amortization time, average concentric Fz, and concentric work. In conclusion, jump height correlated to variables derived from the concentric phase only (work, power, and displacement), while Fz variables from the unloading, eccentric, amortization, and concentric phases correlated highly to RSI and jump time. These observations demonstrate the importance of countermovement Fz characteristics for time-sensitive CMJ performance measures. Researchers and practitioners should include RSI and jump time with jump height to improve their assessment of jump performance.

## Introduction

The vertical jump test is widely used to assess lower body power in sport and correlates well to strength and speed performance (6, 11, 12, 17, 23, 24). Typically, athletes use a countermovement jump (CMJ) strategy to achieve maximum vertical jump height. The maximal CMJ test is reported to have good reliability ( $ICC > 0.989$ ), is a strong assessment of lower body power, and is easier to perform than, for example, drop jumps or approach jumps (22). Therefore, regular maximal vertical jump testing can be effective for both the assessment of jump performance and fatigue, and the development of long-term periodization plans (8, 14, 16).

Jump height is the traditional jump performance measure, but the Reactive Strength Index ( $RSI = \text{jump height} / \text{contact time}$ ) normalizes jump height to ground contact time. RSI is historically evaluated during the drop jump and similar plyometric activities to categorize those movements as fast or slow (7, 11). It is reasonable to presume that temporal normalization of jump height can be used to more effectively quantify jump performance compared to jump height during any jump variation that requires a rapid time between start and takeoff. RSI could be calculated during the countermovement jump, for example, by dividing jump height by jump time (defined as the ground contact time from start to takeoff). Using RSI, jump performance can be improved by increasing jump height, decreasing the jump time between start and takeoff, or both. Thus, RSI appears to be a better-suited measure of jump performance than jump height when the jumping task involves an eccentric component.

There is a wealth of research on the relationship between ground reaction force (GRF) variables (e.g. peak force, rate of force development) and jump height, but it is not clear how

variables relate to RSI or jump time alone. Therefore, the purpose of this study was to determine the relationship between GRF variables to jump height, jump time, and RSI. It was hypothesized that GRF variables would have larger correlations to RSI and jump time than to jump height.

## Methods

### *Experimental Approach to the Problem*

The purpose of this study was to determine the relationship between unloading, eccentric, amortization, and concentric phase GRF variables and performance quantified by jump height, jump time, and RSI. We correlated CMJ GRF variables to jump height, jump time, and RSI. Statistical significance was set *a priori* at  $\alpha = 0.05$ , using Hopkins' interpretation of strength for correlation coefficients.

### *Subjects*

Twenty-six Division I male soccer players ( $179.5 \pm 7.8$  cm,  $75.45 \pm 7.06$  kg,  $19.65 \pm 1.23$  yrs) volunteered to participate in the study. Prior to completing the testing protocol, participants provided written consent as approved by the local Institutional Review Board. All were active members of the university's soccer team at the time of testing and were free of any current injury to the lower extremities. This cohort included five goalkeepers, six defenders, eight midfielders, and seven forwards/wingers.

## *Procedures*

The protocol consisted of a single testing session. Anthropometric and demographic data (height, mass, age, position, dominant leg) were measured and recorded by the research team. Then, participants performed a self-selected warm up consisting of dynamic stretching and practice jumps ( $\leq 10$  min). The typically observed warm up consisted of squatting movements, toe touches, hopping, and practice jumps, and lasted 3-5 minutes. Following the warm up, participants performed three maximum effort CMJs on a dual-force platform system that measured three-dimensional kinetic data bilaterally at a sampling rate of 1000 Hz (Kistler Instruments Corp., Amherst, NY). The dual-force platforms were interfaced to a PC running Bioware<sup>®</sup> (version 4.0.1.2; Kistler Instruments Corp., Amherst, NY).

Countermovement depth was not controlled. However, the participants were asked to keep their hands on their hips throughout the entire jump. We restricted arm swing to minimize the influence of upper body movements on COM location. By restricting arm movements, we could be more focused on force generated via lower extremity (10). Each trial began with the participants standing still with each foot on a force platform. Following initiation of the countermovement, participants attempted to jump vertically as high as possible. Participants were instructed to lower themselves as quickly as possible, jump as high as possible, and return to standing after landing. The research team visually monitored each attempt to identify mistrials. Specifically, a trial was discarded if a participant was unable to land with each foot on a force platform or could not return to a standing position. Participants rested at least 15 seconds between trials while the trial data were saved. Participants were given up to one-minute rest as needed between trials. However, most participants were ready

to jump immediately afterward since a single jump trial was non-fatiguing for these participants. A maximum of six attempts were provided to complete three successful trials. All participants completed the three CMJ trials, though no more than four attempts were needed for any participant.

Raw GRF data were exported for processing using a custom laboratory program (MATLAB, R2015a; The Mathworks, Inc., Natick, MA). The vertical GRF data from each force platform were summed to create a total GRF profile along the vertical axis (Fz). After combining data from both force platforms to create Fz, the summed data were smoothed using a fourth-order low pass Butterworth digital filter with a cutoff frequency of 50 Hz (2).

Vertical acceleration of the COM was calculated using Newton's Law of Acceleration ( $\sum \text{Force} = \text{Mass} * \text{Acceleration}$ ). COM Velocity was calculated as the integral of vertical acceleration with respect to time, and COM position was calculated as the integral of vertical velocity with respect to time. The Fz jump profile (countermovement initiation to takeoff) was divided into unloading, eccentric, amortization, and concentric phases (Figure 1).

The start of the unloading phase was defined as the time when bodyweight was reduced by at least 2.5% (13). Takeoff was defined as the moment the Fz profile decreased below a 20 N threshold. The end of the countermovement phase was defined as the time when COM position reached its lowest depth. Within the countermovement, the unloading phase was defined from start to the minimum Fz, while the eccentric phase was defined as the time between the minimum Fz to the lowest COM position. The concentric phase was defined as the time between the lowest COM position and takeoff. The amortization phase was defined as the period of time when the COM was within a 1 cm threshold relative to the lowest COM position.

The  $\pm 1$  cm threshold was selected as the amortization threshold to reflect the time required to transition into and out of the lowest COM position, which was determined by processing vertical GRF data to first yield acceleration of the COM, then double integrating acceleration to determine COM position data.

The dependent variables evaluated were calculated relative to mass (N/kg) as appropriate. For the unloading phase, variables of interest were the unloading rate of force development (RFD), minimum Fz during the countermovement, COM displacement, and work. For the eccentric phase, variables calculated were eccentric RFD, COM displacement, and work. For the amortization phase, variables of interest were Fz magnitude at the lowest COM position and the time of the amortization phase. For the concentric phase, variables of interest were average concentric force, the slope between the two Fz peaks if applicable (Figure 1), work, and peak COM displacement from the starting (standing) position.

Performance variables for the entire CMJ included jump height, RSI, jump time, and peak power. Jump time was calculated as the ground contact time from start to takeoff, and RSI was calculated as jump height divided by jump time. Table 1 provides a presentation of the dependent variables and how each was calculated. Figure 1 presents both the separation of the Fz profile into the phases described and select dependent variables from the paragraph above.



Figure 1. Exemplar countermovement jump (CMJ) ground reaction force profile. The dashed lines are placed at the minimum vertical ground reaction force ( $F_z$ ) and the end of the countermovement to delineate the phases of the CMJ. RFD = rate of force development.

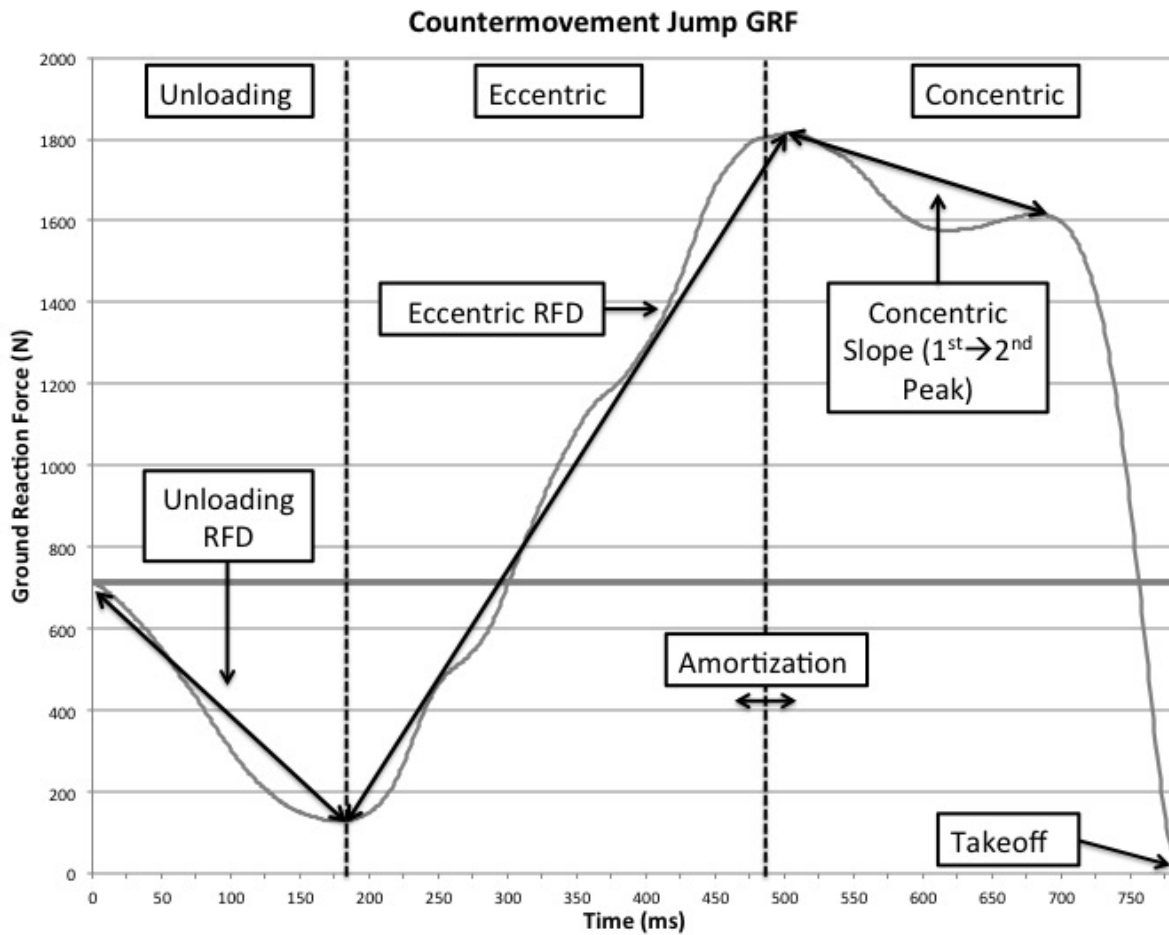


Table 1. Dependent variable calculations. RFD= Rate of Force Development. Fz= Vertical ground reaction force. COM= Center of Mass.

Variable	Calculation
Unloading RFD	(minimum Fz – starting Fz) / (time @ minimum position - 0)
Unloading Fz	Minimum Fz
Eccentric RFD	(1 <sup>st</sup> Fz peak – minimum Fz) / (time)
Eccentric work	Fz*eccentric Displacement
Amortization-Fz	Fz at concentric initiation
Amortization time	Total time it takes the COM to enter and exit countermovement depth within 1cm.
Concentric average force	Mean of Fz in the concentric phase
Concentric slope	(second Fz peak - first Fz peak) / (time)
Concentric displacement	takeoff position – standing position
Concentric Work	Fz*concentric displacement
Jump height	(takeoff velocity) <sup>2</sup> / (2*9.81)
Jump time	Time spent on the ground from the start of downward movement to takeoff.
Reactive strength index	(Jump height)/(Jump time)
Peak kinetic energies	Maximum kinetic energy during the countermovement and concentric phases (1/2mv <sup>2</sup> )
Peak Power	Maximum power during CMJ (Fz*COM velocity)

### Statistical Analysis

All dependent variables were correlated to jump height, jump time, and RSI. The statistical significance threshold for the correlations was set *a priori* at  $\alpha=0.05$ . To assess the strength of the correlations, we used Hopkins' (<http://sportsci.org/>) range for the interpretation of correlation coefficients: trivial ( $\pm 0-0.1$ ), small ( $\pm 0.1-0.3$ ), moderate ( $\pm 0.3-0.5$ ), large ( $\pm 0.5-0.7$ ), or very large ( $\pm 0.7-0.9$ ).

### Results

Correlations between the dependent variables and jump height, RSI, and jump time are presented in Table 2.

Significant correlations were observed between jump height and RSI (0.573,  $p < 0.05$ ), concentric kinetic energy (0.719,  $p < 0.05$ ), peak power (0.781,  $p < 0.05$ ), concentric work (0.660,  $p < 0.05$ ), and concentric displacement (0.590,  $p < 0.05$ ).

Significant correlations were observed between RSI and jump time (-0.812,  $p < 0.05$ ), peak power (0.623,  $p < 0.05$ ), unload Fz (-0.467,  $p < 0.05$ ), eccentric work (0.607,  $p < 0.05$ ), eccentric RFD (0.755,  $p < 0.05$ ), amortization Fz (0.725,  $p < 0.05$ ), amortization time (-0.589,  $p < 0.05$ ), 2<sup>nd</sup> Fz peak (0.464,  $p < 0.05$ ), average concentric Fz (0.823,  $p < 0.05$ ), and concentric displacement (0.407,  $p < 0.05$ ).

Significant correlations were observed between jump time and unload Fz (0.544,  $p < 0.05$ ), eccentric work (-0.629,  $p < 0.05$ ), eccentric RFD (-0.826,  $p < 0.05$ ), amortization Fz (-0.782,  $p < 0.05$ ), amortization time (0.668,  $p < 0.05$ ), average concentric Fz (-0.759,  $p < 0.05$ ), and concentric work (0.412,  $p < 0.05$ ). Descriptive statistics are listed in table 3.

Table 2. Correlation Results. \* =  $p < 0.05$ . RSI= Reactive Strength Index. Fz= Vertical Ground Reaction Force. RFD= Rate of Force Development.

	Jump Height	RSI	Jump Time
Jump Height	1	0.573*	-0.008
Reactive Strength Index	0.573*	1	-0.812*
Jump Time	-0.008	-0.812*	1
Countermovement Kinetic Energy	-0.021	0.048	-0.134
Concentric Kinetic Energy	0.719*	0.277	0.118
Peak Power	0.781*	0.623*	-0.206
Unload Fz	-0.101	-0.467*	0.544*
Unload RFD	0.018	-0.246	0.356
Eccentric Work	0.125	0.607*	-0.629*
Eccentric RFD	0.097	0.755*	-0.826*
Amortization Fz	0.11	0.725*	-0.782*
Amortization Time	-0.076	-0.589*	0.668*
1 <sup>st</sup> Fz Peak	0.081	0.32	-0.353
2 <sup>nd</sup> Fz Peak	0.198	0.464*	-0.407
Average Concentric Fz	0.302	0.823*	-0.759*
Concentric Slope	0.022	0.073	-0.030
Concentric Work	0.660*	0.019	0.412*
Concentric Displacement	0.590*	0.407*	-0.098

Table 3. Dependent Variable Descriptive Statistics. Fz= Vertical Ground Reaction Force. RFD= Rate of Force Development.

	Mean	Std. Deviation	Min	Max
Jump Height (m)	0.37	0.04	0.30	0.45
Reactive Strength Index	0.50	0.09	0.36	0.72
Jump Time (s)	0.76	0.10	0.55	0.96
Countermovement Kinetic Energy (J)	63.97	19.06	25.14	110.55
Concentric Kinetic Energy (J)	302.73	44.86	243.75	380.47
Peak Power (W/kg)	54.62	5.88	44.22	66.55
Unload Fz (N/kg)	2.54	1.39	0.10	6.03
Unload RFD (N/kg/s)	-41.80	13.86	-76.28	-15.30
Eccentric Work (J/kg)	-3.04	0.62	-4.51	-2.05
Eccentric RFD (N/kg/s)	78.00	35.58	31.25	196.41
Amortization Fz (N/kg)	24.47	3.38	16.28	32.27
Amortization Time (s)	0.08	0.01	0.06	0.11
1 <sup>st</sup> Fz Peak (N/kg)	24.47	3.38	9.77	32.61
2 <sup>nd</sup> Fz Peak (N/kg)	22.07	3.79	15.00	32.44
Average Concentric Fz (N/kg)	20.34	1.90	17.65	24.32
Concentric Slope (N/kg/s)	-10.34	10.94	-23.36	68.48
Concentric Work (J/kg)	8.04	0.91	6.41	9.96
Concentric Displacement (m)	0.12	0.05	-0.02	0.21

## Discussion

### *Main Observations*

The main findings of this study were that Fz variables derived from the unloading, eccentric, amortization, and concentric phase were strongly correlated to RSI and jump time, but not to jump height. Specifically, jump height correlated strongly with peak power, concentric kinetic energy, concentric work, and concentric displacement prior to takeoff, but none of the Fz variables specific to the unloading, eccentric, or amortization phases. Therefore,

our hypothesis that phase-specific Fz variables would correlate to RSI and jump time more than jump height was confirmed.

