

# Effects of Load on Lower Extremity Joint Kinetics and Kinematics during Hexagonal Barbell Jump Squats

Jacob F. Remmert<sup>1</sup>, Abigail K. Salvadore<sup>2\*</sup>, Adam E. Jagodinsky<sup>3</sup>, Marcel Lopes dos Santos<sup>3</sup> and Michael R. Torry<sup>3</sup>

<sup>1</sup>Department of Exercise Science and Health Promotion, Florida Atlantic University, Boca Raton, Florida, USA; <sup>2</sup>Department of Kinesiology, University of Massachusetts, Amherst, Massachusetts, USA; <sup>3</sup>School of Kinesiology and Recreation, Illinois State University, Normal, Illinois, USA

\*Corresponding Author: [asalvadore@umass.edu](mailto:asalvadore@umass.edu)

## ABSTRACT

Strength and conditioning coaches often recommend athletes perform loaded jumps with an external load that maximizes peak power output to improve performance. However, there is debate regarding the training load that maximizes acute total body power, and power at individual lower extremity joints. The purpose of this study was to investigate lower extremity kinetic and kinematic variables across a spectrum of loads during jump squats using a hexagonal barbell. Participants performed jumps with a range of loads from 10% to 60% of hexagonal barbell deadlift estimated 1-repetition maximum (e1RM), as well as an unloaded countermovement jump. Using cameras and force plates, lower extremity angles, velocities, moments, powers, as well as total body power, were assessed for each jump. As load increased, there was a decrease in power at the total body level and the hip, but ankle power increased. All joint moment magnitudes increased with load, and flexion angle and velocity at the hip and knee decreased with load. Results suggest that increasing load impacts kinetic and kinematic variables and alters the jumping task, and that the majority of these changes occur when loading exceeds approximately 20-30% 1RM. Further, knee kinetics measures were most strongly related to total body power.

**Keywords:** biomechanics; strength and conditioning, peak power output, athletic performance

## INTRODUCTION

Loaded jump training employing an external load to maximize power output is often implemented by strength coaches to enhance athletic performance. Indeed, in the absence of any other resistance training, Marian et al.<sup>1</sup> observed a significant increase in countermovement jump (CMJ) height from  $45.1 \pm 5.5$  cm to  $50.4 \pm 6.2$  cm after 8 weeks of barbell jump squat (BJS) training at loads that maintained  $\geq 90\%$  of peak power output. However, even with different training strategies, the total body peak power output (TBP<sub>peak</sub>) is often found at 0-20% of the one-repetition maximum (1RM). For example, 0-20% of back squat 1RM has been shown to maximize TBP<sub>peak</sub> when performing the BJS<sup>2-7</sup>. Studies often prescribe loads for the hexagonal barbell jump squat (HBJS) using back squat 1RM<sup>8,9</sup>, which may be suboptimal for individualized loading. Swinton et al.<sup>6</sup> prescribed loads using hexagonal barbell deadlift (HBD) 1RM and found maximal TBP<sub>peak</sub> at 0-20% 1RM.

Further exploration of data reveals additional differential biomechanical outcomes at individual joints, although the data are limited with the use of BJS or HBJS. Moir et al.<sup>10</sup> examined peak power

output (W/kg) at the ankle, knee, and hip across various loads using the BBJs. They reported peak ankle and knee power at 0% back squat 1RM, while hip power peaked at 42% 1RM<sup>10</sup>. In a similar study also utilizing BBJs, Jandacka et al.<sup>11</sup> found peak ankle power at 70% back squat 1RM and peak knee power at 0% 1RM, but they did not observe a significant effect of load on peak hip power. Although not in the jump squat exercise, other data suggest the relative muscular effort<sup>2</sup>, power<sup>12</sup>, work<sup>13</sup>, and net joint moment<sup>13,14</sup> at the lower extremity joints are impacted differently across various loads. Because of this potential for incongruent differences in joint-level mechanics across loads, it is conceivable that the optimal load to be used may differ based on the specific sport or individual needs of the athlete.

Measuring TBPpeak in the field or laboratory has been widely adopted because it is methodologically easier than measuring individual joint powers. However, a more well-defined relationship between joint-level mechanics and TBPpeak may provide greater insights into individual joint contributions to performance and thus have important implications for athletes and strength coaches. A clearer picture of these relationships is needed to determine whether optimizing total-body outputs also optimizes joint-specific demands, or whether different loading strategies may be required depending on performance goals.

Therefore, the purposes of this study were threefold: to identify the load, based on HBD 1RM, that optimizes TBPpeak in the HBJs; to assess individual joint kinetics and kinematics across various submaximal loads; and to examine the relationships between individual joint-level mechanics and TBPpeak. We hypothesize that TBPpeak would occur at 0-20% HBD 1RM, in alignment with prior data prescribing loads using HBD 1RM<sup>6</sup>. Second, we hypothesize that peak power at individual joints would be optimized at different loads but generally decrease with additional load. Third, we hypothesize that peak flexion angle at each joint would be significantly correlated with TBPpeak, but that the correlation between peak power at individual joints and TBPpeak would differ between joints.

