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Research article

Correlational Analysis between Joint-level Kinetics of Countermovement Jumps and Weightlifting Derivatives

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Abstract
The purpose of this study was to investigate the mechanical similarity between net joint moments (NJM) of the countermovement jump (CMJ) and the hang power clean (HPC) and jump shrug (JS). Twelve male Lacrosse players performed three maximal effort CMJs and three repetitions of the HPC and JS at 30%, 50%, and 70% of their HPC one repetition maximum (1-RM). Ground reaction forces and motion capture data were used to calculate the NJM of the hip, knee, and ankle joints during each exercise. Statistical comparison of the peak NJM indicated that NJM during the HPC and JS across all loads were equal to or greater than the NJM during the CMJ (all $p < 0.025$). In addition, correlation analyses indicated that CMJ hip NJM were associated (all $p < 0.025$) with HPC hip NJM at 30% and 70% ($r = 0.611–0.822$) and JS hip NJM at 50% and 70% ($r = 0.674–0.739$), whereas CMJ knee NJM were associated with HPC knee NJM at 70% ($r = 0.638$) and JS knee NJM at 50% and 70% ($r = 0.664–0.732$). Further, CMJ ankle NJM were associated with HPC ankle NJM at 30% and 50% ($r = 0.615–0.697$) and JS ankle NJM at 30%, 50%, and 70% ($r = 0.735–0.824$). Lastly, knee and ankle NJM during the JS were greater than during the HPC at 30% and 50% of 1-RM (all $p < 0.017$). The degree of mechanical similarity between the CMJ and the HPC and JS is dependent on the respective load and joint.

Key words: Biomechanics, net joint moments, power training, specificity, vertical jumping.

Introduction

Weightlifting exercises and their derivatives are commonly included in strength and conditioning programs that aim to enhance the rapid force production characteristics of the lower body musculature (Kawamori et al., 2005; Kilduff et al., 2007; Suchomel et al., 2017). The inclusion of these exercises is based on to their biomechanical similarity to athletic movements because they all share similar movement patterns, which are characterized by a rapid and forceful extension of the hip, knee, and ankle joints (Canavan et al., 1996; Cleather et al., 2013; Cushion et al., 2016; Hori et al., 2005). In addition, performance in these exercises has been associated with performance in change of direction tasks, short sprints, and various jumping motions (Hori et al., 2008).

The biomechanical characteristics of weightlifting exercises and their derivatives have been described across a range of studies, which have compared the effects of different exercises and loads (Comfort et al., 2011a; 2011b; 2012; Dahlin et al., 2018; Kipp et al., 2011; 2018; Suchomel et al., 2014a; 2014b; 2017a; 2017b). For example, the kinematics and kinetics of the hang power clean (HPC) and jump shrug (JS) have been compared across a series of studies, which show that the JS consistently elicits higher ground reaction forces as well as center-of-mass power outputs than the HPC (Suchomel et al., 2014a; 2014b). These differences are not surprising since during the JS the center-of-mass of the athlete and barbell system must be accelerated sufficiently to permit the athlete to actually jump with the barbell, whereas during the HPC the barbell mass must only be accelerated sufficiently to move the bar into the front rack position on the shoulders. Performing the JS with increases in load results in a decrease in velocity and power, with a concomitant increase in force, as would be expected (Suchomel and Sole, 2017a; 2017b). In contrast, increasing load during the HPC results in an increase in force and power with no significant decrease in velocity (Suchomel and Sole, 2017a; 2017b). In addition to the gross kinetic and kinematic measures, researchers have also compared the effect of load and exercises at the joint level (Cushion et al., 2016; Dahlin et al., 2018; Kipp et al., 2011; 2018).