Our observations appear similar to other jumping studies (4, 5). However, the observations of the present study conflict with one report that eccentric RFD and average concentric Fz were the strongest correlates to jump height (9). Maximum jump height across participants in our study was 0.45 meters, whereas the aforementioned study had a number of participants jump higher than 0.6 meters. It is possible that the range of jump heights observed in our study was too narrow (0.30-0.45m) compared to that study to reveal eccentric RFD and average concentric Fz relationships with jump height. Furthermore, their sample included basketball, football, and baseball athletes who may have performed movements during training and/or competition more strongly related to jumping ability than the current sample of soccer players.

In team sport competition, the environment is dynamic and time-constrained. This can be understood when considering the environment from offensive and defensive perspectives. Both offensive and defensive players are in a reactionary cycle relative to field and inter-individual dynamics. Because a reaction is inherently behind the agent of reaction, most tasks in competition must be time sensitive. Based on the current results, time-constrained tasks and/or environmental situations (e.g. match play) may rely more heavily on eccentric and amortization force production. Therefore, jump performance normalized to time may be more useful to assess jump performance and stretch-shortening cycle capacity in athletes.

Elastic energy storage at the end of the countermovement and concentric force production is strongly associated with RSI and jump time. However, unloading, eccentric, and

amortization force production did not relate to CMJ jump height. Therefore, braking characteristics appear to be associated with decreasing time more than increasing height. Given that observation, it is important to consider movement strategy.

### *Elastic Energy and Movement Strategy*

The unloading phase is the first stage of the countermovement during which negative (downward) kinetic energy is developed. Theoretically, changes in unloading strategy would manipulate downward kinetic energy, which alters the demand for eccentric force production and elastic energy storage. In support of this claim, strong negative relationships were observed between unload  $F_z$  and countermovement kinetic energy ( $-0.681$ ,  $p < 0.001$ ) and eccentric RFD ( $-0.590$ ,  $p < 0.001$ ). Ultimately, an athlete with greater eccentric force production capacity may have a greater range of braking strategies to choose from, which may be of interest when selecting the braking or landing rates during competition. For example, urgent competition scenarios (e.g. unexpected change of direction) may warrant greater eccentric braking compared to less urgent scenarios (e.g. deceleration following a dead ball whistle). Furthermore, greater eccentric braking increases costs for the SEC's elastic energy output while decreasing energy cost of the muscle.

The storage of elastic energy in the series elastic component during the countermovement is returned during concentric initiation, which is represented by the amortization  $F_z$  (3). A forward dynamics simulation demonstrated that increasing countermovement velocity and muscle excitation while maintaining hip, knee, and ankle angular displacements increased the amount of elastic energy stored (3). It was concluded that,

“stored elastic energy increases the efficiency of doing positive work, but not the total amount of positive work” (3). That conclusion opposes the idea that storage and reutilization of elastic energy allows additional work to be done. As such, it is reasonable to conclude that countermovement characteristics are strongly associated with elastic energy utilization and eccentric force production demands. For example, greater unloading could lead to greater elastic energy storage during maximal CMJ. In support of this, we observed a strong intra-phase correlation between the unload  $F_z$  and eccentric RFD ( $r = -0.627$ ,  $p < 0.05$ ), and a moderate correlation between eccentric RFD and amortization  $F_z$  ( $r = -0.402$ ,  $p < 0.05$ ).

Understanding an athlete’s capacity for eccentric force production and elastic energy storage may be critical to advising stretch-shortening cycle strategies in team sport and endurance events. For example, it may be inadvisable to instruct a weaker athlete to hit the ground harder and faster prior to improving their eccentric force production capacity via strength and plyometric training methods. For example, high running injury rates to the hip and knee with rearfoot strike patterns have led some runners to transition to forefoot strike patterns via minimalist footwear. However, an abrupt transition may place eccentric stress that is too great for the ankle extensors and cause injury without prior strength training (1)

Energy economy is improved with greater SEC contributions, which is of interest to competition requiring prolonged activity (i.e. matches or races) and single effort performance (i.e. jumping or sprinting). Training is reported to improve eccentric phase CMJ  $F_z$  profiles(5) Furthermore, eccentric training methods have reported reduced hamstring strains prospectively (19) and improvements in achilles(18) and patellar(25) tendinopathy symptoms. Considering these reports and our strong correlations between RSI and  $F_z$  variables from



unloading, eccentric, and amortization phases, eccentric training methods appear useful for both injury prevention and performance enhancement during time-sensitive tests or activities.

Regarding fatigue and endurance, a spring-mass model investigation reported increases in leg stiffness at the end of a 24-hour run (15) . Given the durability of tendon relative to muscle, a shift in energy appropriation to the SEC rather than the muscle may be necessary to complete the task before exhaustion. Furthermore, explosive strength and plyometric training were reported to improve run times, plyometric jump performance, and intermittent endurance capacity in cross country and soccer athletes (20, 21) Therefore, improving the elastic energy capacity of the muscle tendon unit appears important to performance during many activities using the stretch-shortening cycle. Eccentric RFD and the amortization Fz may be useful to coaches and researchers looking for practical ways to measure elastic energy capacity during various movements for performance monitoring and injury prevention. Furthermore, coaches monitoring jump performance should include RSI and jump time as jump performance as indirect measures of elastic energy capacity.

### *Limitations*

Our study only measured the CMJ in one sample of athletes. Therefore, the ability to generalize our results to other athletes is limited by the range of jump heights observed in our study. Another potential limitation is the protocol cues. We instructed participants to lower themselves as quickly as possible, but some participants may not be accustomed to this cue and technique because they entered the study with different jumping experience despite all participants being collegiate athletes.

## Practical Applications

In conclusion, jump height correlated to variables derived from the concentric phase only (work, power, and displacement). Fz variables from the unloading, eccentric, amortization, and concentric phases correlated highly to RSI and jump time, demonstrating the importance of elastic energy for time-sensitive jump performance. Despite this study only assessing the CMJ, eccentric RFD and amortization Fz in a variety of jump tests or movements utilization the stretch-shortening cycle may provide a strong assessment tool for coaches and athletes hoping to reduce injury, improve performance, and monitor fatigue with measures of eccentric force production and elastic energy. Coaches and researchers should include RSI and jump time with jump height to assess jumping performance.

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# EFFECT OF LOAD AND DEPTH OF JUMP SQUAT ON GROUND REACTION FORCES DURING THE ECCENTRIC AND AMORTIZATION PHASES

## Significance of the Chapter

The previous chapter reported the ground reaction force (GRF) variables from eccentric and amortization phases were strongly correlated (greater than 0.5) to jump time and RSI, but not jump height. Thus, the eccentric and amortization phases are the focus of Chapter 3. The purpose of this study was to investigate the influence of load and countermovement technique on center of mass kinetics during the eccentric and amortization phases, including: eccentric rate of force development, eccentric work, amortization force, and amortization time. Dependent variables describing performance were also included: jump height, RSI, peak and average concentric power, and countermovement depth. In this chapter, eccentric and amortization phases are discussed in regard to developing deceleration abilities using exercises with different countermovement depths.

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## Abstract

There is limited research on the eccentric and amortization phases of the jump squat (JS). The purpose of this study was to compare vertical ground reaction forces (Fz) from the eccentric and amortization phases of the JS across loads and countermovement techniques. A convenience sample of 12 healthy, resistance-trained men ( $24.8 \pm 4.04$  yrs,  $86.71 \pm 15.59$  kg,  $1.78 \pm 0.79$  m, 3-RM Back Squat:  $123.2 \pm 23.79$  kg) were recruited from the university kinesiology department. On day one, participants performed a 3-repetition maximum (RM) back squat. On day two, participants performed JS with 0%, 15%, 30%, 45%, and 60% of estimated 1-RM using three countermovement techniques: preferred (PREF), quarter (QTR), and full (FULL) depths. Dependent variables included two eccentric rate of force development (RFD1 and RFD2) measures, first Fz peak (Fz1), amortization Fz and time, jump height, Reactive Strength Index (RSI), peak and average concentric power, and countermovement depth. Eccentric RFD1 did not change with increasing loads ( $p > 0.05$ ), but eccentric RFD2 decreased with increasing loads ( $p < 0.05$ ). Amortization Fz was not different among the loaded conditions ( $p > 0.05$ ), but was greater with load (15%-60% of 1-RM) than without (0% of 1-RM). Jump height and RSI declined with increasing loads ( $p < 0.05$ ), and power peaked using 15% and 30% of 1-RM. QTR JS resulted in greater amortization Fz, RSI, peak power, and average power ( $p < 0.05$ ). Based on the current study, it is recommended that QTR techniques be used in conjunction with FULL or PREF techniques throughout a comprehensive training plan purposed for development of stretch-shortening cycle performance.



## Introduction

The barbell jump squat (JS) involves using external load (i.e., barbell and any added weight) during a countermovement jump. It has been reported that the JS is an effective exercise to provide mechanical overload to the countermovement jump (MacKenzie, Lavers, & Wallace, 2014) and is used to train jumping ability (Baker, Nance, & Moore, 2001; Cormie, McBride, & McCaulley, 2008; Loturco et al., 2015; Irineu Loturco et al., 2016; Jeffrey M McBride, Triplett-McBride, Davie, & Newton, 2002). McBride et al. (2002) conducted a JS training study comparing jump height, peak force, peak power, and peak velocity during an 8-week training program using 30% or 80% 1-RM loads. The 30% training group displayed improvements in the 30% and 80% 1RM jump squat height (+17%, +9%), peak force (+4%, +6%), peak power (+10%, +18%), and peak velocity (+9%, +9%). The 80% training group displayed improvements in the 80% 1-RM jump squat peak force(+8%) and power (+13%). Thus, lighter jump squat loads may be the most effective for developing lower body power.

Although some benefits of using JS are known, the mechanisms for training improvements using a JS are not fully understood. A challenge with understanding the training mechanism is that the JS intensity can be manipulated by changing barbell load, depth of squat, as well as velocity of movement. McBride et al. (2010) reported peak power, peak force, jump height, and net vertical impulse across a range of loads (0-40% 1-RM) and depths (0.15-0.75 m) in the JS and concluded that net vertical impulse and peak power best predict JS height regardless of load or depth. However, jump height may not be the most relevant measure of jump performance (Barker, Harry, & Mercer, 2017) and/or representative of the stress placed on the system.

Recently, countermovement jump (i.e., 0% 1-RM JS) performance was assessed using the Reactive Strength Index (RSI) and jump height (Barker et al., 2017). RSI correlated strongly ( $r > 0.5$ ) to eccentric, amortization, and concentric phase variables, while jump height was only correlated to concentric phase variables (Barker et al., 2017). Therefore, force production during eccentric and amortization phases appears to be important for jump performance when time must be minimized.

Training has been reported to influence jumping performance related to the eccentric phase with and without load. Ground reaction forces during the eccentric rate of force development during a JS using 0% 1RM were reported higher ( $55.36 \pm 26.79$  vs  $32.96 \pm 14.83$  N/kg/s) in men following training (Cormie, McBride, & McCaulley, 2009). Further, strength (>70% 1RM) and power (0-30% 1RM) training were reported to improve 0% 1RM jump performance due to increased eccentric phase force production, which correlated ( $r > \pm 0.7$ ) to increased concentric phase force and power production (Cormie, McGuigan, & Newton, 2010). From a mechanical perspective, across increasing absolute loads (0-80 kg) of the JS, the analysis conducted by Cormie et al. (2008) revealed different displacement, velocity, force, and power patterns during the eccentric and concentric phases. Cormie et al. (2008) reported eccentric rate of force development (RFD) differences during JS between 0 kg and 60 kg, and between 0 kg and 80 kg. Although concentric phase variables such as peak power and velocity are well researched, there is less information on parameters during eccentric and amortization phases of a JS.

Using external loading across a range of loads appears to be effective at improving jump performance (Hoffman et al., 2005; McBride et al., 2002), but force production during the

eccentric and amortization phases are not understood as well as the concentric phases during the JS. The principle of *specific adaptations to imposed demands* would dictate there are different eccentric and amortization phase training stimuli across loads, which may partly explain the velocity specific adaptations to various loads used in previous JS training studies (McBride et al., 2002). Therefore, the purpose of this study was to compare eccentric and amortization force production during the JS across a range of external loads (0%, 15%, 30%, 45%, 60% of 1-RM). It was hypothesized that eccentric and amortization phase force production increases non-linearly with added load with a plateau being reached with loads approaching 1-RM. Furthermore, it was recognized that different JS techniques – specifically, depth of squat – may influence force production. Therefore, a secondary purpose of this study is to compare eccentric and amortization force production during the JS with three techniques (preferred, quarter, full countermovement depths). This study aims to support coaches’ and athletes’ understanding of eccentric and amortization force production during the JS, which can support training stimuli awareness and exercise instruction to improve training and performance.

## Methods

### *Experimental Approach to the Problem*

The JS is used as a training stimulus to improve power output and jump performance. However, eccentric and amortization phase force production has not been examined across a range of loads and depths. As such, a within-participants comparison was performed on the JS across five loads (0%, 15%, 30%, 45%, 60%) and three depths (preferred, quarter, full) in recreationally trained males.

### *Participants*

A convenience sample of 12 healthy, resistance-trained men ( $24.80 \pm 4.04$  yrs,  $86.71 \pm 15.59$  kg,  $1.78 \pm 0.79$  m, 3-RM Back Squat:  $123.2 \pm 23.79$  kg) were recruited from the university kinesiology department. Participants were required to have at least one year of resistance training ( $\geq 2x/week$ ) including variations of jumping and squatting, and without any injury that would affect their ability to jump with external resistance. Participants wore their own shod athletic shoes, but were not allowed to wear specialized Olympic weightlifting or powerlifting shoes because the elevated heel in these shoes could influence results. All volunteers were briefed on the risks and benefits of the study. Prior to participation all participants signed informed consents approved by the local Institutional Review Board.

### *Procedures*

A dual force platform setup (9281CA & 9281B, Kistler Instruments, Corp., Amherst, NY, USA,) was used to measure vertical ground reaction forces for each foot at a sampling frequency of 1,000 Hz during all JS. Each participant completed two data collection sessions at least 48 hours apart and within 10 days.

On the first session, anthropometric and demographic data (height, weight, body composition, age, shoe size, sex, and general sport participation) were measured and recorded. Participants presented to the data collection fasted from water and food for 3 hours to standardize the body composition test (InBody 770, InBody, CA, USA). After body composition measures were taken, participants were allowed water and/or food prior to testing. All participants completed a standardized warm up consisting of two sets of 10 repetitions of

squats, lunges, vertical jumps. The 3-RM back squat test followed the protocol recommended by the National Strength and Conditioning Association (Haff & Triplett, 2015). The first warm up set required 5-10 repetitions. The second warm up set and beyond required 2-5 repetitions until a 3-RM was attempted. Participants were verbally encouraged to move the barbell as quickly as possible during the 3-RM attempt. Participants were instructed to attain a depth that placed their thighs parallel to the ground, and was supervised by a certified strength and conditioning specialist. Participants were allowed multiple attempts at the 3-RM to attain the highest load possible. The 3RM was recorded and used to calculate an estimated 1RM back squat to prescribe relative JS loads on the second data collection. The 3-RM represented 90% of estimated 1RM ( $3RM / 0.9 = 1RM$ ).

Session two collection began with the standardized warm up. For this session, participants used the barbell during the warm up for their vertical jumps to get familiar with the collection set up. All trials began with the participant standing still and ended by returning to a stand. Participants performed the JS at incremental loads (0%, 15%, 30%, 45%, 60% of estimated 1-RM back squat) with a return to 0% for the last condition. The return to a 0% JS load was used to determine if fatigue or potentiation occurred due to the protocol. They were instructed to lower themselves as quickly as possible and jump as high as possible for each trial. The preferred countermovement depth (PREF) was performed prior to the quarter or full depths, and was cued as “lower yourself to your preferred depth to jump as high as possible”. To cue the quarter depth (QTR) JS, participants were instructed to lower themselves to as “short a depth as possible, similar to a quarter squat”. To cue the full depth (FULL) JS, participants were instructed to lower themselves “as far as possible while maintaining their

back posture.” Each load condition required three successful trials with PREF, followed by QTR or FULL in a counterbalanced order (e.g. PREF then QTR/FULL). A successful trial required a smooth transition from countermovement to concentric phases in addition to landing and returning to a standing position. Participants were given five seconds between trials to reset. Between load-technique conditions, participants were allowed 30-120 seconds of rest. They were not allowed to start before 30 seconds or after 120 seconds. Participants were made aware of the current recovery time and verbally acknowledged when they were ready to start the next set of three trials. Participants took longer than one minute to recover only during the 45% and 60% 1RM conditions, and frequently began JS trials after 30 seconds. Each participant completed the protocol with no more than three mistrials. Fifty-four successful trials (load (6) x technique (3) x trials (3)) were required to complete the second session’s data collection.

#### *Data Reduction*

Vertical ground reaction force (Fz) data were exported and analyzed using a custom MATLAB (2016a, MathWorks, Natick, MA, USA) script. Prior to analysis, Fz signals from each force platform were smoothed with a fourth-order low-pass Butterworth filter with a cutoff of 50 Hz. Total Fz was calculated by adding Fz from each force platform and used for subsequent calculations and analysis.