## METHODS

### Participants

Ten resistance-trained men completed this study. The participant characteristics are summarized in Table 1. Participants' eligibility required them to have a minimum of two years of experience with resistance training, have specific familiarity with the HBD and CMJ, and be free from injury to the spine or lower extremity within the previous two years. All participants supplied written informed consent prior to testing. This study was approved by the University's Institutional Review Board.

### Instrumentation

Ground reaction forces in each trial were measured using two force plates (AMTI; Watertown, MA) sampling at 1000 Hz. Joint and body segment locations over time were tracked using a 10-camera motion capture system (Vicon; Denver, CO) sampling at 200 Hz.

### Procedures

Participants visited the laboratory for data collection two times separated by at least 48 hours. Session 1 consisted of health history and training history questionnaires as well as HBD 1RM determination. In the training history questionnaire, participants reported their age, injury history, body mass, height, and estimated HBD 1RM. Investigators utilized the reported HBD 1RM estimation to choose loads for warm-up sets during 1RM determination, which was performed according to previously validated procedures<sup>16</sup>. Briefly, participants first completed 10 repetitions using an unloaded 20kg hexagonal barbell, with the handle position in line with the weight lever arms, followed by 20% of participant-estimated 1RM for 8 repetitions, 40% of participant-estimated 1RM for 5 repetitions, and 60% of participant-estimated 1RM for 5 repetitions. Then, 5 repetitions were attempted using 80% of participant-estimated 1RM. If more than five repetitions could have been completed, the load was increased in 2-10kg increments until a load was reached where

**Table 1.** Participant Characteristics

	Age (years)	Height (cm)	Body Mass (kg)	Hexagonal Barbell Deadlift e1RM (kg)
Mean	20.40	184.60	108.80	216.60
Standard Deviation	2.41	5.76	14.02	10.91

Notes: e1RM = estimated 1-repetition maximum based on Epley formula<sup>15</sup>.

no more than five repetitions (sub-5RM) could be completed. A minimum of 3 minutes of rest was provided between each set. Once sub-5RM was determined, HBD 1RM was estimated (e1RM) using the Epley formula<sup>15</sup>, which has been demonstrated to result in minimal error in 1RM predictions<sup>17</sup>.

Session 2 consisted of HBJS testing at various loads calculated as a percentage of HBD e1RM determined in session 1. During data collection, participants wore compression clothing and had 33 reflective markers attached to the body for motion tracking. Markers were placed at the sacrum and the iliac crest, trochanter, thigh (four-marker rigid cluster), medial epicondyle, lateral epicondyle, shank (three-marker rigid cluster), medial malleolus, lateral malleolus, calcaneus, 1<sup>st</sup> metatarsal, and 5<sup>th</sup> metatarsal of both lower extremities. Participants positioned their feet side-by-side on separate force plates at self-selected spacing. Wooden boxes were set up on either side of the force plates to hold the barbell off the ground slightly, allowing the participant to lift the barbell to a standing position with less effort than would be required to lift the hexagonal barbell from the floor. Once in a standing position while holding the hexagonal barbell, participants were instructed to perform a countermovement to a similar depth as they would for an unloaded vertical jump, then jump as high as possible. Participants were allowed practice trials to ensure proper technique prior to actual data collection. Participants performed HBJS using 10%, 20%, 30%, 40%, 50%, and 60% of HBD e1RM, as well as an unloaded CMJ (Control), in randomized order. Five trials were completed for each condition, with a minimum of two minutes and thirty seconds rest between each trial. Only the concentric portion of each jump was focused upon for analysis, defined as the time between the point at which the reflective marker at the sacrum reached a minimum vertical position (bottom position of countermovement) and the point at which the vertical ground reaction forces reached a minimum just before take-off.

The raw, unfiltered reflective marker XYZ positions and force plate data from each trial were imported into analysis software (Visual3D; Germantown, MD) and filtered at 13Hz using a low-pass Butterworth filter.

To calculate total body power, a three-dimensional model of the lower extremity was constructed for each participant, from which the lower extremity center of mass (COM) position was determined as the location of the sacrum marker. Vertical

COM velocity (COMv) was calculated as the first derivative of the vertical COM position during the concentric phase. Vertical ground reaction force data were extracted from both force plates and summed to yield the total vertical force applied during the concentric phase ( $GRF_{total}$ ). For each trial, total body power was calculated as the product of  $GRF_{total}$  and COMv during the concentric phase.  $GRF_{total}$  for each trial was normalized to the body mass of the participant. Peak total body power (TBPpeak) was calculated as the maximum TBP during the concentric phase for each trial. For each participant, the average TBPpeak was calculated across five trials for each condition.