Far fewer studies have investigated the similarities between jumping motions and either weightlifting exercises or derivatives (Cleather et al., 2013; Cushion et al., 2016; Garhammer and Gregor, 1992; MacKenzie et al., 2014). For example, Cleather et al. (2013) studied the association between net joint moments of the countermovement vertical jump (CMJ) and the push jerk, and found that the peak hip and knee moments during these two exercises were correlated. Similarly, Cushion et al. (2016) examined the effects of increasing the external load of the push jerk and jump squat on their similarity to the countermovement jump. More specifically, they examined the effects of load-dependent changes on hip, knee, and ankle joint kinetics, which were used to quantify the extent of dynamic correspondence between exercises (Cushion et al., 2016). The authors reported that the mechanical similarity was greatest between the push jerk and the countermovement jump, but only when the push jerk was performed at relatively low loads (Cushion et al., 2016). These results are important findings in the strength and conditioning literature, because they illustrate that the degree of mechanical similarity between resistance training and jumping exercises depends on the respective exercise and changes with the load that is prescribed for each exercise.

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Given the increase in popularity of weightlifting exercises and their purported positive effects on increasing jump performance (Berton et al., 2018), the overall goal of this research project was to investigate the mechanical similarity between peak net joint moments of the CMJ and two weightlifting derivatives; the HPC and JS. The primary aim was to determine whether the joint-specific mechanical demands of weightlifting derivatives across a range of HPC and JS loads exceed the mechanical demands of the CMJ. The secondary aim was to determine whether HPC and JS load affected the correlations between the mechanical demands of the CMJ and weightlifting derivatives. The tertiary aim was to determine joint- and load-dependent differences between the HPC and JS. We hypothesized that the NJM of the weightlifting derivatives would be comparable to, if not greater than, the NJM of the CMJ. We also hypothesized that the NJM of the weightlifting derivatives would be correlated with the NJM of the CMJ, and that these correlations would differ between the HPC and JS, and exhibit load-dependent behavior. Finally, we hypothesized that the HPC and JS would demonstrate joint- and load-dependent differences in joint mechanics.

Methods

Participants

Fifteen male, NCAA DI lacrosse players (Mean±SD; age: 20.1±1.2 years, range 19-22; height: 1.78±0.07 m; body mass: 80.4±8.1 kg; 1-RM HPC: 100.4±8.1 kg; relative 1-Repetition Maximum [1-RM] HPC: 1.25±0.13 $kg \cdot kg^{-1}$) participated in this study. All participants had previously engaged in a periodized strength and conditioning program and were familiar with weightlifting exercises and their derivatives. All testing occurred during the off-season phase of the training program. The study was approved by the University's Institutional Review Board and all subjects provided written informed consent before the beginning of any data collection.

Subject preparation

Eighteen reflective markers were attached to the pelvis, thigh, shank, and foot segments of the right leg according to the standard Plug-in Gait marker set (Vicon, Oxford, UK). These markers were attached with double-sided tape and secured with extra tape as necessary. Markers were attached to the bi-lateral anterior and posterior superior iliac spines, the femoral epicondyles, malleoli, heel and toe (2^{nd} metatarsal) of each leg. In addition, asymmetrical off-axis markers were attached to the thighs and shanks of each leg. Each participant then performed a static trial for which they stood in an anatomically neutral position.

Testing protocol

All participants performed a short general dynamic warm-up consisting of body-weight calisthenic exercises, such as lunges and squats. Each participant then performed several warm-up CMJ that progressed from sub-maximal to maximal intensity (i.e., height). Participants performed three maximal effort CMJ with approximately 20-30 seconds of rest between jumps. For each CMJ, participants were asked to place their hands on their hip, squat down to their preferred depth, and jump as high as possible. Participants then performed a weightlifting-specific warm-up of two sets of three repetitions of the HPC at 30% and 50% of 1RM of HPC 1-RM. The 1-RM for the HPC was based on 1-RM testing results from the previous week. The 1-RM testing session occurred in the athlete's regular workout facility and was monitored by a certified strength and conditioning coach. Participants then moved on to perform work sets at 30%, 50%, and 70% of 1-RM HPC of either the HPC or JS exercise. The exercise order was counterbalanced so that after completing all work sets for one exercise, participants switched to perform the other exercise after approximately 90 seconds rest. The order of work sets was also randomized (e.g., 50%, 70%, 30%), and remained the same for the HPC and JS. Each work set involved the completion of three repetitions and was performed as a cluster set with 20 seconds of rest between each repetition. Approximately 90 seconds of rest were allowed between each work set.