The start of the countermovement was identified as the moment Fz was reduced below 7.5% of the system weight (N, participant and barbell). Takeoff was calculated as the moment Fz went below 25 N prior to flight. Vertical acceleration of the center of mass (COM) was calculated using Fz and Newton’s Law of Acceleration ( $a = (Fz - \text{system weight})/\text{mass}$ ). Vertical

velocity of the COM was calculated by integrating vertical acceleration with respect to time.

Vertical displacement of the COM was calculated by integrating vertical velocity with respect to time.

The JS phases were divided in accordance with a recent analysis of countermovement jumps (Barker et al., 2017). The eccentric phase begins at the minimum Fz and ends when the COM reaches its lowest position. Two separate methods were used to calculate eccentric RFD: from minimum Fz to the first peak Fz (Eccentric RFD1), and from minimum Fz to the amortization Fz (Eccentric RFD2).

The amortization phase was identified as beginning when the COM position was 1 cm away from the lowest position and ending 1 cm after reaching the lowest position. The concentric phase was defined as occurring from the lowest COM position to takeoff, but was not used for any discrete variables in this study. It is important to note that the amortization phase overlaps into both eccentric and concentric phases, which is represented by amortization time. Calculations of these dependent variables are provided in Table 1. All Fz variables (amortization Fz, Eccentric RFD, Eccentric RFD2, Fz1, peak power) were normalized to participant mass for statistical analysis and reporting results. The trial that yielded the highest jump height was selected for analysis.

### *Statistical Analysis*

There were ten dependent variables focused on jump performance, eccentric force production, and amortization force production (Table 1). Jump performance variables included jump height, RSI, countermovement depth, and peak power. Eccentric force production

variables included Eccentric RFD, Eccentric RFD2, 1<sup>st</sup> peak Fz (Fz1), and time to Fz1 relative to countermovement time (Fz1 Time). Amortization force production variables included amortization Fz and amortization time.

A 3x5 (technique x load) repeated measures ANOVA (RM-ANOVA) was conducted on all dependent variables. Mauchly's test for sphericity determined if differences in variances met requirements for a RM-ANOVA. If Mauchly's test was violated, the Greenhouse-Geisser adjustment of degrees of freedom was used to report a more conservative p-value. If a depth by load interaction was present, planned comparisons were executed with one-way RM-ANOVAs on each level of depth and load factors (i.e., 8 one-way RM-ANOVAs per interaction). If no depth by load interaction was present, simple main effects were analyzed. If a main effect was present, pairwise comparisons were made. A paired samples t-test was executed on the first and last 0% load condition to determine any fatiguing or potentiating effects of the protocol.



Table 4. Dependent variable calculations. RFD= Rate of Force Development. Fz= Vertical ground reaction force. COM= Center of Mass. Fz1 = first peak Fz

Variable	Unit	Calculation
Jump height	Meters (m)	$(\text{takeoff velocity})^2 / (2 * 9.81)$
Reactive strength index	N/A	$(\text{Jump height}) / (\text{Time from start to takeoff})$
Countermovement Depth	Meters (m)	Minimum COM displacement from standing position
Peak Power	Watts/mass (W/kg)	Maximum power during the jump (Fz*COM velocity)
Average Concentric Power	Watts/mass (W/kg)	Average power (Fz*COM velocity) from countermovement depth to takeoff
Eccentric RFD1	Newtons/mass/time (N/kg/s)	$(1^{\text{st}} \text{ Fz peak} - \text{minimum Fz during the countermovement}) / (\text{time})$
Eccentric RFD2	Newtons/mass/time (N/kg/s)	$(1^{\text{st}} \text{ Fz peak} - \text{Amortization Fz}) / (\text{time})$
Fz1	Newtons/kg (N/kg)	The 1 <sup>st</sup> local maximum following the minimum Fz from the unloading phase
Fz1 Time	Time (s)	$(\text{Time to Peak Fz}) / (\text{Time to countermovement depth}) * 100$
Amortization Fz	Newtons/kg (N/kg)	Fz at lowest countermovement depth
Amortization time	Time (s)	Total time it takes the COM to enter and exit lowest countermovement depth within 1cm.

## Results

### *Eccentric Phase*

Eccentric RFD1, Eccentric RFD2, and Fz1 were not influenced by the interaction between technique and load ( $p > 0.05$ ), thus pairwise comparisons are reported for significant main effects. Eccentric RFD1 was similar across loads ( $p > 0.05$ ), but increased with QTR ( $92.77 \pm 34.36$  N/kg/s) technique compared to PREF ( $67.24 \pm 23.80$  N/kg/s,  $p < 0.05$ , ES: 0.91) and FULL ( $63.63 \pm 23.06$  N/kg/s,  $p < 0.05$ , ES: 1.05) techniques. Eccentric RFD1 was similar ( $p > 0.05$ ) between PREF and FULL. Eccentric RFD2 was different between all loads (0%:  $72.25 \pm 35.15$  N/kg/s, 15%:  $66.47 \pm 25.60$  N/kg/s, 30%:  $58.84 \pm 19.67$  N/kg/s, 45%:  $52.08 \pm 22.51$  N/kg/s, 60%:  $42.80 \pm 20.68$  N/kg/s,  $p < 0.05$ , ES range: 0.34-1.08) except between 0%-15%, 30%-45%, and 45%-60% ( $p > 0.05$ ). Eccentric RFD2 was significantly different among all techniques (PREF:  $51.51 \pm 18.44$

N/kg/s, QTR:  $79.98 \pm 30.05$  N/kg/s, FULL:  $43.97 \pm 16.08$  N/kg/s,  $p < 0.05$ , ES range: 0.46-1.58), with the QTR eliciting the greatest Eccentric RFD2. Fz1 was not influenced by load (0%:  $22.95 \pm 4.92$  N/kg, 15%:  $24.46 \pm 5.00$  N/kg, 30%:  $23.92 \pm 4.87$ , 45%:  $24.24 \pm 5.02$  N/kg, 60%:  $24.89 \pm 4.33$  N/kg,  $p > 0.05$ ), but presented significant differences among techniques (PREF:  $23.26 \pm 3.69$  N/kg, QTR:  $27.13 \pm 5.03$  N/kg, FULL:  $21.90 \pm 4.10$  N/kg,  $p < 0.05$ , ES range: 0.37-1.20).

Fz1 Time was influenced by the interaction between technique and load ( $p < 0.05$ ), thus planned comparisons are reported. With the 0% and 15% 1-RM load, Fz1 Time was similar across techniques ( $p > 0.05$ ). With the 30% 1-RM load, Fz1 Time was similar between PREF and QTR ( $p > 0.05$ ) and different between PREF and FULL ( $p < 0.05$ ), and between QTR and FULL ( $p > 0.05$ ). With the 45% and 60% 1-RM load, Fz1 Time was similar between PREF and FULL ( $p > 0.05$ ) and different between PREF and QTR ( $p < 0.05$ ), and between QTR and FULL ( $p < 0.05$ ). Using the PREF technique, all loads were different ( $p < 0.05$ ) except between 0% and 15% ( $p > 0.05$ ), 0% and 30% ( $p > 0.05$ ), and 15% and 30% ( $p > 0.05$ ). Using the QTR technique, Fz1 Time was significantly different between 60% and 0%, 15%, and 30% ( $p < 0.05$ ), but the remaining load comparisons were similar ( $p > 0.05$ ). Using the FULL technique, Fz1 Time was significantly different between all loads ( $p < 0.05$ ) except 0% and 15% ( $p > 0.05$ ), 15% and 30% ( $p > 0.05$ ), 30% and 45% ( $p > 0.05$ ), and between 45% and 60% ( $p > 0.05$ ).

Figure 2. Eccentric RFD1. RFD1 was similar across loads ( $p>0.05$ ). Eccentric RFD1 was significantly higher with a QTR technique than PREF ( $p<0.05$ ) and FULL ( $p<0.05$ ) techniques across all loads.

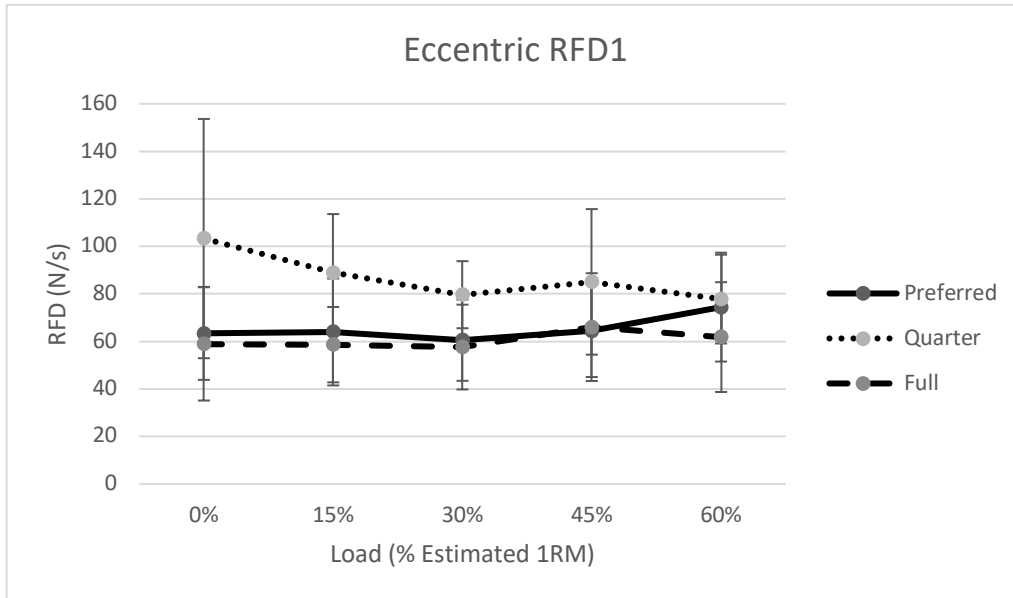


Figure 3. Eccentric RFD2. RFD2 was different among all load comparisons except 0% and 15% ( $p<0.05$ ), 30% and 45% ( $p<0.05$ ), and 45% and 60% ( $p<0.05$ ). Eccentric RFD2 was significantly different among all techniques.

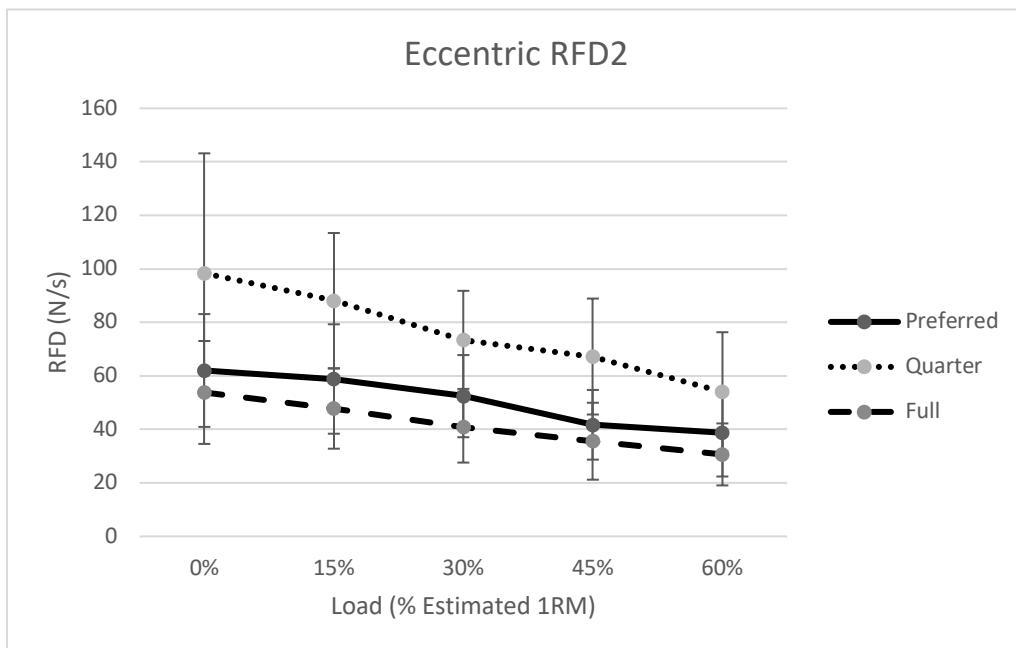
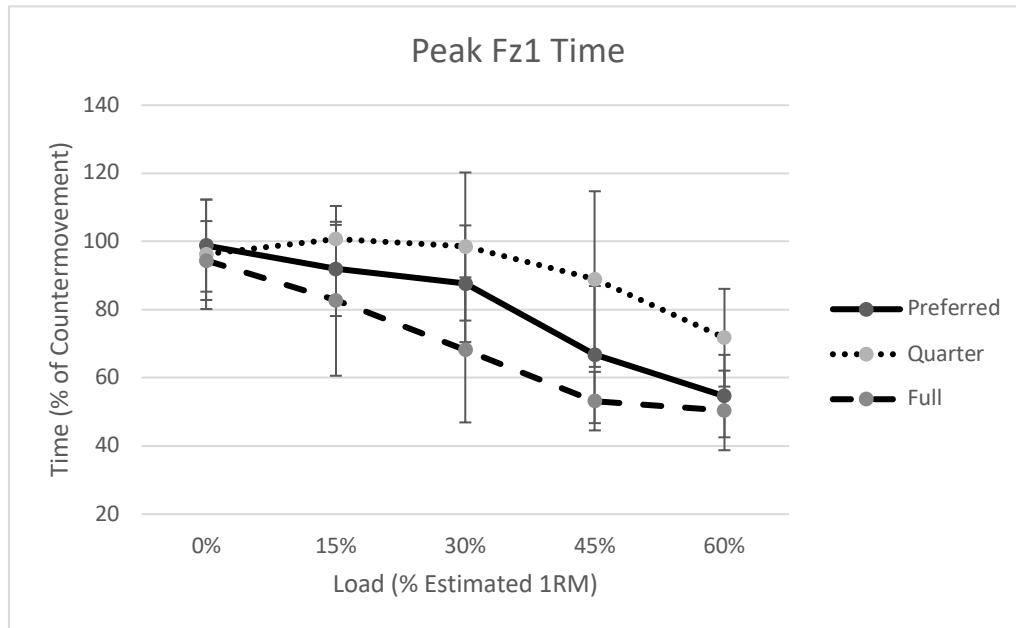


Figure 4. Timing of the first peak Fz (Fz1). Fz1 Time is expressed as a percentage of countermovement duration. Statistical results are provided in the text.



#### Amortization Phase

Amortization time was not influenced by the interaction between technique and load ( $p > 0.05$ ), thus pairwise comparisons are reported for significant main effects. Amortization time significantly increased across increasing loads (0%:  $0.08 \pm 0.01$  s, 15%:  $0.09 \pm 0.01$  s, 30%:  $0.10 \pm 0.02$  s, 45%:  $0.12 \pm 0.02$  s, 60%:  $0.15 \pm 0.03$  s,  $p < 0.05$ , ES range: 1.05-3.3), but was not different across techniques (PREF:  $0.11 \pm 0.03$  s, QTR:  $0.10 \pm 0.02$  s, FULL:  $0.12 \pm 0.04$  s,  $p > 0.05$ ).

Amortization Fz was not influenced by the interaction between technique and load ( $p > 0.05$ ), thus pairwise comparisons are reported for significant main effects. Amortization Fz was greater with QTR than PREF ( $26.97 \pm 3.58$  vs  $24.41 \pm 3.02$  N/kg,  $p < 0.05$ , ES: 0.81), but similar ( $p > 0.05$ ) between PREF and FULL ( $24.42 \pm 3.45$  N/kg), and between QTR and FULL.

Amortization Fz was different between 0% and 15% 1-RM ( $22.86 \pm 3.78$  vs  $24.66 \pm 3.20$  N/kg,

$p < 0.05$ , ES: 0.54), and between 0% and 30% 1-RM ( $22.86 \pm 3.86$  vs  $25.60 \pm 2.83$  N/kg,  $p < 0.05$ , ES: 0.87). Amortization Fz trended differently between 0% and 45% 1-RM ( $22.86 \pm 3.86$  vs  $26.34 \pm 2.97$  N/kg,  $p = 0.051$ , ES: 1.08), and between 0% and 60% 1-RM ( $22.86 \pm 3.86$  vs  $26.87 \pm 3.57$  N/kg,  $p = 0.055$ , ES: 1.15). All loaded conditions (15%-60% 1-RM) were similar ( $p > 0.05$ ).

Figure 5. Amortization Time. Amortization time significantly increased with increasing loads ( $p < 0.05$ ), but was similar among techniques ( $p > 0.05$ ).