To calculate the individual joint biomechanics, standard inverse dynamic methods employing the ground reaction force, captured segmental positions, and estimated joint centers were utilized within the Visual3D software to calculate 3-degree of freedom joint angles (deg), joint velocities (deg/s), joint moments (Nm/kg body mass), and joint powers (W/kg body mass) at each joint of the lower extremity. A numerical programming software (MATLAB; Natick, MA) was used to organize the Visual3D output data and perform all further mathematical operations. Kinetics were normalized to body mass to allow for comparison across participants. Relevant values were extracted from the time series data, and averages were calculated across all five trials for each condition within each participant. Only data from the dominant limb (all participants noted their right limb) were used for statistical analysis. The decision to only analyze the dominant limb data was to reduce model complexity and the number of comparisons across a very large dataset. Furthermore, this approach is consistent with prior bilateral jump analysis e.g.,<sup>11</sup>.

### Statistical Analysis

Statistical analysis was done using SPSS software (version 18.0, SPSS Inc., Chicago, IL, USA). Significance was set a priori at a level of  $\alpha \leq 0.05$ .

All  $GRF_{total}$  and COMv data satisfied tests of normality. A one-way repeated measures analysis of variance (ANOVA) was used to assess differences in TBPpeak across conditions. Post hoc tests with Bonferroni adjustments were conducted if significant main effects were observed.

All joint level data satisfied initial tests of normality, with the exception of peak knee angle, for which a natural logarithmic transformation was performed.

For each variable of interest, a one-way repeated measures ANOVA was used to assess differences across conditions. Post hoc tests with Bonferroni adjustments were conducted if significant main effects were observed. Cohen's *d* effect sizes (ES) were calculated for each joint-level variable across conditions and interpreted using previously outlined ranges (<0.2 = negligible, small 0.2-0.5 = small, 0.5-0.8 = moderate, >0.8 = large)<sup>18</sup>. Bivariate correlations were run between TBPpeak and each variable of interest for each of the loading conditions.

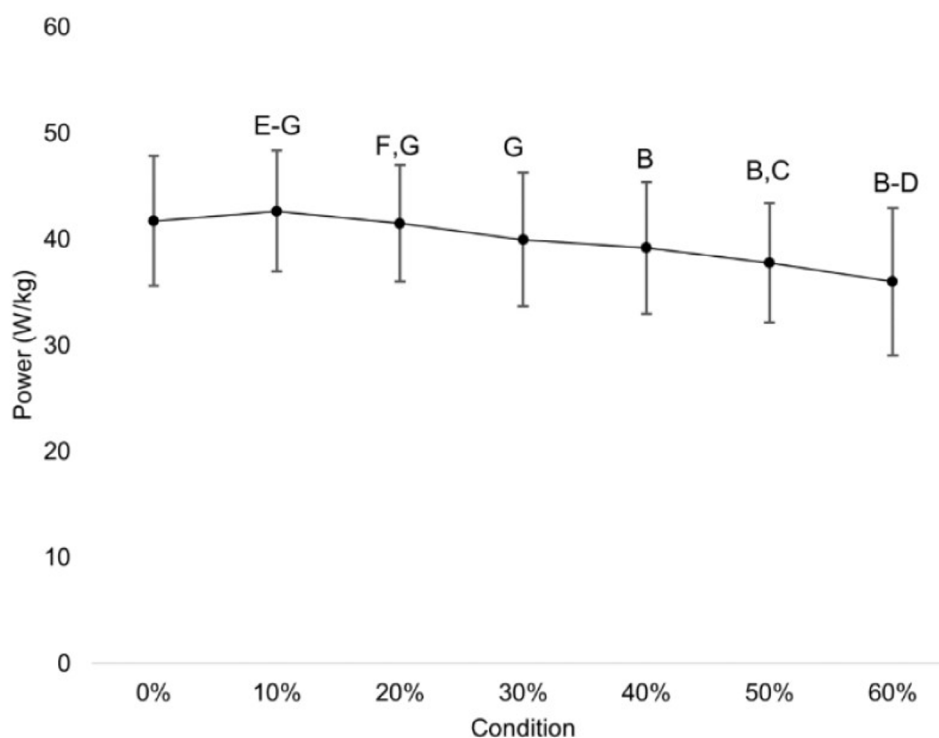
## RESULTS

One-way RMANOVA revealed a significant difference in TBPpeak as load increased ( $p < 0.001$ ). Specifically, the highest TBPpeak was achieved with 10% 1RM ( $42.64 \pm 5.69$ ) but was not significantly different from control ( $41.71 \pm 6.10$ ,  $p > 0.999$ ) or 20% 1RM ( $41.47 \pm 5.49$ ,  $p = 0.497$ ). However, TBPpeak at 10% 1RM was significantly higher than 30% 1RM ( $39.96 \pm 6.28$ ,  $p = 0.015$ ,  $d = 0.47$ ), 40% 1RM ( $39.16 \pm 6.21$ ,  $p = 0.001$ ,  $d = 0.62$ ), 50% 1RM ( $37.76 \pm 5.62$ ,  $p < 0.001$ ,  $d = 0.91$ ), and 60% 1RM ( $35.98 \pm 6.95$ ,  $p = 0.002$ ,  $d = 1.10$ ).