Data collection and processing

A 14-camera motion analysis system (T-Series Cameras, Vicon Denver, Centennial, CO, USA) was used to record the positions of the reflective markers at 100 Hz. In addition, two in-ground force plates (Models OR6-6, Advanced Mechanical Technologies Inc., Watertown, MA, USA) were used to record ground reaction force data at 1000 Hz. Participants positioned themselves such that one foot was on each force plate. A computer with Nexus 1.8.5 software (Vicon Denver, Centennial, CO, USA) was used to simultaneously collect motion capture and ground reaction force data. These data were combined with basic anthropometric data in a standard biomechanical model (Plug-in Gait, Vicon Denver, Centennial, CO, USA) to calculate hip, knee, and ankle net joint moments (NJM). By convention, NJM are expressed as internal moments and are presented so that positive magnitudes reflect extension moments at the knee and hip, and plantar-flexion moments at the ankle. NJM were normalized to each subject's body-mass (i.e., $N \cdot m \cdot kg^{-1}$). Peak positive (i.e., extension) NJM from each joint during the execution of the CMJ, HPC, and JS were extracted for analysis. NJM data from all the three trials were averaged into a three-trial average for each of the exercises. (Kipp et al., 2018). The intra-class correlations coefficients for three-trial averages of kinetic variables during the execution of the HPC and JS ranged from 0.603 to 0.975 (Kipp et al., 2018).

Statistical analyses

Data are presented as Mean±SD. The dependent variable was the peak NJM and the independent variables were exercise (HPC / JS), load (30% / 50% / 70%), and joint (hip / knee / ankle). Statistical assumptions for each respective statistical analysis were checked before the data were analyzed.

NJM from the CMJ were compared to NJM from the HPC and JS with paired *t*-tests. Pair-wise comparisons for each joint were made for each load of the HPC and JS. Correlations between the NMJ of the CMJ and HPC, as well as between CMJ and JS were investigated with linear regression. Again, correlations were calculated for each joint and load of the HPC and JS. Confidence intervals

(95%) were calculated for the correlation coefficients. Bootstrap resampling was performed 100 times to establish 95% confidence intervals for each set of correlation analyses. Because each NJM pair-wise comparison and correlation was made twice (i.e., CMJ vs. HPC and CMJ vs. JS), the alpha-level was adjusted to account for family-wise error rates. The adjusted alpha level for all comparisons and correlations was thus set to 0.025. In addition, only correlation coefficients where the 95% confidence interval did not cross zero were interpreted as significant. The strengths of the correlation coefficients were interpreted based on their magnitudes as follows: 0.00-0.10 = trivial, 0.10–0.29 = small, 0.30–0.49 = medium, 0.50-1.00 = large (Cohen 1988).

A three-way repeated measure analysis of variance was used to compare NJM across exercise, load, and joint conditions. Greenhouse-Geisser corrections were applied if Mauchly's Test of Sphericity was significant. Data were pooled (i.e., averaged) in case of any significant two-way interaction effects data across whichever variable was not part of the interaction (e.g., for the joint x exercise interaction, pooled NJM were calculated by averaging across all loads). Post-hoc comparisons were made with paired t-tests. The threshold for obtaining statistical significance was set at $\alpha = 0.05$. A Bonferroni correction ($\alpha = 0.017$) was applied to the threshold during post-hoc testing to account for multiple comparisons. All statistical analyses were performed in SPSS 24 (IBM Corporation, Armonk, NY, USA).