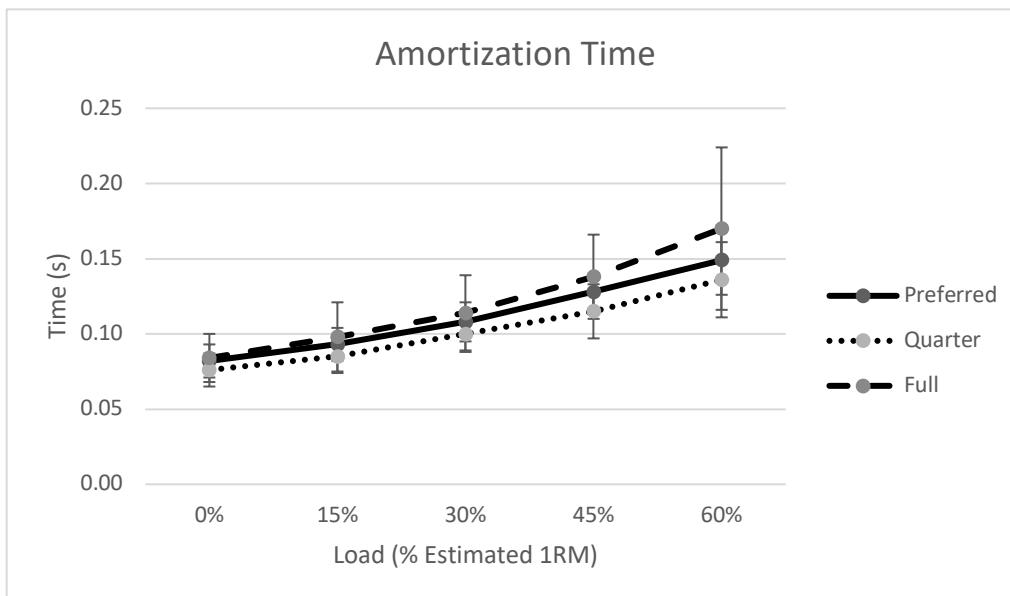
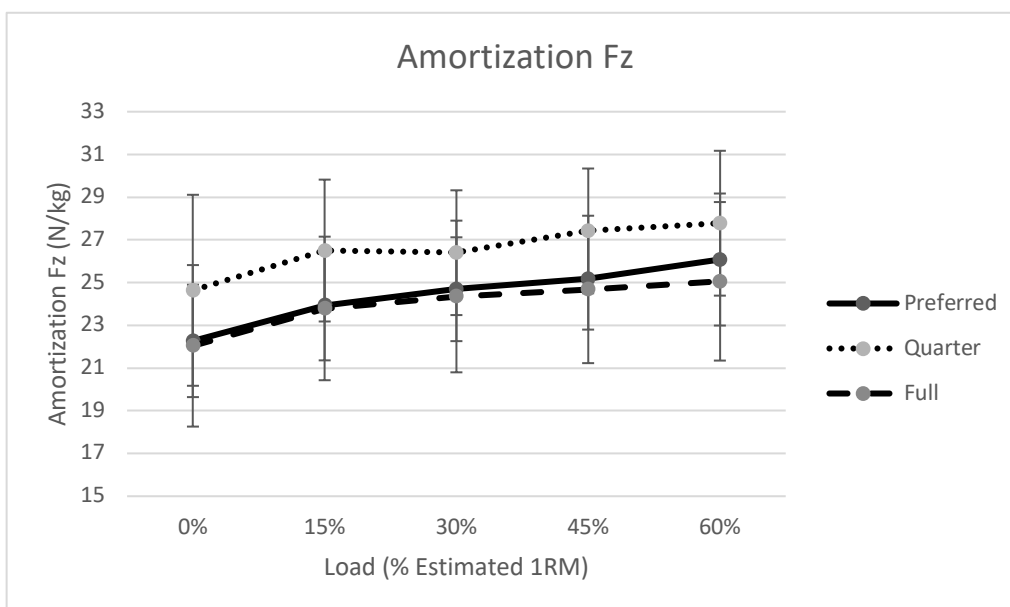


Figure 6. Amortization force (Fz). Amortization Fz was greater with QTR than PREF ( $p < 0.05$ ), but similar between PREF and FULL ( $p > 0.05$ ), and between QTR and FULL ( $p > 0.05$ ). Amortization Fz, among all loaded conditions, was similar ( $p > 0.05$ ), while significant differences were observed between 0% and 15%, and between 0% and 30% ( $p > 0.05$ ).



## *Performance*

Jump height, peak power, and average concentric power were not influenced by the interaction between technique and load ( $p>0.05$ ), thus pairwise comparisons are reported for significant main effects. Jump height significantly decreased with increasing loads (0%:  $0.36 \pm 0.09$  m, 15%:  $0.28 \pm 0.06$  m, 30%:  $0.21 \pm 0.04$  m, 45%:  $0.15 \pm 0.04$  m, 60%:  $0.12 \pm 0.05$  m,  $p<0.05$ , ES range: 0.70-3.47). Jump height was significantly lower with the QTR ( $0.21 \pm 0.10$  m) technique than the PREF ( $0.23 \pm 0.10$  m,  $p<0.05$ , ES: 0.21) or FULL ( $0.23 \pm 0.12$  m,  $p<0.05$ , ES: 0.19), while PREF and FULL were similar ( $p>0.05$ ). Peak power was significantly greater during 15% than 45% ( $53.58 \pm 8.74$  vs  $50.61 \pm 6.89$  W/kg,  $p<0.05$ , ES: 0.40), and greater during 30% than 45% ( $52.01 \pm 7.28$  vs  $50.61 \pm 6.89$  W/kg,  $p<0.05$ , ES: 0.21). Peak power was significantly higher with QTR than FULL ( $53.08 \pm 8.08$  vs  $50.37 \pm 8.37$  W/kg,  $p<0.05$ , ES: 0.35), while peak power was similar ( $p>0.05$ ) between QTR and PREF ( $51.72 \pm 7.98$  W/kg) and between PREF and FULL ( $p>0.05$ ). Average concentric power was significantly different across all techniques (PREF:  $25.20 \pm 4.28$  W/kg, QTR:  $27.79 \pm 4.71$  W/kg, FULL:  $23.42 \pm 3.99$  W/kg,  $p<0.05$ , ES range: 0.45-1.06). Average concentric power was greatest during the QTR technique and lowest during the FULL technique. Average concentric power was significantly different between all loads (0%:  $27.90 \pm 4.34$ , 15%:  $27.55 \pm 4.35$  W/kg, 30%:  $25.84 \pm 4.23$  W/kg, 45%:  $23.46 \pm 3.85$  W/kg, 60%:  $22.60 \pm 4.24$  W/kg,  $p<0.05$ , ES range: 0.42-1.30), except between 0%-15% ( $p>0.05$ ), and 45%-60% ( $p>0.05$ ) 1-RM loads.

RSI was influenced by the interaction between technique and load ( $p<0.05$ ), thus planned comparisons are reported. With a 30% and 45% 1-RM load, RSI was significantly different between all techniques ( $p<0.05$ ). With a 15% 1-RM load, RSI was significantly different

between QTR and FULL ( $p>0.05$ ). With the 0% 1-RM load, RSI was similar between PREF and FULL ( $p>0.05$ ). With the 60% 1-RM load, RSI was significantly different between PREF and QTR ( $p<0.05$ ), and QTR and FULL ( $p<0.05$ ). Using all PREF, QTR, and FULL techniques, RSI significantly decreased across increasing loads ( $p<0.05$ ).

Countermovement depth was influenced by the interaction between technique and load ( $p<0.05$ ), thus planned comparisons are reported. With the 0%, 15%, and 45% 1-RM loads, countermovement depth was significantly different across all techniques ( $p<0.05$ ). With the 30% and 60% 1-RM loads, countermovement depth was similar between PREF and FULL techniques ( $p>0.05$ ). Using the PREF, QTR, or FULL techniques, countermovement depth was not significantly different across loads ( $p>0.05$ ). Therefore, the QTR and FULL depths were distinct throughout, but countermovement depth was similar between PREF and FULL at 30% and 60% 1-RM loads.

With the QTR technique, jump height was not different between the first and last 0% 1-RM loads ( $p>0.05$ ). With the PREF and FULL technique, jump height was significantly greater with the first 0% 1-RM load compared to the last (PREF:  $0.36 \pm 0.05$  m vs  $0.33 \pm 0.06$  m,  $p<0.05$ , FULL:  $0.38 \pm 0.07$  vs  $0.34 \pm 0.05$  m,  $p<0.05$ ). Therefore, minor fatigue (defined by jump height) occurred due to the protocol.



Table 5. Means and standard deviations: jump height, Reactive Strength Index (RSI), countermovement depth, peak power, first Fz peak (Fz1), and average concentric power. # = significantly different across all loads for reach technique. \* = significantly different across all techniques for each load. Significant load and technique comparisons are provided in the text.

Variable		Load				
		0%	15%	30%	45%	60%
Jump Height (m)	PREF	0.36 ± 0.06	0.30 ± 0.07	0.22 ± 0.03	0.16 ± 0.03	0.12 ± 0.03
	QTR	0.33 ± 0.06	0.27 ± 0.04	0.21 ± 0.04	0.15 ± 0.03	0.12 ± 0.03
	FULL	0.38 ± 0.07	0.28 ± 0.05	0.21 ± 0.04	0.15 ± 0.03	0.14 ± 0.06
RSI	PREF	0.47 ± 0.12	0.34 ± 0.11	0.23 ± 0.05	0.15 ± 0.04	0.11 ± 0.03
	QTR	0.55 ± 0.13	0.40 ± 0.08	0.29 ± 0.06	0.19 ± 0.04	0.13 ± 0.05
	FULL	0.41 ± 0.11	0.28 ± 0.05	0.18 ± 0.04	0.12 ± 0.03	0.09 ± 0.03
CM Depth (m)	PREF	-0.36 ± 0.06	-0.38 ± 0.08	-0.38 ± 0.09	-0.36 ± 0.08	-0.32 ± 0.08
	QTR	-0.26 ± 0.06	-0.26 ± 0.05	-0.26 ± 0.05	-0.24 ± 0.04	-0.23 ± 0.06
	FULL	-0.44 ± 0.06	-0.48 ± 0.06	-0.46 ± 0.10	-0.44 ± 0.08	-0.37 ± 0.16
Peak Power (W/kg)	PREF	53.02 ± 8.72	55.06 ± 9.82	52.97 ± 9.77	50.34 ± 7.86	49.39 ± 6.16
	QTR	54.86 ± 8.36	55.67 ± 6.89	54.20 ± 8.09	52.46 ± 8.80	50.34 ± 7.84
	FULL	52.01 ± 8.55	51.98 ± 8.21	50.83 ± 7.81	48.89 ± 5.94	51.79 ± 11.09
Peak Fz1 (N/kg)	PREF	22.2 ± 3.47	23.37 ± 3.90	23.68 ± 3.87	22.47 ± 3.96	23.78 ± 3.79
	QTR	24.07 ± 5.86	26.92 ± 3.98	27.24 ± 4.22	27.68 ± 4.10	26.78 ± 3.82
	FULL	21.32 ± 4.49	22.31 ± 5.15	20.97 ± 4.59	20.65 ± 2.47	22.26 ± 3.74
Average Con. Power (W/kg)	PREF	27.53 ± 4.00	27.51 ± 4.51	25.62 ± 4.03	23.05 ± 3.28	22.28 ± 2.88
	QTR	29.92 ± 4.77	30.05 ± 4.26	28.22 ± 4.34	26.26 ± 3.49	24.50 ± 4.71
	FULL	26.24 ± 3.69	25.10 ± 2.87	23.67 ± 3.23	21.10 ± 3.04	21.01 ± 4.46

## Discussion

### *Main Observations*

A major observation of this study is that amortization Fz relative to participant mass, which represents storage of elastic strain energy in the system at concentric initiation (Bobbert, Gerritsen, Litjens, & VanSoest, 1996), increased from 0% to 15% and 0% to 30% 1-RM but did not differ among loads. Further, the QTR technique elicited greater amortization Fz at all loads

compared to PREF and FULL techniques. In addition, eccentric RFD1 and Eccentric RFD2 were greater during the QTR JS compared to PREF and FULL across loads. Therefore, across loads, the QTR JS elicited lesser jump heights, but greater RSI, eccentric RFD1, Eccentric RFD2, Fz1, and amortization Fz. Thus, short amplitude JS appears to stimulate stretch-shortening cycle characteristics more than the PREF or FULL techniques. However, it is important to elaborate on the various methods of calculating eccentric RFD, specifically pertaining to the effect of load on GRFs during the JS.

The difference between Eccentric RFD1 and Eccentric RFD2 may reveal unique information on eccentric force production. In the current literature, there is variation in methods for calculating eccentric rate of force development (RFD) during countermovement jumps. One report investigating loading comparisons calculated eccentric RFD as the change in Fz magnitude from the countermovement initiation to the amortization phase (Cormie et al., 2008), while another report investigating countermovement jumping (i.e. 0% 1-RM JS) calculate eccentric RFD from the minimum Fz to Fz1 (Laffaye & Wagner, 2013). Calculating eccentric RFD from the countermovement initiation to amortization Fz discounts the influence of the initial unloading of system mass, which generates kinetic energy (during downward movement) and is associated with subsequent eccentric demands (Barker et al., 2017). Alternatively, calculating eccentric RFD from the minimum Fz to Fz1 may not be appropriate for the JS with external load. Once external load is applied (i.e. during the JS), Fz1 occurs before the amortization Fz and does not completely capture the eccentric phase of the countermovement. Therefore, two methods of calculating RFD seemed appropriate for this study: from the minimum Fz to Fz1 divided by time (eccentric RFD1), and from minimum Fz to amortization Fz divided by time (Eccentric

RFD2). To further support the need for two variables to represent eccentric RFD, Fz1 Time was influenced by the interaction of technique and load. During the QTR JS, Fz1 Time occurred closer to the amortization Fz (i.e. ~100%) than the PREF or FULL JS with loads of 30% and higher, but was similar to FULL JS with 0% and 15% loads. With light loads, the depth does not appear to influence the amortization Fz from the Fz1. But with moderate loads, Fz1 would necessarily need to increase in magnitude to generate a large enough vertical impulse for amortization Fz and Fz1 to align in the time domain. However, there was no influence of load on Fz1 magnitude, which led to the delay of amortization Fz from Fz1 as loads increased. However, Fz1 was 2-5 N/kg higher with the QTR JS across all loads compared to PREF and FULL JS. The QTR JS, again, appears to hold potential as a training stimulus for these eccentric force production characteristics despite minimal influence on peak power and a decrease in jump height.

Our results are comparable to the amortization Fz and eccentric RFD outcomes reported in previous research (Cormie et al., 2009, 2010; Laffaye & Wagner, 2013). During countermovement jumps (i.e. 0% 1-RM), one study calculating eccentric RFD from countermovement initiation to end reported  $32.93 \pm 16.02$  N/kg/s (Cormie et al., 2009). Two studies calculating eccentric RFD from minimum Fz to maximum Fz in the eccentric RFD reported values ranging 50 N/kg/s to 150 N/kg/s (Cormie et al., 2010; Laffaye & Wagner, 2013). Therefore, our values for eccentric RFD and Eccentric RFD2 are within the range of expected values. Loaded JS have not been investigated for eccentric RFD to compare results.

There was an interesting observation regarding the load that decreased Fz1 Time below 90% of the countermovement duration. The QTR JS went below 90% at 45% 1-RM, the PREF JS

at 30% 1-RM, and the FULL JS at 15% 1-RM. The length-tension relationship contributes to the explanation of the eccentric and amortization prowess of the QTR JS, which has potential to optimize actin-myosin interaction. However, the length-tension relationship of muscle does not represent all sources of elastic strain energy in the system, in addition to unknown muscle fascicle lengths in vivo. Connective tissue in muscle includes predominantly titin and fascia surrounding contractile elements, both of which are mediated by calcium to suggest voluntary control of elastic stiffness (Herzog, Schappacher, DuVall, Leonard, & Herzog, 2016). But, tendon and bone contribute strain energy to the system as well, and may absorb strain energy more effectively. This is a reasonable conclusion in vivo with a recent investigation reporting faster movements induced greater tendon strain (Earp, Newton, Cormie, & Blazevich, 2016), and the evidence reporting increased joint loading with stiffer landings (Devita & Skelly, 1992; Hewett et al., 2005; Pollard, Sigward, & Powers, 2010). Furthermore, in stiff stretch-shortening cycle movements such as running, tendon buffers energy by lengthening while muscle acts nearly isometrically during muscle-tendon unit lengthening, allowing the muscle greater time and lesser displacement to disperse forces and reduce work (Konow, Azizi, & Roberts, 2012; Roberts & Konow, 2013). This interaction between muscle and tendon effectively allows strain to be dispersed towards more resilient tissues than muscle (Roberts & Konow, 2013). Therefore, fast movements utilizing a stretch-shortening cycle appear to strain connective tissue throughout the system more than the contractile elements of muscle alone (Earp et al., 2016; Earp, Newton, Cormie, & Blazevich, 2017; Konow et al., 2012; Roberts & Konow, 2013).

Maximizing power output is a justifiably common objective of strength and power training programs, but coaches and athletes may benefit from emphasizing eccentric and

amortization phases of movements to develop performance and durability during fast stretch-shortening cycle movements. Although the QTR JS presented some advantages for stretch-shortening cycle characteristics in the current study, competition often demands fast stretch-shortening cycle performance from a variety positions and postures. Therefore, a diverse exercise selection may be warranted to develop stretch-shortening cycle abilities for a variety of environments, and cues to encourage a fast countermovement or change of direction may be the most practical way to stress the elastic strain energy capacity of a given movement. The countermovement depth of the QTR was significantly shorter than FULL (approximately -0.25 m vs -0.45 m) across all loads, but the PREF depth fluctuated toward the QTR depth during the 0% and 60% 1-RM loads, and toward the FULL depth during the 15% 1-RM loads. Therefore, the verbal cues used in this study were effective at inducing a distinct range of countermovement depths and variable preferred countermovement depths.