TBPpeak across loads is depicted in Figure 1.

On the individual joint level, one-way RMANOVA analyses revealed significant effects of load on hip power ( $p < 0.001$ ), moment ( $p < 0.001$ ), velocity ( $p < 0.001$ ), and angle ( $p = 0.001$ ); knee power ( $p < 0.001$ ), moment ( $p < 0.001$ ), velocity ( $p < 0.001$ ), and angle ( $p < 0.001$ ); and ankle power ( $p < 0.001$ ) and moment ( $p < 0.001$ ), but not ankle velocity ( $p = 0.053$ ) or angle ( $p = 0.111$ ). Significant differences between loads for each of these variables can be seen in Table 2, with a visual representation in Figure 2.

Significant negative correlations with TBPpeak were observed for hip moment (10%:  $p = 0.009$ ; 50%:  $p = 0.036$ ) and ankle moment (Control:  $p = 0.018$ ). Significant positive correlations with TBPpeak were observed for knee power (all  $p < 0.040$ ), knee moment (all  $p < 0.017$ ), and ankle power (10%:  $p = 0.022$ ; 20%:  $p = 0.016$ ). No significant correlations were observed between TBPpeak and hip power, nor between TBPpeak and velocity or angle for any joint. All correlation coefficients for each variable at each load can be seen in Table 3.



**Figure 1.** Mean  $\pm$  SD TBPpeak (watts/kg) across loading conditions. Letters denote significant difference from 0% (A), 10% (B), 20% (C), 30% (D), 40% (E), 50% (F), 60% (G).  $p < 0.05$ ; ES > 0.5

**Table 2.** Peak power, moment, velocity, and angle at the hip, knee, and ankle across loading conditions. Values presented as mean (SD).