### *Confounding Factors*

While the differences in depths were distinct between the QTR and FULL techniques, there may have been some novelty to participants executing the JS using three separate depths based on verbal cues. The standardized warm up and practice jumps ameliorated this concern, but manipulating countermovement with verbal cues may yield greater variability than a strict control such as an auditory cue or defined squat depth. However, this study analyzed one trial for each load-technique condition and used a within-participants design, thus there is no within-participant variability assessment.

Lastly, it is important to recognize that 1-RM might be different based upon depth of squat. A quarter squat 1-RM will likely be greater than a full squat 1-RM, which would make the loads prescribed from a full squat 1-RM too light for the QTR JS. However, consistency with loads and depths was a priority of this study.

### *Limitations*

This study measured GRF alone, but using GRF to interpret stretch-shortening cycle characteristics is debatable because of the diverse characteristics (i.e. fiber type, size, shape, and function) among muscles of the lower extremity. The data presented on the center of mass is useful to understand system force production during the JS of various loads and depths, but it is not clear if lower extremity joints and muscle-tendon units present varying characteristics among those different JS styles.

Lastly, conclusions from this study should not be generalized to females, and caution should be taken generalizing to specific sporting populations. Although these participants were recreationally trained males, training backgrounds varied between subjects and it is not clear if eccentric and amortization GRF variables would differ with females or populations that perform more (or less) specific training. For example, Olympic weightlifters utilize large ranges of motion during the catch but short ranges of motion during the jerk. In contrast, strength and power sports such as basketball, football, soccer, and running may use predominantly short range of motion movements in competition and training. The ability to optimize the stretch-shortening cycle will likely differ between these groups, and practitioners should consider countermovement depths aligning with sport specific movements.

## *Conclusion*

In conclusion, our hypothesis remains tenable that eccentric and amortization GRFs would increase non-linearly. Eccentric RFD2 increased with load, while eccentric RFD1 did not. Amortization Fz exhibited a plateau among loads. Furthermore, the QTR JS displayed significantly higher rates of force production during eccentric and amortization phases. Further studies may be warranted with different populations to support or refute these current results. Based on the current study, it is recommended that QTR techniques be used in conjunction with FULL or PREF techniques throughout a comprehensive training plan purposed for development of stretch-shortening cycle performance.

## Practical Applications

Strength and conditioning professionals selecting exercises to maximize eccentric and amortization Fz should consider the JS with light loads and quarter depth JS with light and moderate loads. Although maximizing speed, power, and strength are strong stimuli for developing these qualities in athletes, specialized training to develop eccentric and amortization phases during movements utilizing the stretch-shortening cycle should be considered similarly important for performance and durability. If an athlete can improve their eccentric and amortization force production at higher relative loads, they may see improved stretch-shortening cycle capacity during competition when abrupt changes of direction from high speeds or with external load is demanded.

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# EFFECT OF LOAD AND DEPTH OF JUMP SQUAT ON JOINT KINETICS DURING THE ECCENTRIC AND AMORTIZATION PHASES

## Significance of the Chapter

The purpose of chapter 4 is to investigate and discuss the influence of load and countermovement technique on joint kinetics during the eccentric and amortization phases. The results from chapter 3 indicated that eccentric rate of force development can be calculated using two methods; (1) from the minimum ground reaction force to the first peak (RFD1), and (2) from the minimum ground reaction force to the force at amortization (RFD2). RFD1 was not influenced by load and technique, but RFD2 decreased with load (PREF: 62.01 to 38.74, QTR: 98.35 to 54.04, FULL: 53.80 to 30.64 N/kg/s). Further, amortization force did not increase as hypothesized with increasing loads. It is not clear why amortization force appeared to plateau with increasing loads, but two considerations are proposed in this chapter, which demonstrated similar kinetic responses of the center of mass and individual joints during amortization. In this chapter, the concept of deceleration demands due to kinetic energy will be discussed and how the muscle spindle and Golgi tendon organ may adjust countermovement strategies to reduce the development of downward kinetic energy with increasing external loads.

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## Abstract

There is limited research on joint kinetics during the eccentric and amortization phase of the jump squat. Therefore, the purpose of this study was to compare joint kinetics during the eccentric and amortization phases of the JS across a range of loads and depths. A second purpose of this study is to compare the deceleration contributions from the hip and knee. A convenience sample of 10 healthy, resistance-trained men ( $24.80 \pm 4.24$  yrs,  $88.35 \pm 16.71$  kg,  $178.15 \pm 7.15$  cm, 3-RM Back Squat:  $119.27 \pm 21.78$  kg) performed jump squats across a range of loads (0%, 15%, 30%, 45%, 60% of 1-RM) and countermovement techniques (QTR, PREF, and FULL). Eccentric joint work, eccentric hip to knee work ratio, amortization joint moment, and performance variables were analyzed with a 3x5 repeated measures ANOVA. To summarize the eccentric phase, hip and knee joint work was reduced using a quarter depth across all loads ( $p < 0.05$ ), and eccentric hip to knee work ratio was greatest with FULL JS ( $p < 0.05$ ). Amortization hip moment was significantly less using a QTR technique compared to PREF or FULL ( $p < 0.05$ ). Amortization knee or ankle moments were not influenced by technique ( $p > 0.05$ ). Amortization hip moments were not influenced by load ( $p > 0.05$ ). Amortization ankle moments were significantly greater with 0% than 15% 1-RM ( $p < 0.05$ ), but similar among all loads ( $p > 0.05$ ). There was no observed main effect of load on amortization knee moments ( $p > 0.05$ ). The QTR technique elicited the greatest RSI, peak power, and average concentric power ( $p < 0.05$ ), and the lowest jump height and peak countermovement kinetic energy ( $p < 0.05$ ). In conclusion, coaches should consider QTR and FULL JS techniques separate exercises and stimuli during jump training. It may be best to focus on developing the technique closely related to the competition movement. Further, coaches should consider defining, monitoring, and cueing

specific countermovement strategies for consistent training programs aiming to improve deceleration abilities.

## Introduction

The jump squat (JS) is an effective training exercise for externally loading the countermovement jump (CMJ) to improve strength, power, and speed in sporting populations (Cormie, McBride, and McCaulley 2008; Dugan et al. 2004; I Loturco et al. 2015; Irineu Loturco et al. 2015; MacKenzie, Lavers, and Wallace 2014; McBride et al. 2010; Moir et al. 2012). Power is a key mechanical variable, which can be developed using the JS in training to improve sport performance (Cormie, McCaulley, and McBride 2007; Cronin and Hansen 2005; McBride et al. 2002; Sleivert and Taingahue 2004). At the joint level, angular power is calculated as the product of joint moment and angular velocity. At the system level, power is the product of center of mass (COM) vertical velocity and vertical ground reaction force (vGRF) when using force platforms (Dugan et al. 2004).

Selecting loads in training that maximize power is important for coaches and athletes, but lower extremity joint powers and system power peak at different loads. Across a range of JS loads, it has been reported that joint powers peak in the ankle and knee at 0% of 1-repetition maximum (1-RM) back squat, while hip joint power was maximized when using 42% of 1-RM (Moir et al. 2012). Further, system power was maximized with 0% 1-RM and was related to peak ankle and knee joint powers but not peak hip joint power (Moir et al. 2012). In contrast, another study reported peak ankle and knee joint powers at 0% and 70% of 1-RM, while loads maximizing system power did not simultaneously maximize individual joint powers (Jandacka et al. 2014). Taken together, there is no singular external load eliciting peak joint powers in the JS (Jandacka et al. 2014; Moir et al. 2012), and it appears lower extremity joint power and system power peak at different points as JS loads increase.

A limitation of the research done to date is that peak joint and system power is isolated to the concentric phase of the JS (Jandacka et al. 2014; Moir et al. 2012). There is limited research on joint kinetics during the eccentric and amortization phases of the JS (Cormie, McBride, and McCaulley 2008). A recent analysis investigated system kinetics in the eccentric and amortization phases of CMJ (Barker, Harry, and Mercer 2017). During a CMJ, jump height was strongly correlated ( $r > 0.5$ ) to only concentric kinetics, while the Reactive Strength Index (RSI = jump height/jump time), a time-sensitive jump performance parameter, was strongly correlated eccentric, amortization, and concentric kinetics (Barker, Harry, and Mercer 2017). Therefore, greater eccentric and amortization kinetics is related to faster jump performance rather than higher jump performance.

Faster movement speeds were reported to increase tendon strain, especially during the eccentric phase of a maximum speed JS compared to a slow-tempo squat (Earp et al. 2016). Incorporating fast, externally loaded movements into training programs to induce tendon strain has potential to improve deceleration and stretch-shortening cycle abilities associated with fast movements like jumping, running, and change of directions. These notions are confirmed by a report demonstrating both strength and power training improved jump performance due to changes in eccentric phase kinetics (Cormie, McGuigan, and Newton 2010). Since eccentric training can benefit performance and durability (Brughelli and Cronin 2007; Petersen et al. 2011), training program design could benefit from improved understanding of the eccentric and amortization phase kinetics of the JS utilizing different loads and depths.

A recent investigation of the JS across five loads and three countermovement depths reported varying eccentric and amortization kinetics (Barker & Mercer, in press). Across all



loads, the quarter depth JS increased amortization GRF by approximately 2 N/kg across loads compared to the preferred countermovement depth, but interestingly, was similar to the full depth JS (Barker & Mercer, in press). Further, amortization GRF was different between 0% and the loaded conditions, but similar across 15%-60% 1-RM (Barker & Mercer, in press). Eccentric rate of force development (RFD) was highly variable in response to load and depth, but was maximized with the quarter depth and light loads (Barker & Mercer, in press). Thus, from a system perspective, it appears deceleration kinetics are maximized with light loads and shorter countermovement depths and stressed with moderate and heavy loads or deeper countermovement depths (Barker & Mercer, in press) . It is not clear how joint kinetics during eccentric and amortization phases respond to JS loads and depths.

If system and joint kinetics are not simultaneously maximized in the concentric phases of the JS (Jandacka et al. 2014; Moir et al. 2012), exploration of joint kinetics during eccentric and amortization phases is warranted to better understand the training stimuli of these phases. Therefore, the purpose of this study was to compare joint kinetics during the eccentric and amortization phases of the JS across a range of loads and depths. A second purpose of this study is to compare the deceleration contributions from the hip and knee.

## Methods

### *Experimental Approach to the Problem*

The effect of load and depth on eccentric and amortization joint kinetics during the JS is not understood. As such, a within-participants comparison was performed on the JS across five loads (0%, 15%, 30%, 45%, 60%) and three depths (preferred, quarter, full) in recreationally

trained males. To investigate joint kinetics during the JS, a biomechanical analysis was performed on ground reaction forces and sagittal lower extremity kinematics.

### *Participants*

A convenience sample of 10 healthy, resistance-trained men ( $24.80 \pm 4.24$  yrs,  $88.35 \pm 16.71$  kg,  $178.15 \pm 7.15$  cm, 3-RM Back Squat:  $119.27 \pm 21.78$  kg) were recruited from the university kinesiology department. Participants currently resistance training ( $\geq 2x/week$ ) for at least 1 year, which included jumping and squatting exercises, and without any injury that would affect their ability to jump with external resistance. Participants wore traditional shod athletic shoes. All volunteers were briefed on the risks and benefits of the study. Prior to participation, all participants signed informed consents approved by the local Institutional Review Board.

### *Procedures*

These procedures are described elsewhere (Barker & Mercer, 2018, in press), but are restated here in brief. A dual force platform setup (9281CA & 9281B, Kistler Instruments, Corp., Amherst, NY, USA,) was used to measure vertical ground reaction forces for each foot at a sampling frequency of 1,000 Hz during all JS. A 12-camera 3D motion capture system (Vicon Motion Capture Systems, CA, USA) collected lower extremity reflective markers. Each participant completed two data collection sessions at least 48 hours apart and within 10 days.

On the first session, anthropometric and demographic data (height, weight, body impedance, age, shoe size, gender, and general sport participation) were measured and recorded. Participants presented to the data collection fasted from water and food for three

hours to standardize the body composition estimation (InBody 770, InBody, CA, USA). After body impedance measures were taken and body composition estimation recorded, participants were allowed water and/or food prior to testing. All participants completed a standardized warm up consisting of two sets of ten repetitions of squats, lunges, vertical jumps. The 3-RM back squat test followed the protocol recommended by the National Strength and Conditioning Association (Haff & Triplett, 2015). The first warm up set required 5-10 repetitions. The second warm up set and beyond required 2-5 repetitions until a 3-RM was attempted. Participants were verbally encouraged to move the barbell as quickly as possible during the 3-RM attempt. Participants were instructed to attain a depth that placed their thighs parallel to the ground, and was supervised by a Certified Strength and Conditioning Specialist. Participants were allowed multiple attempts at the 3-RM to attain the highest load possible. The 3RM was recorded and used to calculate an estimated 1-RM back squat to prescribe relative JS loads on the second data collection. The 3-RM represented 90% of estimated 1-RM ( $3\text{-RM} / 0.9 = 1\text{-RM}$ ).

At the beginning of the second session, participants were outfitted with lower extremity reflective markers. Bilateral bony landmarks included: Posterior superior iliac spine, sacrum, Iliac crest, greater trochanter, medial/lateral knee, medial/lateral malleoli, 1<sup>st</sup> metatarsal, 5<sup>th</sup> metatarsal. Rigid body clusters were attached bilaterally to the thigh, leg, and heel. The rigid body clusters were worn during dynamic trials only, while the bony landmarks were worn during a static calibration trial only. The posterior superior iliac spine (2) and sacrum remained for dynamic trials to track the pelvis segment. The foot, shank, thigh, and hip were modeled as cylinders. The hip segment model did not include the anterior superior iliac spine because those markers can be occluded at amortization during PREF and FULL JS. Omitting these markers

resulted with incorrect standing segment angles of the pelvis (i.e. excessive posterior tilt) that were corrected by setting the standing pelvis angle to 0°. The hip joint's center of rotation was not influenced by the pelvic markers, thus the model did not require further adjustments to attain joint moment data.

Following marker placement, participants performed the standardized warm up. For this day, participants used the barbell during the warm up for their vertical jumps to get familiar with the data collection set up. All trials began with the participant standing still and ended by returning to a stand. Participants performed the JS at incremental loads (0%, 15%, 30%, 45%, 60% of estimated 1-RM back squat) with a return to 0% for the last condition. The return to a 0% JS load was used to determine if fatigue or potentiation occurred due to the protocol. They were instructed to lower themselves as quickly as possible and jump as high as possible for each trial. The preferred countermovement depth (PREF) was performed prior to the quarter (QTR) or full (FULL) techniques, and was cued as "lower yourself to your preferred depth to jump as high as possible". To cue the QTR technique, participants were instructed to lower themselves to as "short a depth as possible, similar to a quarter squat". To cue the FULL JS, participants were instructed to lower themselves "as far as possible while maintaining their back posture." Each load condition required three successful trials with PREF, followed by QTR or FULL in a counterbalanced order (e.g. PREF then QTR/FULL). A successful trial required a smooth transition from countermovement to concentric phases in addition to landing and returning to a standing position. During data processing, some trials were deemed mistrials due to large fluctuations in standing vertical ground reaction forces prior to initiating the JS, particularly at the 45% and 60% 1-RM conditions. Participants were given five seconds between

trials to reset (i.e. sets of three repetitions). Between load-technique conditions, participants were allowed 30-120 seconds of rest. They were not allowed to start before 30 seconds or after 120 seconds. Participants were made aware of the current recovery time and verbally acknowledged when they were ready to start the next set of three trials. Participants took longer than one minute to recover only during the 45% and 60% 11RM conditions, and frequently began JS trials after 30 seconds. Each participant completed the protocol with no more than three mistrials. 54 successful trials (load (6) x technique (3) x trials (3)) were required to complete the second session.

#### *Data Reduction*

Individual marker data were exported to Visual3D software (C-Motion, Inc. MD, USA) to build a kinematic model of the lower extremity. Position data were interpolated, then filtered with a fourth-order Butterworth low-pass filter using a cutoff frequency of 10 Hz. Fz signals from each force platform were filtered with a fourth-order low-pass Butterworth filter with a cutoff of 50 Hz. The model was synchronized with the bilateral 3D GRFs to calculate joint angles and moments using inverse dynamics. Joint moments were defined as positive for extensor moments (Moir et al., 2012). The model data (kinematics and GRF) were exported again, and processed by a custom computer program (MATLAB 2016b, MathWorks, MA, USA) to extract dependent variables.

Fz was summed from each force platform for total Fz, which was used to analyze COM kinetics and derive COM acceleration, velocity, and displacement. The start of the countermovement was identified as the frame Fz was reduced below 7.5% of the system

weight (N, participant and barbell). This threshold was used (in contrast to 5%) to improve the consistency of identifying the countermovement initiation with the heavier loads. Takeoff was calculated as the moment  $F_z$  went below 25 N prior to flight. Vertical acceleration of the center of mass (COM) was calculated using  $F_z$  and Newton's Law of Acceleration (acceleration =  $(F_z - \text{system weight})/\text{mass}$ ). Vertical velocity of the COM was calculated by integrating vertical acceleration with respect to time. Vertical displacement of the COM was calculated by integrating vertical velocity with respect to time.

The JS phases were divided in accordance with a recent analysis of countermovement jumps (Barker, Harry, and Mercer 2017). The eccentric phase begins at the minimum  $F_z$  and ends when the COM reaches its lowest position. During the eccentric phase, joint work was calculated as the area under the moment-angle curve for the hip and knee. The ankle was not included in eccentric work because it plays a minimal role during the eccentric phase. Eccentric hip work was related to eccentric knee work using a hip to knee ratio (HKR) calculated by dividing eccentric hip work by eccentric knee work (i.e. HKR=1 is evenly distributed).

The amortization phase was identified as beginning when the COM position was 1 cm away from the lowest position and ending 1 cm after reaching the lowest position. Amortization joint moments were extracted from this lowest COM position. It is important to note that the amortization phase overlaps into both eccentric and concentric phases.

### *Statistical Analysis*

There were eleven dependent variables focused on jump performance, eccentric joint work, and amortization joint moments (Table 6). Jump performance variables included jump

height, RSI, countermovement depth, peak power, and average concentric power. Eccentric variables include eccentric joint work from the hip and knee, and eccentric work HKR.

Amortization variables include amortization joint moments from the hip, knee, and ankle.

A 3x5 (technique x load) repeated measures ANOVA (RM-ANOVA) was conducted on all dependent variables. Mauchly's test for sphericity determined if differences in variances met requirements for a RM-ANOVA. If Mauchly's test was violated, the Greenhouse-Geisser adjustment of degrees of freedom was used to report a more conservative p-value. If a technique by load interaction was present, planned comparisons were executed with one-way RM-ANOVAs on each level of depth and load factors (three- 1x5 one-way ANOVAs for load factor, five- 1x3 one-way ANOVAs for technique factor). If no technique by load interaction was present, simple main effects were analyzed. If a main effect was present, pairwise comparisons were made and effect sizes are reported for the statistically significant pairwise comparisons. A paired samples t-test was executed on jump height of the first and last 0% load condition to determine any fatiguing or potentiating effects of the protocol. Statistical significance was set a priori at  $\alpha = 0.05$ .

Table 6. Dependent variable calculations. RFD= Rate of Force Development. Fz= Vertical ground reaction force. COM= Center of Mass.

Variable	Unit	Calculation
Jump height	Meters (m)	$(\text{takeoff velocity})^2 / (2 * 9.81)$
Reactive strength index	N/A	$(\text{Jump height}) / (\text{Time from start to takeoff})$
Countermovement Depth	Meters (m)	Minimum COM position
Peak Power	Watts/mass (W/kg)	Maximum power during the jump (Fz*COM velocity)
Average Concentric Power	Watts/mass (W/kg)	Average power (Fz*COM velocity) from countermovement depth to takeoff
Eccentric Joint Work	Joules (J)	Area under the moment-angle curve during the eccentric phase
Eccentric Hip/Knee Ratio (HKR)	N/A	Eccentric Hip Work/Eccentric Knee Work
Amortization Joint Moment	N*m	The joint moment when the COM reaches the end of the countermovement
Peak Countermovement Kinetic Energy	J	The maximum kinetic energy ( $1/2 * m * v^2$ ) attained during the countermovement

## Results

### *Eccentric Phase*

Eccentric hip work was influenced by the interaction between technique and load ( $p < 0.05$ , Figure 7a). With 0% and 30% 1-RM, eccentric hip work was significantly less with QTR than PREF or FULL techniques ( $p < 0.05$ ), but similar between PREF and FULL ( $p > 0.05$ ). With 15%, 45%, and 60% 1-RM, eccentric hip work was significantly different among all techniques ( $p < 0.05$ ). FULL elicited the greatest eccentric hip work while QTR elicited the least eccentric hip work. Using the PREF technique, eccentric hip work was significantly less with 0% than 15%, 30%, 45%, and 60% 1-RM ( $p < 0.05$ ), and significantly less with 15% than 45% 1-RM ( $p < 0.05$ ) while all other load comparisons were similar ( $p > 0.05$ ). Using the QTR technique, eccentric hip



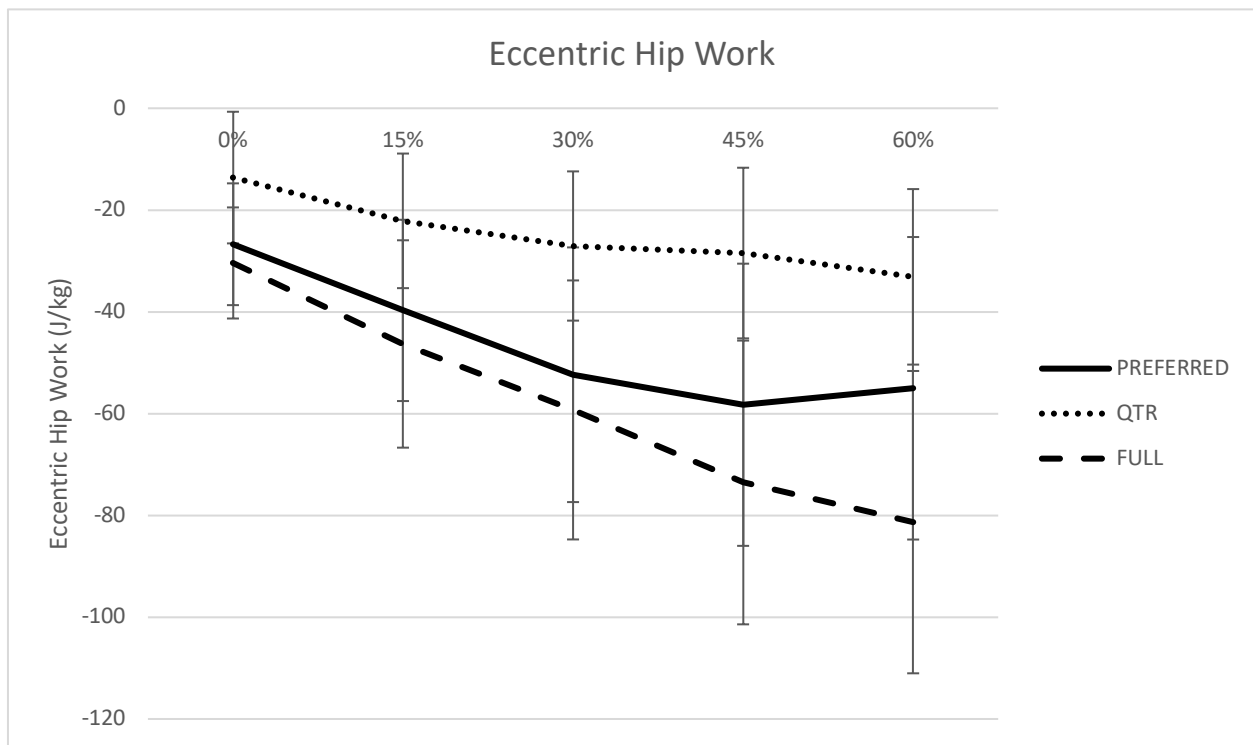
work was significantly less with 0% than 30%, 45%, and 60% 1-RM ( $p < 0.05$ ) while all other load comparisons were similar ( $p > 0.05$ ). Using the FULL technique, eccentric hip work significantly decreased with increasing loads ( $p < 0.05$ ) except between 45% and 60% 1-RM ( $p > 0.05$ ).

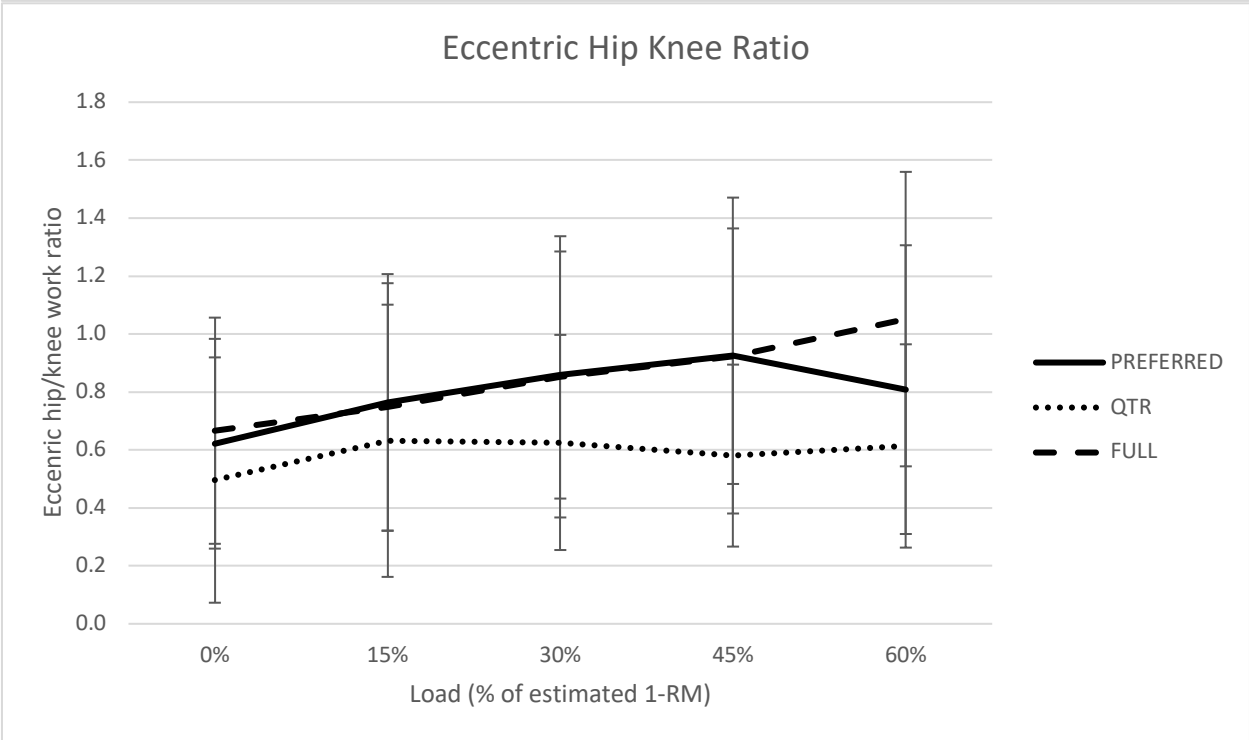
Eccentric knee work was not influenced by the interaction between technique and load ( $p > 0.05$ , Figure 7b); main effects were observed for technique ( $p < 0.05$ ) and load ( $p < 0.05$ ). For the main effect of technique, eccentric knee work significantly increased from QTR to PREF ( $-63.11 \pm 19.52$  vs  $-44.97 \pm 17.41$  J/kg,  $p < 0.05$ , ES: 1.03), QTR to FULL ( $-44.97 \pm 17.41$  vs  $-74.93 \pm 25.37$  J/kg,  $p < 0.05$ , ES: 1.45), and from PREF to FULL techniques ( $-63.11 \pm 19.52$  vs  $-74.93 \pm 25.37$  J/kg,  $p < 0.05$ , ES: 0.55). FULL elicited the greatest eccentric knee work while QTR elicited the least. For the main effect of load, eccentric knee work was similar between 60% ( $-73.68 \pm 27.91$  J/kg) and 45% ( $-69.34 \pm 23.70$  J/kg), 30% ( $-62.91 \pm 20.73$  J/kg), and 15% ( $-55.36 \pm 19.00$  J/kg) 1-RM ( $p > 0.05$ ), while all other load comparisons significantly increased with increasing loads (0:  $-43.73 \pm 17.72$  J/kg,  $p < 0.05$ , ES range: 0.67-1.35).

Eccentric HKR was influenced by the interaction between technique and load ( $p < 0.05$ , Figure 7c). With 0% and 15% 1-RM, eccentric HKR was not significantly different among techniques. With 30% 1-RM, eccentric HKR was significantly less using QTR compared to PREF ( $p < 0.05$ ), and similar between PREF and FULL ( $p > 0.05$ ), and QTR and FULL ( $p > 0.05$ ). With 45% 1-RM, eccentric HKR was significantly less using QTR compared to PREF or FULL ( $p < 0.05$ ), and similar between PREF and FULL ( $p > 0.05$ ). With 60% 1-RM, eccentric HKR was significantly less with QTR than FULL ( $p < 0.05$ ), but similar between PREF and FULL ( $p < 0.05$ ) or QTR ( $p < 0.05$ ). Using the PREF technique, eccentric HKR was significantly less with 0% than 15%, 30%, and 45% 1-RM ( $p < 0.05$ ), but similar between all other load comparisons. Using the QTR technique,

eccentric HKR was not significantly different among loads. Using the FULL technique, eccentric HKR was significantly less with 0% compared to 30%, 45%, and 60% 1-RM ( $p < 0.05$ ), and significantly less with 15% than 45% or 60% 1-RM ( $p < 0.05$ ) while all other load comparisons were similar ( $p > 0.05$ ).

Figure 7a/b/c. Eccentric joint work. Eccentric hip (7a) and knee (7b) work, and eccentric hip/knee ratio (7c) are depicted across loads and techniques. Statistical results presented in text.