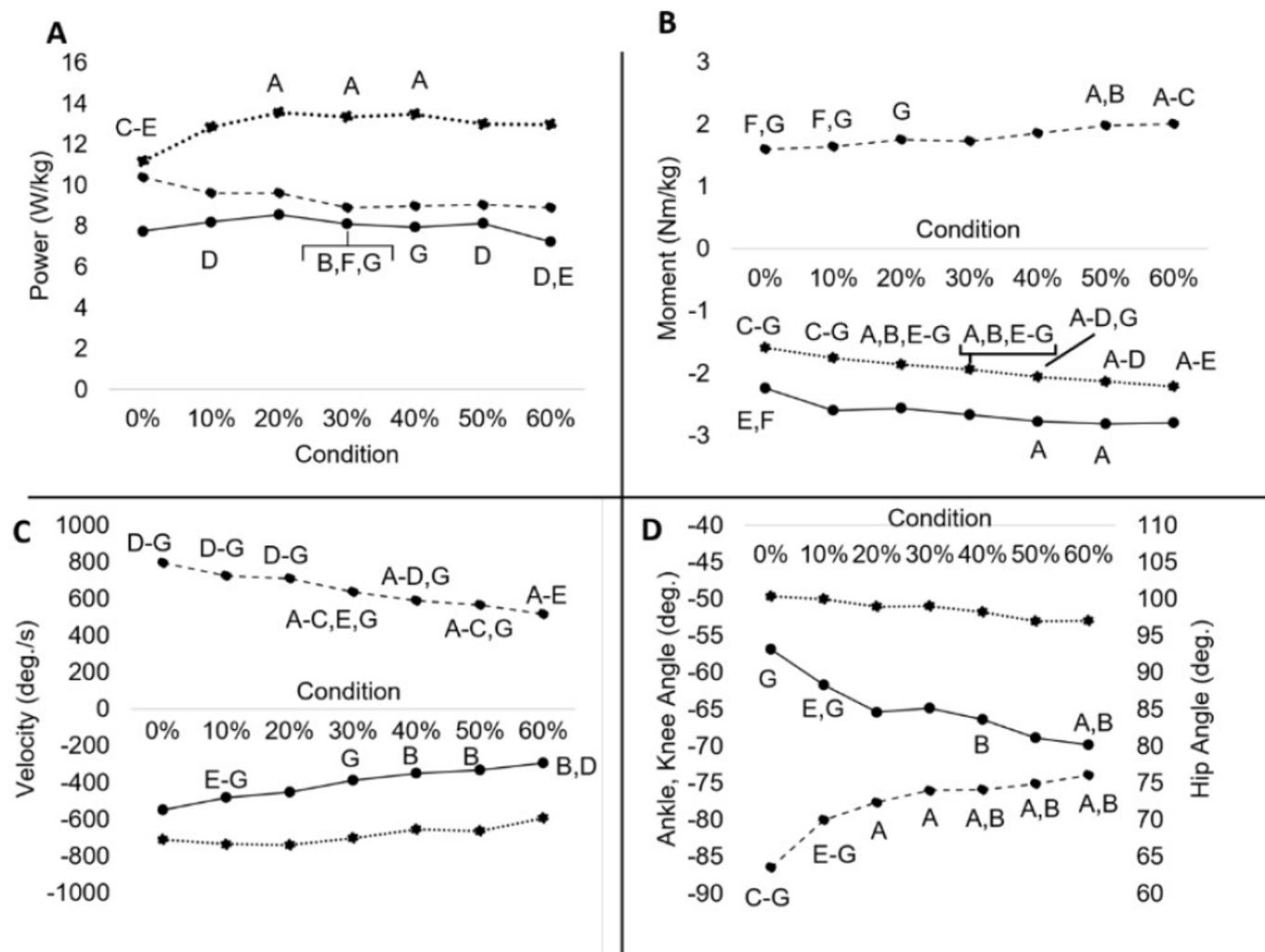
Joint	Variable	ANOVA main effect	Load Condition (% e1RM)						
			Control	10%	20%	30%	40%	50%	60%
Hip	Power (Watts/kg)	$p < 0.001^*$	7.74 (1.90)	8.19 (2.02)	8.56 (2.23)	8.10 (1.66)	7.95 (1.57)	8.13 (2.23)	7.24 (1.72)
	Moment (Nm/kg)	$p < 0.001^*$	-2.24 (0.40)	-2.60 (0.14)	-2.56 (0.14)	-2.67 (0.12)	-2.78 (0.12)	-2.81 (0.15)	-2.80 (0.17)
	Velocity (deg/s)	$p < 0.001^*$	-549.93 (136.29)	-483.42 (82.76)	-452.12 (117.82)	-387.57 (73.08)	-349.33 (73.91)	-333.87 (71.49)	-294.56 (60.45)
	Angle (deg)	$p = 0.001^*$	93.14 (14.58)	88.32 (12.92)	84.60 (11.75)	85.14 (12.34)	83.62 (12.02)	81.09 (13.22)	80.17 (12.54)
Knee	Power (Watts/kg)	$p < 0.001^*$	10.37 (2.98)	9.61 (0.98)	9.61 (0.81)	8.89 (1.02)	8.96 (0.92)	9.04 (0.85)	8.90 (0.78)
	Moment (Nm/kg)	$p < 0.001^*$	1.59 (0.36)	1.64 (0.13)	1.75 (0.14)	1.72 (0.15)	1.86 (0.13)	1.98 (0.12)	2.01 (0.13)
	Velocity (deg/s)	$p < 0.001^*$	794.04 (171.16)	725.34 (114.91)	708.94 (128.06)	637.55 (103.84)	589.12 (92.26)	565.11 (94.90)	515.42 (84.59)
	Angle (deg)	$p < 0.001^*$	-86.48 (10.67)	-80.05 (6.76)	-77.64 (7.87)	-76.03 (8.10)	-75.93 (7.19)	-75.10 (7.46)	-73.96 (7.88)
Ankle	Power (Watts/kg)	$p < 0.001^*$	11.17 (2.25)	12.83 (0.73)	13.56 (0.79)	13.35 (0.70)	13.46 (0.65)	12.99 (0.62)	12.96 (0.69)
	Moment (Nm/kg)	$p < 0.001^*$	-1.60 (0.26)	-1.76 (0.08)	-1.86 (0.07)	-1.94 (0.07)	-2.06 (0.07)	-2.14 (0.07)	-2.21 (0.07)
	Velocity (deg/s)	$p = 0.053$	-711.18 (191.57)	-736.42 (182.80)	-741.60 (171.40)	-703.80 (175.12)	-656.8 (139.56)	-664.78 (127.22)	-592.78 (133.24)
	Angle (deg)	$p = 0.111$	-49.70 (6.99)	-50.08 (6.58)	-51.09 (4.88)	-50.97 (6.76)	-51.83 (6.34)	-53.05 (3.92)	-53.00 (8.26)

Notes: e1RM = estimated 1-repetition maximum. \*Significant main effect of load ( $p < 0.05$ )

**Table 3.** Correlation coefficients between TBPpeak and peak power, moment, velocity, and angle at the hip, knee, and ankle across loading conditions. Values presented as mean (SD).

Joint	Variable	Load Condition (% e1RM)						
		Control	10%	20%	30%	40%	50%	60%
Hip	Power (Watts/kg)	-0.494	-0.477	-0.099	-0.419	-0.498	-0.523	-0.469
	Moment (Nm/kg)	-0.587	-0.771*	-0.345	-0.546	-0.546	-0.666*	-0.466
	Velocity (deg/s)	0.043	-0.308	0.121	-0.003	0.011	-0.138	0.004
	Angle (deg)	0.341	0.315	0.174	0.328	0.375	0.201	0.153
Knee	Power (Watts/kg)	0.719*	0.710*	0.705*	0.785*	0.755*	0.773*	0.654*
	Moment (Nm/kg)	0.728*	0.848*	0.847*	0.873*	0.827*	0.809*	0.728*
	Velocity (deg/s)	-0.105	0.382	0.275	0.165	0.140	0.076	0.218
	Angle (deg)	-0.140	-0.214	-0.135	-0.432	-0.288	-0.208	-0.434
Ankle	Power (Watts/kg)	0.528	0.720*	0.731*	0.558	0.513	0.431	0.440
	Moment (Nm/kg)	-0.724*	-0.560	-0.621	-0.528	-0.616	-0.613	-0.475
	Velocity (deg/s)	0.205	-0.504	-0.406	-0.236	-0.160	-0.113	-0.104
	Angle (deg)	0.086	-0.302	-0.082	0.079	0.024	0.355	0.120