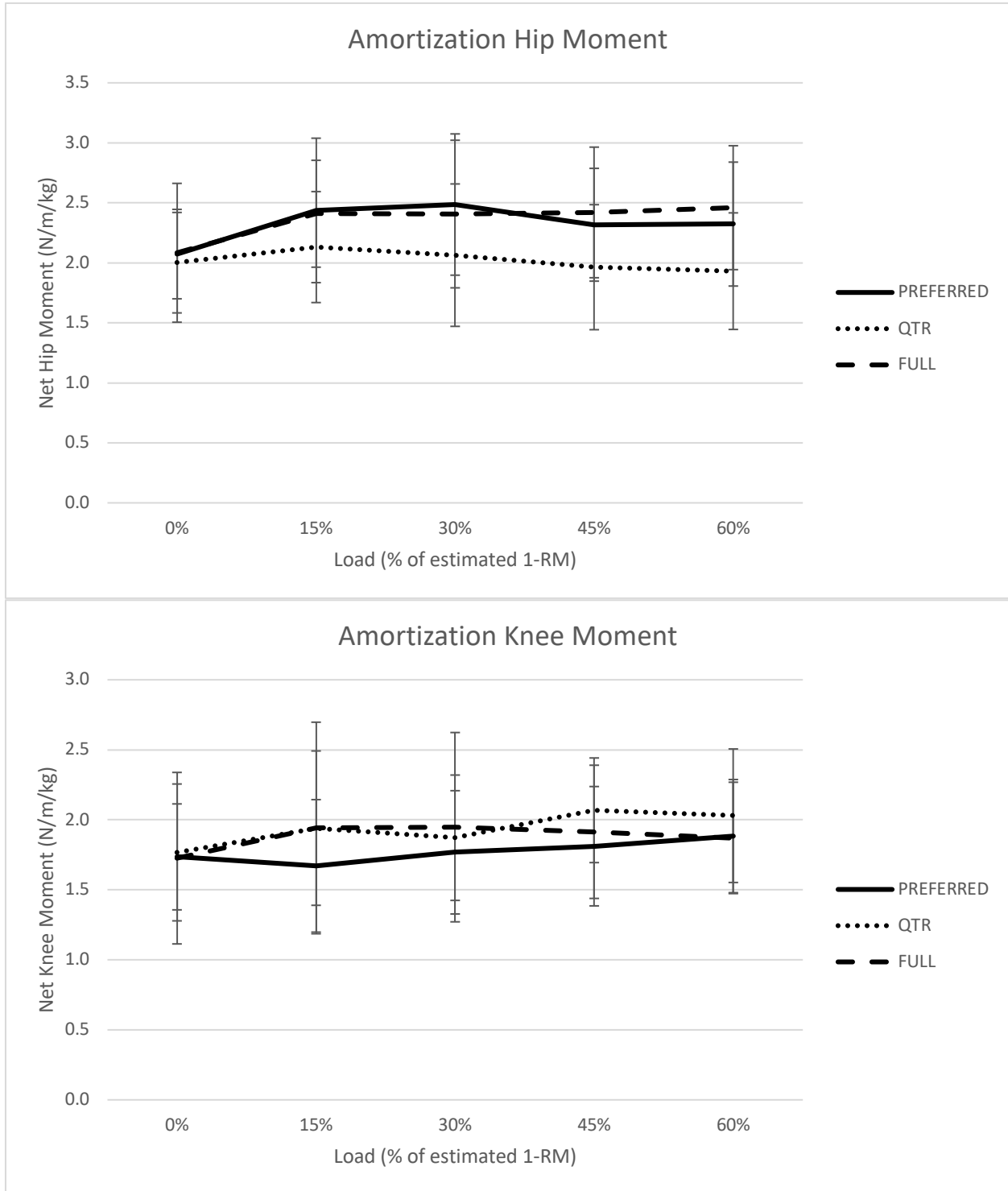


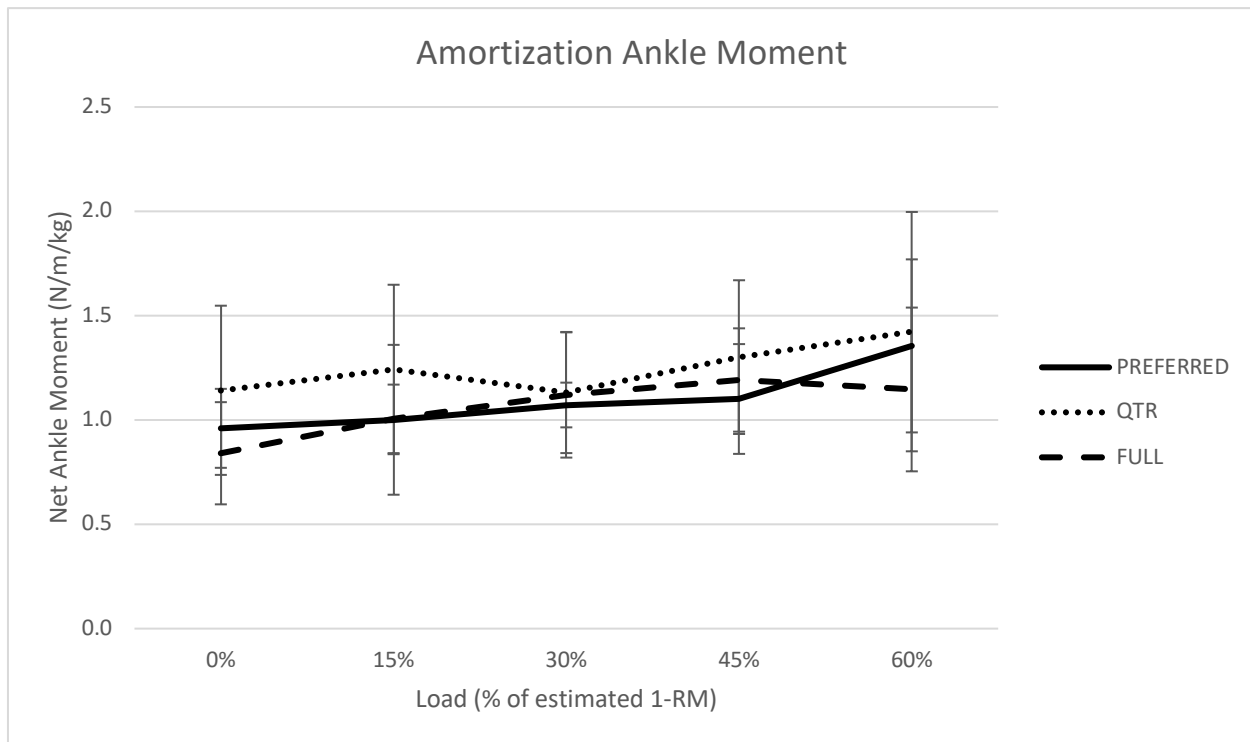


### *Amortization Phase*

Amortization joint moments were not influenced by the interaction between technique and load ( $p < 0.05$ ). There was a main effect of technique ( $p < 0.05$ ). Amortization hip moment (Figure 8a) was significantly less using a QTR technique ( $2.02 \pm 0.48$  N/m/kg) compared to PREF ( $2.33 \pm 0.52$ ,  $p < 0.05$ , ES: 0.65) or FULL ( $2.36 \pm 0.54$  N/m/kg,  $p < 0.05$ , ES: 0.69). There was no main effect of technique on amortization knee or ankle moments ( $p > 0.05$ , Figure 8b, 8c, respectively). Amortization hip moments were not influenced by load ( $p > 0.05$ ). Amortization ankle moments were significantly greater with 0% than 15% 1-RM ( $0.98 \pm 0.31$  vs  $1.08 \pm 0.33$  N/m/kg,  $p < 0.05$ , ES: 0.33), but similar among all loads ( $p > 0.05$ ). There was no observed main effect of load on amortization knee moments ( $p > 0.05$ ).

Figure 8a/b/c. Amortization joint moment (mean and standard deviation). Amortization moment of the hip (8a), knee (8b), and ankle (8c) are depicted across loads and techniques. Extensor moments are defined as positive. Statistical results presented in text.





### Performance

Mean and standard deviations of performance dependent variables are provided in table 7. Jump height was influenced by the interaction between technique and load ( $p < 0.05$ ). With 0% 1-RM, jump height was significantly lower with the QTR technique than PREFERRED ( $p < 0.05$ ) and FULL ( $p < 0.05$ ), but similar between PREFERRED and FULL ( $p > 0.05$ ). With all other loads, jump height was not different among techniques ( $p > 0.05$ ). When using the PREFERRED technique, jump height significantly decreased with each increase in load ( $p < 0.05$ ). Using the QTR technique, jump height was significantly different among all loads ( $p < 0.05$ ) except between 45% and 60% 1-RM ( $p > 0.05$ ). Using the FULL technique, jump height was significantly different among all loads ( $p < 0.05$ ) except between 30% and 60% 1-RM ( $p > 0.05$ ), and 45% and 60% 1-RM ( $p > 0.05$ ).

RSI was influenced by the interaction between technique and load ( $p < 0.05$ ). With 0%, 15%, and 60% 1-RM, RSI was significantly greater with QTR than PREF or FULL ( $p < 0.05$ ), but similar between PREF and FULL ( $p > 0.05$ ). With 30% and 45% 1-RM, RSI was significantly different among all techniques. Using PREF and QTR techniques, RSI was significantly different among all loads ( $p < 0.05$ ). Using the FULL technique, RSI was significantly different among all loads ( $p < 0.05$ ) except between 45% and 60% 1-RM ( $p > 0.05$ ).

Average concentric power was not influenced by an interaction between technique and load ( $p > 0.05$ ), but significant main effects were observed for technique and load ( $p < 0.05$ ). For the main effect of technique, average concentric power was significantly greater during QTR ( $28.76 \pm 4.50$  W/kg) than PREF ( $25.11 \pm 3.63$  W/kg,  $p < 0.05$ , ES: 0.94) or FULL ( $23.78 \pm 3.57$  W/kg,  $p < 0.05$ , ES: 1.29), but similar between PREF and FULL ( $p > 0.05$ ). For the main effect of load, average concentric power was significantly different among all loads (0%:  $28.45 \pm 3.94$  W/kg, 15%:  $28.15 \pm 4.35$  W/kg, 30%:  $26.06 \pm 3.78$  W/kg, 45%:  $23.78 \pm 3.38$ , 60%:  $22.99 \pm 3.93$  W/kg,  $p < 0.05$ , ES range: 0.54-1.46) except between 0% and 15% 1-RM ( $p > 0.05$ ), 30% and 60% 1-RM ( $p > 0.05$ ), and 45% and 60% 1-RM ( $p > 0.05$ ).

Peak power was not influenced by an interaction between technique and load ( $p > 0.05$ ), but significant main effects were observed for technique and load ( $p < 0.05$ ). For the main effect of technique, peak power was significantly greater during QTR ( $53.75 \pm 6.59$  W/kg) than PREF (vs  $50.74 \pm 5.30$ ,  $p < 0.05$ , ES: 0.53) or FULL ( $50.09 \pm 6.14$  W/kg,  $p < 0.05$ , ES: 0.61), but similar between PREF and FULL ( $p > 0.05$ ). For the main effect of load, peak power was significantly different between 45% ( $49.71 \pm 4.66$  W/kg) and 0% ( $52.53 \pm 5.78$  W/kg,  $p < 0.05$ , ES: 0.57), 15%

( $53.42 \pm 6.21$  W/kg,  $p < 0.05$ , ES: 0.71), and 30% 1-RM ( $51.79 \pm 6.05$  W/kg,  $p < 0.05$ , ES: 0.41).

Peak power was similar among other load comparisons (60%:  $50.17 \pm 7.57$  W/kg).

Countermovement depth was not influenced by an interaction between technique and load ( $p > 0.05$ ), but significant main effects were observed for technique and load ( $p < 0.05$ ). For the main effect of technique, countermovement depth was significantly different among all techniques (PREF-QTR:  $-0.37 \pm 0.08$  vs  $-0.24 \pm 0.06$  m,  $p < 0.05$ , ES: 1.94, PREF-FULL:  $-0.37 \pm 0.08$  vs  $-0.44 \pm 0.11$  m,  $p < 0.05$ , ES: 0.77, QTR-FULL:  $-0.24 \pm 0.06$  vs  $-0.44 \pm 0.11$  m,  $p < 0.05$ , ES: 2.38). For the main effect of load, countermovement depth was not significantly different among all loads ( $p > 0.05$ ). Thus, the cues used for each technique were effective at creating distinct countermovement depths that were maintained across loads.

Peak countermovement kinetic energy was not influenced by an interaction between technique and load ( $p > 0.05$ ), but significant main effects were observed for technique and load ( $p < 0.05$ ). Peak countermovement kinetic energy was significantly lower using a QTR technique ( $71.25 \pm 25.94$  J) compared to PREF ( $92.64 \pm 33.67$  J,  $p < 0.05$ , ES: 0.75) and FULL ( $102.54 \pm 37.27$  J,  $p < 0.05$ , ES: 1.03), but was similar between PREF and FULL ( $p > 0.05$ ). Peak countermovement kinetic energy was significantly less during 0% than 15% of 1-RM ( $86.37 \pm 34.23$  vs  $100.43 \pm 38.71$  J,  $p < 0.05$ , ES: 0.41), and less during 60% ( $72.37 \pm 29.29$  J) than 15% ( $100.43 \pm 38.71$  J,  $p < 0.05$ , ES: 0.86) and 30% of 1-RM ( $96.84 \pm 36.60$  J,  $p < 0.05$ , ES: 0.78). Peak countermovement kinetic energy was greatest using a FULL technique with 15% of 1-RM ( $117.43 \pm 39.03$  J).



Table 7. Performance Variables. Jump height, Reactive Strength Index (RSI), peak power, average concentric, countermovement (cm) depth, and peak countermovement kinetic energy are presented across loads and preferred (PREF), quarter (QTR), and full (FULL) techniques. Statistical results presented in text.

VARIABLE		LOAD				
		0%	15%	30%	45%	60%
JUMP HEIGHT (M)	PREF	0.36 ± 0.05	0.27 ± 0.05	0.21 ± 0.02	0.16 ± 0.03	0.12 ± 0.03
	QTR	0.32 ± 0.05	0.28 ± 0.04	0.21 ± 0.05	0.15 ± 0.03	0.12 ± 0.04
	FULL	0.36 ± 0.04	0.29 ± 0.04	0.21 ± 0.04	0.15 ± 0.03	0.14 ± 0.07
RSI	PREF	0.48 ± 0.13	0.32 ± 0.08	0.23 ± 0.05	0.15 ± 0.04	0.11 ± 0.03
	QTR	0.57 ± 0.11	0.44 ± 0.11	0.3 ± 0.08	0.2 ± 0.04	0.15 ± 0.05
	FULL	0.43 ± 0.08	0.3 ± 0.05	0.19 ± 0.04	0.12 ± 0.03	0.1 ± 0.04
PEAK POWER (W/KG)	PREF	52.5 ± 6.87	51.41 ± 5.94	51.2 ± 4.99	49.9 ± 4.83	48.68 ± 3.52
	QTR	54.7 ± 5.69	57.12 ± 7.2	54.71 ± 6.82	51.28 ± 4.8	50.93 ± 7.26
	FULL	50.38 ± 4.2	51.74 ± 3.81	49.45 ± 5.52	47.96 ± 4.19	50.91 ± 10.76
AVERAGE CON. POWER (W/KG)	PREF	28.04 ± 4.03	26.5 ± 3.55	25.22 ± 2.9	23.44 ± 2.44	22.35 ± 2.3
	QTR	30.8 ± 4.11	31.62 ± 4.67	28.98 ± 3.95	26.58 ± 2.99	25.84 ± 4.32
	FULL	26.5 ± 2.51	26.33 ± 2.55	23.98 ± 2.64	21.32 ± 2.55	20.78 ± 3.33
CM DEPTH (M)	PREF	-0.36 ± 0.07	-0.39 ± 0.05	-0.39 ± 0.08	-0.35 ± 0.07	-0.33 ± 0.09
	QTR	-0.24 ± 0.06	-0.25 ± 0.08	-0.24 ± 0.06	-0.24 ± 0.05	-0.21 ± 0.05
	FULL	-0.45 ± 0.07	-0.47 ± 0.08	-0.46 ± 0.1	-0.46 ± 0.09	-0.38 ± 0.18
PEAK CM KINETIC ENERGY (J)	PREF	85.72 ± 31.57	106.3 ± 37.84	106.98 ± 39.57	87.63 ± 29.46	76.55 ± 22.47
	QTR	66.74 ± 27.01	77.56 ± 30.03	77.55 ± 30.36	76.95 ± 23.19	57.42 ± 14.62
	FULL	106.66 ± 34.11	117.43 ± 39.43	105.99 ± 34.77	99.49 ± 35.72	83.14 ± 40.62

## Discussion

### *Main Observations*

A main finding of the study was that eccentric hip and knee work generally increased with increasing loads during a JS for all techniques. Along with this, eccentric hip work was less using the QTR technique than PREF or FULL techniques for all loads. Although eccentric work was influenced by load, amortization hip and knee moments did not change with increasing loads. Thus, the storage of elastic strain energy at amortization appears to maintain its

magnitude as load increases to 60% of 1-RM. Although there is limited research to compare results, the angular displacement and joint moment curves in the current study were similar to those reported in previous research (Moir et al. 2012). In addition, the performance variables (e.g. jump height, peak power) in the current study are in line with previous research (Cormie, McBride, and McCaulley 2009), thus the current data were deemed accurate and reasonable.

The amortization joint moment during a ballistic movement (e.g., countermovement jump) compared to a concentric only movement (e.g. squat jump) represents the stored elastic strain energy in the joint (Bobbert et al. 1996). A primary benefit of the countermovement is the extra time allowed to build up an active muscle state at amortization, which manifests as additional work during the early phase of concentric motion compared to a concentric only movement (Bobbert et al. 1996). It is not clear if the observed plateau in amortization joint moment would continue with loads greater than 60% of 1-RM. The mechanism of this plateauing effect may originate from muscle tendon unit (MTU) dynamics and their interaction with the nervous system.

Tendon stress and strain were recently reported to be greater during a jump squat compared to a traditional back squat because it is a slower movement (Earp et al. 2016). In addition, there was no influence of load on peak tendon strain during 0%-90% of 1-RM back squats despite increases in estimated tendon force and RFD (Earp et al. 2017). During active MTU lengthening, a greater portion of MTU lengthening is due to tendon lengthening while the muscle acts nearly isometrically (Roberts and Konow 2013). This mechanism has been proposed as a protective effect: the tendon absorbs strain energy (i.e. lengthens) rapidly during the eccentric phase and releases that energy (i.e. shortens) more slowly to the muscle fascicles,

thereby attenuating power demands- but not total work- on the muscle (Roberts and Konow 2013). The recoil of elastic energy by tendons occurs during the amortization phase, when the MTU is observed to act isometrically due to tendon shortening and muscle lengthening (Roberts and Konow 2013). Therefore, eccentric muscle action predominantly occurs during the amortization phase of high effort stretch shortening cycle movements (e.g., jumping, running) (Roberts and Konow 2013). Considering these MTU patterns, it is hypothesized the Golgi tendon organs (which would cause inhibition of the agonist) play a role in governing how rapidly the eccentric work (i.e. rapid work with higher average tension or slow work with lower average tension) is performed and thus the initial energy absorption characteristics of the tendon. Golgi tendon organs may modulate deceleration demands by indirectly decreasing countermovement velocity, which decreases downward kinetic energy. In contrast, it is hypothesized the muscle spindles may be most active during the amortization phase when greater muscle fascicle strain rates and magnitudes occur. Thus, the alpha motor neuron may be maximally activated during the amortization phase even at light loads due in part to peak muscle fascicle lengthening. This may contribute to the observed plateau in joint moments at amortization up to 60% of 1-RM. However, it is not clear how loads greater than 60% of 1-RM would influence amortization joint moments. Further, countermovement strategy may be an important factor determining deceleration demands during the JS.

Deceleration demand is based on the need to stop the downward kinetic energy of the system within a given displacement. Therefore, deceleration demands cannot be based solely on external load because kinetic energy takes mass and velocity into consideration. Participants could decrease countermovement COM velocity to decrease downward kinetic energy despite

an increase in system mass (i.e. external loading). In the current study, peak countermovement kinetic energy peaked using FULL technique during 15% and 30% of 1-RM conditions, which is evidence that greater external load does not ensure greater deceleration demand even during maximal effort JS cued to perform the countermovement as quickly as possible. Furthermore, peak kinetic energy was lowest using a QTR technique across loads. Therefore, although the QTR technique resulted in greater system power output and RSI values across loads, the deceleration demand was also lower because there was not enough space or time to generate similar peak kinetic energies to the PREF and FULL techniques. Given velocity's exponential contribution to kinetic energy ( $KE = \frac{1}{2} \times \text{mass} \times \text{velocity}^2$ ), manipulating and/or measuring velocity may be more appropriate than manipulating mass to observe and develop deceleration abilities in training. For example, plyometrics performed without external load can reach high magnitudes of downward kinetic energy by manipulating velocity via drop height. Thus, when load increases an athlete maintains some control of downward kinetic energy to adjust deceleration demand. In contrast, increases in drop height *guarantee* predictable increases in downward kinetic energy at the moment of ground contact and deceleration demand would increase if the landing or countermovement depth is controlled. Considering these differences between manipulating load or velocity for deceleration training stimuli, coaches and athletes might consider defining, monitoring, and cueing countermovement techniques for loaded exercises aimed at a specific deceleration goal.