Notes: e1RM = estimated 1-repetition maximum. \*Significant correlation with TBPpeak ( $p < 0.05$ )



**Figure 2.** Mean peak joint power (Panel A; watts/kg), moment (Panel B; Nm/kg), velocity (panel C; deg/s) and angle (Panel D; deg) for the hip (solid), knee (dashed), and ankle (dot-dash) across loading conditions. Letters denote significant difference from 0% (A), 10% (B), 20% (C), 30% (D), 40% (E), 50% (F), 60% (G).  $p < 0.05$ ; ES > 0.5

**DISCUSSION**

The TBPpeak (relative total body power) and peak angle, velocity, relative moment, and relative power at each of the hip, knee, and ankle joints across various loads were examined during the HBJS. Our hypothesis, that 0-20% 1RM would elicit the highest TBPpeak, was supported, as TBPpeak reached its greatest value at 10% e1RM, but was not significantly different from Control, 20% e1RM, or 30% e1RM. Our hypothesis, that peak power relative to body mass at each joint would generally decrease with increasing load, but may be optimized at different loads for different joints, was also supported. Although peak relative power tended to decrease as load increased in general, peak relative power output was observed at 0-20% e1RM for the hip, at 0-20% e1RM for the knee, and at 20-40% e1RM for the ankle. Our hypothesis, that TBPpeak would be positively correlated with peak angle and velocity at all joints but would correlate differently with peak power at each joint, was

partially supported. Indeed, the correlation between TBPpeak and peak power differed between joints: we identified significant positive correlations for the knee joint at all examined loads, but only at select loads (10 and 20% e1RM) for the ankle, and no significant correlations were observed for hip power and TBPpeak. However, no correlations between TBPpeak and peak angle or peak velocity were significant at any load for any joint.

Much prior research (e.g.<sup>2-7</sup>) has investigated loading to optimize TBPpeak. In the current study, 10% e1RM elicited the highest TBPpeak values, but these were not significantly different from Control, 20%, or 30% e1RM. Thus, our data indicate 0-30% of HBD e1RM optimizes TBPpeak, which is consistent with prior literature on the topic<sup>6</sup>. However, this may warrant further study as some data<sup>8,9</sup> are the result of programming loads using back squat 1RM rather than HBD 1RM.

While prior research has largely investigated

loading to maximize TBPpeak to optimize athletic performance, our data add to a growing body of literature indicating that peak power at each lower extremity joint may be optimized at different loads. We observed that while 0-30% e1RM maximized TBPpeak, peak hip power occurred at 20% e1RM, peak knee power at 0% e1RM, and peak ankle power at 20-40% e1RM. The current findings regarding knee power, peaking in unloaded conditions and decreasing with added load, are consistent with previous data<sup>10,11</sup>; however, our data regarding hip and ankle power contrasts prior research. Specifically, Moir et al.<sup>10</sup> reported peak ankle power ( $1.68 \pm 0.59$  Watts/kg) at 0% 1RM and Jandacka et al.<sup>11</sup> ( $1209 \pm 107$  Watts) at 70% 1RM, while our data suggest 20-40% e1RM optimizes ankle power ( $13.56 \pm 0.79$  Watts/kg). Further, we observed peak hip power ( $8.56 \pm 2.23$  Watts/kg) at 20% e1RM, while it was reported in Moir et al.<sup>10</sup> to be maximized ( $1.57 \pm 0.82$  Watts/kg) at 42% 1RM, and Jandacka et al.<sup>11</sup> found no significant differences for hip power between 0-70% 1RM. These discrepancies may be due to differences in methodology.

Regarding the magnitude of power outputs observed, Jandacka et al.<sup>11</sup> reported non-normalized power output; they also reported the body mass of their participants to be  $103 \pm 14$  kg. Thus, relative to body mass, Jandacka et al.<sup>11</sup> found comparable power outputs to the present study. Further, Moir et al.<sup>10</sup> reported average power outputs across the propulsive phase of the jump, not peak power outputs achieved during the propulsive phase, as did both Jandacka et al.<sup>11</sup> and the present study, which may explain why the power outputs reported in Moir et al.<sup>10</sup> are much lower. Regarding the load at which joint power was maximized, Jandacka et al.<sup>11</sup> speculated that they found maximal ankle power at a much higher %1RM than Moir et al.<sup>10</sup> because they standardized countermovement depth to 90 degrees of knee flexion, while the uncontrolled countermovement depth in Moir et al.<sup>10</sup> may have led to different knee flexion angles and thus altered length-tension and force-velocity relationships of the plantar flexors. Our study did not control for countermovement depth either, which may partially explain why we found ankle power to be maximized at loads closer to those reported by Moir et al.<sup>10</sup>. While Markovic and colleagues<sup>19</sup> did not find significant correlations between countermovement depth and TBPpeak when normalizing to body mass ( $r = 0.10$ ), their work was only in unloaded jumps and thus there may be differences in loaded conditions. This difference in controlled versus uncontrolled countermovement depth may also

explain the differences in the load found to optimize hip power in these studies. Although the current state of the literature on individual joint power outputs across various loads is mixed, it appears that peak joint powers may indeed be optimized at different loads, and that these loads may also differ from that which optimizes TBPpeak.

Given this complexity, it seems prudent to examine the relationship between individual joint powers and TBPpeak (Table 3). The strongest association with TBPpeak appears to be knee power, as we identified significant positive correlations between TBPpeak and knee power at all examined loads ( $r$ -values range from 0.654 to 0.785,  $p$ -values range from 0.007 to 0.040). We also found significant positive correlations between TBPpeak and ankle power at 10% ( $r = 0.720$ ,  $p = 0.019$ ) and 20% e1RM ( $r = 0.731$ ,  $p = 0.016$ ). However, we did not observe any significant correlations between TBPpeak and hip power at any load. Further, we identified significant positive correlations between knee moment and TBPpeak at all loads ( $r$ -values range from 0.728 to 0.873,  $p$ -values range from 0.001 to 0.017), and significant negative correlations between TBPpeak and hip moment at 10% ( $r = -0.771$ ,  $p = 0.009$ ) and 50% e1RM ( $r = -0.666$ ,  $p = 0.036$ ), and between TBPpeak and ankle moment at Control ( $r = -0.724$ ,  $p = 0.018$ ). In general, it may therefore be concluded that knee kinetics are most closely associated with power output at the total body level; thus, athletes and coaches may be best served to avoid practices that reduce knee kinetic outputs. Instead, it is suggested practitioners implement training strategies which emphasize rapid and forceful knee extension to enhance total body power.

Other analyses of the current study agree with prior research. Peak moment at all joints increased with increasing loads, which is in agreement with Moir et al.<sup>10</sup>. We also observed that peak flexion values at each joint were maximized at 0% e1RM and decreased with all increasing loads. Similarly, Feeney et al.<sup>20</sup> reported decreased countermovement depth with additional load ( $R^2=0.93$ ,  $p < 0.001$ , see<sup>20</sup>) added to a weighted vest worn by participants, indicating greater peak flexion angles with lower loads. Further, our data show peak joint velocity at 0% e1RM, decreasing with additional load. Although their participants performed the back squat rather than HBJS, Kellis et al.<sup>21</sup> also reported decreasing joint velocities with loaded movements compared to unloaded. However, Kellis et al.<sup>21</sup> noted differences at all three joints combined rather than individually. Likewise

to our kinetic data, we also ran correlation analyses to identify relationships between kinematics and TBPpeak. However, none were statistically significant. This aligns with results of Markovic et al.<sup>19</sup> who did not observe a significant correlation between countermovement depth (i.e., peak flexion angle) and peak power ( $r = 0.10$ , see<sup>19</sup>).

This study is not without limitations. Testing was only done using load intervals of 10% e1RM, and it is possible that differences in mechanics may occur at more nuanced points in the loading spectrum than found with this design. In addition, the right lower extremity was used for data collection for all participants; this does not account for leg dominance or symmetry, which could possibly affect the results. Future work should investigate whether bilateral comparisons reveal meaningful differences in joint-level contributions during loaded jumping. Further, only trained men were included in this study, so these results cannot be extrapolated to other populations. Lastly, the findings herein reflect acute performance in a controlled setting and may not translate directly to complex training sessions.

## FUTURE RECOMMENDATIONS

During the HBJs, loads greater than 30% of HBD e1RM negatively impacted TBPpeak, although loads greater than 20% e1RM decreased hip and knee power, and loads greater than 40% e1RM decreased ankle power. Because of this discrepancy between joints, it may benefit practitioners to identify which joint is most important to maximize power for a given athlete's sport and subsequently train at a load to optimize power output at that specific joint. Given that knee kinetics appear most strongly related to TBPpeak, it seems appropriate to generally train HBJs with 20% 1RM or lower loads. Future work should investigate whether the identified joint-specific load-power relationships persist under different session structures and with alternative load implementations.

## CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

## FUNDING

No funding was involved in any part of this work.

## ETHICAL APPROVAL

Ethics for this study were approved in line with the University's ethics procedure.