Deceleration demands were different among countermovement techniques, but joint contributions to eccentric work were also influenced by load and technique. Eccentric work HKR was lower using QTR technique at loads greater than 15% of 1-RM, indicating a knee dominant

movement with the QTR technique. However, at 0% and 15% of 1-RM, HKR was not different among techniques. Using PREF technique, the hip contributed more relative eccentric work with load compared to no load, but did not increase within the 15%-45% of 1-RM. Interestingly, HKR was similar between 0% and 60% of 1-RM. These results are in slight contrast with a recent report that hip muscular contribution increased with increasing loads during the back squat (Bryanton et al. 2012), but only the concentric phase was investigated, JS differ from traditional back squats, and the range of loads was 50%-90%. Eccentric work HKR was not influenced by load when using the QTR technique. During competition in team sports like basketball and volleyball, a QTR technique may be used more frequently than a PREF or FULL technique. Joint contributions to deceleration appear to exhibit distinct strategies during the countermovement of the JS.

It is conjectured that athletic populations may benefit from a variety of countermovement techniques. A recent investigation reported superior performance improvements in addition to increases in force production at the end range of motion in of a bench press training program (5 weeks, equal concentric work) with variable countermovement depths compared to full depth only (Clark, Bryant, and Humphries 2008). Partial range of motion exercises may also benefit rehabilitation programs (Barak, Ayalon, and Dvir 2004) and maximal strength gains when supplementing full range of motion back squats (Bazylar et al. 2014). In contrast, full range of motion exercises may be better for increases in strength at end ranges of motion, muscle size, and range of motion (Morton et al. 2011; Pinto et al. 2012). There appears to be a variety of benefits and stresses exclusive to partial or full range of motion exercises. Therefore, a range of countermovement techniques should be incorporated into

comprehensive training plans to develop deceleration abilities and movements utilizing the stretch-shortening cycle.

### *Confounding Factors*

The differences in deceleration demands have been thoroughly discussed, but a confounding factor is that the 1-RM load for a FULL back squat is likely to be less than the 1-RM load for a QTR back squat. However, it was necessary to control the loads as an independent variable. Another consideration is that participants were more familiar with PREF and FULL JS than QTR JS. We provided practice and performed a within-subject analysis in attempt to control this factor.

Another confounding factor lies within the amortization phase. The current study uses a system approach to the COM displacement by integrating acceleration. Amortization was defined as when the COM position was one cm away from the lowest position and ending one cm after reaching the lowest position. However, the lower extremity joints reach peak joint flexion at different times. Therefore, individual joints may be going through amortization before or after the COM's amortization phase. The current study aimed to standardize the amortization phase based on the system to maintain consistency with previous work (Barker & Mercer, in press). Timing of joint amortization to system amortization may be an area of interest for future research, especially in response to load and technique.

### *Limitations*

The current study cohort did not include females and athletes participating in competitive sport. Therefore, we cannot generalize these results to those populations. Training status of the cohort was recreational in nature, but it's not clear how athletes from specific training backgrounds would perform. Athletes familiar with short ranges of motion may perform JS differently across loads and techniques than athletes familiar with full ranges of motion.

The current study protocol required loads up to 60% of 1-RM, but greater loads are used in training. It is not recommended to generalize the observed results to heavier loads based on the current data. Future research might investigate different loading increments and ranges to better understand deceleration strategies during the JS.

### Practical Applications

Load and technique of JS has influence on eccentric and amortization performance. The current evidence suggests the QTR technique elicits greater power output and RSI values and the knee dominates eccentric work. The FULL technique resulted in peak deceleration demands using 15% and 30% of 1-RM, with increasing deceleration contributions from the hip. Given the observed performance differences, coaches should consider QTR and FULL JS techniques separate exercises and stimuli during jump training. It may be best to focus on developing the technique closely related to the competition movement. Further, coaches should consider defining, monitoring, and cueing specific countermovement strategies for consistent training programs aiming to improve deceleration abilities.

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## OVERALL CONCLUSIONS

In general conclusion, jump height should not be the only measure of jump performance. RSI has a strong association with unloading, eccentric, and amortization ground reaction forces of the CMJ, and is a strong practical solution for sporting organizations to assess time-sensitive jump performance and deceleration abilities or strategy. Kinetic data from the countermovement phase was not associated with jump height, but strongly related to faster jumping performance, which may be particularly beneficial during dynamic tasks in competitive environments (e.g. team sports).

Regarding deceleration strategy, the QTR JS exhibited distinct mechanical differences compared to the PREF and FULL JS. A QTR and FULL JS, therefore, should be considered separate exercises to be used cooperatively during training. The QTR technique elicited greater power output, eccentric RFD1 and RFD2, and amortization Fz compared to PREF and FULL JS. Thus, the QTR technique may be particularly useful for training fast stretch-shortening cycle movements, and may have a specificity advantage for jumping sports that use short countermovement depths. In contrast, the PREF and FULL JS elicited greater eccentric joint work, deceleration contributions from the hip joint, and jump height, which may be beneficial for developing eccentric strength and maximum vertical velocity.

Kinetic energy during the countermovement was discussed in Chapter 4. Despite increases in system load, peak countermovement kinetic energy was the highest during the FULL JS with 15% of 1-RM. This observation may reveal important information about deceleration strategy related to the observed plateau of amortization Fz as loads increased. Neural feedback loops (e.g. muscle spindles, golgi tendon organs, joint receptors) may play a

role in governing this deceleration control mechanism. In the current investigation, peak countermovement kinetic energy was less with 60% than 15% and 30% of 1-RM. Thus, the decrease in countermovement velocity outweighed the increase in system mass despite cues to lower themselves as quickly as possible. This resulted in decreasing kinetic energy with increasing loads. Because peak countermovement (or downward) kinetic energy and depth determines deceleration demands, it is suggested that athletes and coaches monitor countermovement velocity, use specific definitions, and verbal cues to improve consistency when training to improve deceleration abilities. As an alternative to loaded exercises, coaches could avoid inconsistencies due to athlete countermovement strategy by prescribing drop jumps (jump preceded by landing from a height) because drop height provides a predictable change in kinetic energy upon impact. If depth is adequately controlled, then deceleration demand can be systematically manipulated with drop height. Regardless, it is important to understand that increases in external load does not ensure an increase in deceleration demand because the athlete can reduce kinetic energy by slowing their countermovement velocity or manipulating depth. Therefore, monitoring, defining, and cueing these countermovement parameters may be critical to organizing a reliable and systematic training program to improve deceleration abilities.

## APPENDIX 1: ARTICLE COPYRIGHT FOR RELATIONSHIPS BETWEEN COUNTERMOVEMENT JUMP GROUND REACTION FORCES AND JUMP HEIGHT, REACTIVE STRENGTH INDEX, AND JUMP TIME

The article within Chapter 2 titled “Relationship Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time” has been published in the *Journal of Strength and Conditioning Research*. Wolters Kluwer Health, Inc., the publisher of the *Journal of Strength and Conditioning Research*, does not require a formal license when the original author is reusing an article in a dissertation.

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APPENDIX 2: ARTICLE COPYRIGHT FOR THE EFFECT OF LOAD AND  
DEPTH OF JUMP SQUAT ON GROUND REACTION FORCES DURING THE  
ECCENTRIC AND AMORTIZATION PHASES

The article within Chapter 3 titled “The Effect of Load and Depth of Jump Squat on Ground Reaction Forces during the Eccentric and Amortization Phases” has been submitted to *Human Movement Science* for publication. Elsevier, who publishes *Human Movement Science*, allows pre-print manuscripts to be included in dissertations. Therefore, no copyright approval was necessary.

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APPENDIX 3: ARTICLE COPYRIGHT FOR THE EFFECT OF LOAD AND  
DEPTH OF JUMP SQUAT ON JOINT KINETICS DURING THE ECCENTRIC  
AND AMORTIZATION PHASES

The article within Chapter 3 titled “The Effect of Load and Depth of Jump Squat on Joint Kinetics during the Eccentric and Amortization Phases” has been submitted to *Human Movement Science* for publication. Elsevier, who publishes *Human Movement Science*, allows pre-print manuscripts to be included in dissertations. Therefore, no copyright approval was necessary.

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## APPENDIX 4: INTRODUCTION REFERENCES

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# CURRICULUM VITAE

**Leland A. Barker, Ph.D., CSCS**  
**BARCEL1@unlv.nevada.edu**

## Education

Ph.D.	University of Nevada, Las Vegas Kinesiology, Biomechanics (Focus) Strength & Conditioning, Neuroscience (support areas)	2018
M.S.	California State University, Fullerton Kinesiology, Biomechanics (Focus) Strength and Conditioning, Exercise Physiology (support areas)	2013
B.S.	Creighton University Exercise Science Minor: Biological Physics	2010
CSCS	National Strength and Conditioning Association	2010
USAW	USA Weightlifting Performance Coach Level 1	2014

## Academic Experiences

### Graduate Assistant

Department of Kinesiology  
University of Nevada, Las Vegas  
2015-present

I perform teaching and research duties in the biomechanics laboratory. I have formally taught Scientific Basis of Strength Training, Biomechanics of Endurance Performance, Biomechanics Laboratory, and Anatomical Kinesiology

### Teaching Associate

Department of Kinesiology  
California State University, Fullerton  
2011-2013

Taught performance basketball courses in addition to lab hours in the exercise physiology and human performance labs.

### Undergraduate and High School Mentorships

Department of Kinesiology  
University of Nevada, Las Vegas

2015-2017

During three summer semesters, I mentored undergraduate (INBRE Program) and high school (STEP UP Program) students through their own research project in the biomechanics laboratory.

### **Published Manuscripts**

Harry, J.R., Barker, L.A., Eggleston, J.D., Dufek, J.S. Evaluating Performance During Maximum Effort Vertical Jump Landings. *Journal of Applied Biomechanics*. TBD.

Barker, L, Mendoza, D, Mercer, J. "Exploring the use of 3D scanning to determine whole body volume while wearing a triathlon wetsuit". *Journal of Functional Morphology and Kinesiology*. TBD.

Barker, L, Burnstein, B, Mercer, J. "Acrobatic Trampoline Act: A Description of Acceleration Profiles in Training and Shows Using Wearable Technology". *Sports Biomechanics*. TBD.

Harry, J.R., Paquette, M.R., Schilling, B.K., Barker, L.A., James, C.R., Dufek, J.S. "Kinetic and Electromyographic Sub-Phase Characteristics with Relation to Countermovement Vertical Jump Performance". *Journal of Applied Biomechanics*. TBD.

Harry, J.R., Barker, L.A., James, C.R., Dufek, J.S. "Performance differences among skilled soccer players of different playing positions during vertical jumping and landing". *Journal of Strength and Conditioning Research*. February 2018;

Barker, LA, Harry, JR, Mercer, JA. "Relationships Between Countermovement Jump Ground Reaction Forces and Jump Height, Reactive Strength Index, and Jump Time". *Journal of Strength and Conditioning Research*. January 2018.

Harry, JR, Barker, LA, Mercer, JA, Dufek, JS. "Vertical and Horizontal Impact Force Comparison During Jump Landings With and Without Rotation in NCAA Division I Male Soccer Players". *Journal of Strength and Conditioning Research*. July 2017.

Barker, LA, Harry, JR, Dufek, JS, Mercer, JA. "Aerial Rotation Effects on Vertical Jump Performance Among Highly Skilled Collegiate Soccer Players". *Journal of Strength and Conditioning Research*. April 2017.

### **Manuscripts Under Review**

Barker, L.A., Mercer, JA. "The Effect of Load and Depth on Eccentric and Amortization Ground Reaction Forces during Jump Squats". Target Journal: *Human Movement Science*. In Review.

### **Manuscripts In Preparation**

Barker, L.A., Mercer, JA. "The Effect of Load and Depth on Eccentric and Amortization Joint Kinetics during Jump Squats". Target Journal: *Human Movement Science*. In Preparation.

Harry, J.R., Barker, L.A., Mercer, J.A., Dufek, J.S. The influence of takeoff and landing distance on total jump distance during the standing long jump. Target Journal: *Journal of Strength and Conditioning Research*. In preparation.

Eggleston, J.D., Barker, L.A., Harry, J.R., Hunt, A.R., Casale, E., & Dufek, J.S. (In preparation). Shoes or no shoes? A methodological consideration for gait analysis in individuals with autism. Target Journal: *Clinical Biomechanics*.

### **Abstracts**

Barker, L, Mercer, J. "The Influence of Load on Preferred Countermovement Depth during Jump Squats." ACSM Conference, 2018.

Harry, J, Barker, L, Dufek, J, James, R. "Force- and Velocity- Profile Differences Between Good and Poor Countermovement Vertical Jumpers." ACSM Conference, 2018.

Barker, L, Burnstein, B, Mercer, J. "Measuring Acceleration of a Trampoline Circus Act during Training and In-Show Using Wearable Technology." ACSM Conference, 2017.

Barker, LA, Harry, JR, Dufek, JS, Mercer, JA. "Performance of Aerial Rotation During Vertical Jumping Among Highly Skilled Collegiate Soccer Players". ASB Conference, 2016.

Barker, LA, Bailey, J, Galor, KS, Soucy, M, Mercer, JA, FACSM. "Technical Ability of Force Application Between Various Stride Frequencies at Constant Velocity". ACSM Annual Meeting, 2016 Poster.

Barker, LA, Bailey, J, Galor, KS, Soucy, M, Mercer, JA FACSM. "Technical Ability of Force Application Between Various Stride Frequencies at Constant Velocity". SWACSM, 2015 Poster

Bailey, J.P., Barker, L., Galor, K., Soucy, M., & Mercer, J.A. FACSM. "Effects of stride frequency perturbations on kinetics during treadmill running". SWACSM, 2015 Poster

Barker LA, DuBois AM, Brown LE, Coburn JW. "Effect of Band-Resisted Jumping on Subsequent Countermovement Jump Performance". SWACSM, 2012 Poster.

Andrea M. DuBois, Leland A. Barker, Lee E. Brown, FACSM, Jared W. Coburn, FACSM. "Effect of Resisted Jumping on Vertical Jump Relative Peak Power"

Barker, Leland. "Effect of a Glute-Targeted Warm-Up on Hip and Knee Moments During a Countermovement Jump". Master's Thesis.

Mercer, JA FACSM, Mata, T., Soucy, M., Barker, L., Gaitlin, T., Bailey, J.  
“Using wearable technology to examine relationship between stride length, frequency, and velocity while running on a treadmill and overground.”

### **Grants**

**Barker, L.**, Mercer, J. NSCA Doctoral Student Research Grant, 2017. \$15,000. Unfunded.

Mercer, JA, Zhan, J, Navalta, J, Lough, N, Gatlin, T, Bailey, JP, **Barker, L.** & Craig-Jones, A.  
National Science Foundation, 2016: Partnerships for Innovation: Building Innovation Capacity.  
\$1,000,000. Unfunded

Mercer, J.A., Bailey, J.P., and **Barker, L.** (2016) United States of America Track and Field.  
\$123,217. Unfunded.

**Barker, L.** AMTI Force & Motion Student Scholarship, 2016. \$10,000. Unfunded.

**Barker, L.**, Mercer, J. NSCA Doctoral Student Research Grant, 2016. \$15,000. Unfunded.

Mercer, J.A., Bailey, J.P., **Barker, L.** and Soucy, M. Arthritis foundation, 2015. \$75,000.  
Unfunded

**Barker, L.**, Mercer, J. NSCA Doctoral Student Research Grant, 2015. \$15,000. Unfunded.

### **Jobs & Professional Development**

Performance Scientist, Cirque du Soleil. *August 2014-present*

Propose research projects to analyze performer workload and fatigue  
Aid in strength and conditioning for performer development and maintenance.

Strength Coach, Cirque du Soleil. *June 2016-present*

Provide performance conditioning training at ‘O!’ with the Resident Show Division.

Owner, Head Coach, Barker Athletics, LLC. *2014-2017.*

Provide private coaching and training to clients in addition to maintaining small business operations.

Journal Reviewer. *Journal of Strength and Conditioning Research. Journal of Applied Biomechanics.*

University of Wisconsin Ultimate Frisbee Strength Coach, *August 2014-August 2015*

Design and develop the strength and conditioning program for the Hodags, the University of Wisconsin’s Ultimate Frisbee team

Cal State Fullerton Olympic Weightlifting Club Founding Member  
*August 2012-August 2013*

Strength and Conditioning Coach Intern, Creighton University Athletic Department, *April 2009-January 2010*

Speed/Strength Coach, Athletic Training Center, Omaha, NE  
*August 2010-October 2010.*

Women's Basketball Team Practice Player, Creighton University  
August 2007- March 2010

Learned and performed opposing team offenses to prepare the team for season play.  
Aided in skill development drills for guards.

Biomechanics Lab Volunteer, Nebraska Biomechanics Core Facility, UNO  
*August 2010-November 2010*

### **Technical Skills**

Force platform analysis  
3D motion capture  
Electromyography  
Accelerometers and Inertial sensors  
Wearable Technology (various devices)  
3D Scanning  
MATLAB  
R Studio  
SPSS Statistics  
Visual3D  
Metabolic Cart  
Shoe Impact Testing  
Microsoft Office Suite