## DATES OF REFERENCE

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## REFERENCES

- Marián V, Katarína L, Dávid O, Matúš K, Simon W. Improved Maximum Strength, Vertical Jump and Sprint Performance after 8 Weeks of Jump Squat Training with Individualized Loads. *J Sports Sci Med* 2016;15:492–500.
- Bryanton MA, Kennedy MD, Carey JP, Chiu LZF. Effect of squat depth and barbell load on relative muscular effort in squatting. *J Strength Cond Res* 2012;26:2820–8. <https://doi.org/10.1519/JSC.0b013e31826791a7>.
- Cormie P, McCaulley GO, Triplett NT, McBride JM. Optimal Loading for Maximal Power Output during Lower-Body Resistance Exercises: Medicine & Science in Sports & Exercise 2007;39:340–9. <https://doi.org/10.1249/01.mss.0000246993.71599.bf>.
- Dayne AM, McBride JM, Nuzzo JL, Triplett NT, Skinner J, Burr A. Power Output in the Jump Squat in Adolescent Male Athletes: *Journal of Strength and Conditioning Research* 2011;25:585–9. <https://doi.org/10.1519/JSC.0b013e3181c1fa83>.
- McBride JM, Haines TL, Kirby TJ. Effect of loading on peak power of the bar, body, and system during power cleans, squats, and jump squats. *Journal of Sports Sciences* 2011;29:1215–21. <https://doi.org/10.1080/02640414.2011.587444>.
- Swinton PA, Stewart AD, Lloyd R, Agouris I, Keogh JWL. Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *J Strength Cond Res* 2012;26:906–13. <https://doi.org/10.1519/JSC.0b013e31822e589e>.
- Turner AP, Unholz CN, Potts N, Coleman SGS. Peak power, force, and velocity during jump squats in professional rugby players. *J Strength Cond Res* 2012;26:1594–600. <https://doi.org/10.1519/JSC.0b013e318234ebe5>.
- Suchomel TJ, McKeever SM, Sijuwade O, Carpenter L, McMahon JJ, Loturco I, et al. The Effect of Load Placement on the Power Production Characteristics of Three Lower Extremity Jumping Exercises. *Journal of Human Kinetics* 2019;68:109–22. <https://doi.org/10.2478/hukin-2019-0060>.
- Turner TS, Tobin DP, Delahunt E. Optimal loading range for the development of peak power output in the hexagonal barbell jump squat. *J Strength Cond Res* 2015;29:1627–32. <https://doi.org/10.1519/JSC.000000000000802>.
- Moir GL, Gollie JM, Davis SE, Guers JJ, Witmer CA. The effects of load on system and lower-body joint kinetics during jump squats. *Sports Biomechanics* 2012;11:492–506. <https://doi.org/10.1080/14763141.2012.725426>.
- Jandacka D, Uchytíl J, Farana R, Zahradník D, Hamill J. Lower extremity power during the squat jump with various barbell loads. *Sports Biomechanics* 2014;13:75–86. <https://doi.org/10.1080/14763141.2013.872287>.

12. Farris DJ, Lichtwark GA, Brown N A. T, Cresswell AG. Deconstructing the power resistance relationship for squats: A joint-level analysis. *Scand J Med Sci Sports* 2016;26:774–81. <https://doi.org/10.1111/sms.12508>.
13. Flanagan SP, Salem GJ. Lower extremity joint kinetic responses to external resistance variations. *J Appl Biomech* 2008;24:58–68. <https://doi.org/10.1123/jab.24.1.58>.
14. Kipp K, Kim H, Wolf WI. Muscle-Specific Contributions to Lower Extremity Net Joint Moments While Squatting With Different External Loads. *J Strength Cond Res* 2020. <https://doi.org/10.1519/JSC.0000000000003874>.
15. Epley, B. Poundage Chart. *Boyd Epley Workout*. Lincoln, NE: Body Enterprises; 1985.
16. Lockie RG, Moreno MR, Lazar A, Risso FG, Liu TM, Stage AA, et al. The 1 Repetition Maximum Mechanics of a High-Handle Hexagonal Bar Deadlift Compared With a Conventional Deadlift as Measured by a Linear Position Transducer. *J Strength Cond Res* 2018;32:150–61. <https://doi.org/10.1519/JSC.0000000000001781>.
17. Nickerson BS, Williams TD, Snarr RL, Garza JM, Salinas G. Evaluation of Load-Velocity Relationships and Repetitions-to-Failure Equations in the Presence of Male and Female Spotters. *Journal of Strength and Conditioning Research* 2020;34:2427–33. <https://doi.org/10.1519/JSC.0000000000003731>.
18. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed. Hoboken: Taylor and Francis; 2013.
19. Markovic S, Mirkov DM, Nedeljkovic A, Jaric S. Body size and countermovement depth confound relationship between muscle power output and jumping performance. *Human Movement Science* 2014;33:203–10. <https://doi.org/10.1016/j.humov.2013.11.004>.
20. Feeney D, Stanhope SJ, Kaminski TW, Machi A, Jaric S. Loaded Vertical Jumping: Force–Velocity Relationship, Work, and Power. *Journal of Applied Biomechanics* 2016;32:120–7. <https://doi.org/10.1123/jab.2015-0136>.
21. Kellis E, Arambatzi F, Papadopoulos C. Effects of load on ground reaction force and lower limb kinematics during concentric squats. *Journal of Sports Sciences* 2005;23:1045–55. <https://doi.org/10.1080/02640410400022094>.