Results

CMJ vs. JS and HPC

Statistical comparison of the peak NJM indicated that lower-extremity NJM during CMJ were generally equal to the NJM during the HPC and JS at the lowest loads, and smaller than the NJM during the HPC and JS at the larger loads (Table 1). The only exception to this generalization was that the NJM of the knee and ankle during CMJ were smaller than the NJM during the JS even at the lowest loads.

Table 1. Mean (±SD) net joint moments [$N \cdot m \cdot kg^{-1}$] during the CMJ, and during the HPC and JS at 30, 50, and 70% of 1-RM HPC.

		Hip	Knee	Ankle
CMJ		2.31 (0.58)	0.36 (0.20)	1.58 (0.24)
HPC	30	2.74 (0.66)	0.75 (0.57)	1.88 (0.59)
	50	3.28 (0.94)*	0.90 (0.53)*	2.19 (0.53)*
	70	3.68 (0.71)*	0.83 (0.53)*	2.47 (0.37)*
JS	30	2.66 (0.88)	1.47 (0.63)*	2.60 (0.44)*
	50	3.14 (0.87)*	1.50 (0.66)*	2.71 (0.41)*
	70	3.32 (0.89)*	1.42 (0.65)*	2.76 (0.33)*

* $p < 0.05$. CMJ = counter-movement jump, HPC = hang-power clean, JS = jump shrug.

Correlation analyses indicated several significant positive correlations between the NJM during the CMJ and the NJM during the HPC and JS (Tables 2-4). For the hip joint CMJ NJM was correlated with HPC NJM at 30% and 70% 1RM, but not at 50% 1RM. In contrast, CMJ NJM was correlated with JS NJM at 505 and 70% 1RM, but not at 30% 1RM. (Table 2). For the knee joint, correlations between NJM of the CMJ and HPC and JS existed at 70% of 1-RM and at 50% and 70%, respectively (Table 3). For the ankle joint, correlations between NJM of the CMJ and HPC and JS existed at 30% and 50% of 1-RM and at 30%, 50%, and 70%, respectively (Table 4).

Table 2. Correlation coefficients (95% confidence intervals) between hip net joint moments during the CMJ and hip net joint moments of the HPC and JS at 30, 50, and 70% of 1-RM HPC.

	CMJ	CMJ	CMJ
HPC30	.611 (.027-.898)*		
JS30	.577 (-.227-.860)		
HPC50		.592 (.167-0.914)	
JS50		.674 (.157-.909)*	
HPC70			.822 (.480-.946)*
JS70			.739 (.320-.929)*

* $p < 0.025$. CMJ = counter-movement jump, HPC = hang-power clean, JS = jump shrug.

Table 3. Correlation coefficients (95% confidence intervals) between knee net joint moments during the CMJ and knee net joint moments of the HPC and JS at 30, 50, and 70% of 1-RM HPC.

	CMJ	CMJ	CMJ
HPC30	.600 (.130-0.890)		
JS30	.569 (.142-0.824)		
HPC50		.389 (-.250-.727)	
JS50		.732 (.474-.905)*	
HPC70			.638 (.054-.882)*
JS70			.664 (.241-.886)*

* $p < 0.025$. CMJ = counter-movement jump, HPC = hang-power clean, JS = jump shrug.

Table 4. Correlation coefficients (95% confidence intervals) between ankle net joint moments during the CMJ and ankle net joint moments of the HPC and JS at 30, 50, and 70% of 1-RM HPC.

	CMJ	CMJ	CMJ
HPC30	.615 (.258-.906)*		
JS30	.824 (.548-.970)*		
HPC50		.697 (.510-.919)*	
JS50		.763 (.462-.930)*	
HPC70			.612 (.296-.925)
JS70			.735 (.42 -.945)*

* $p < 0.025$. CMJ = counter-movement jump, HPC = hang-power clean, JS = jump shrug.

JS vs. HPC

The three-way interaction between exercise, load, and joint was not significant (Table 1). However, all three of the two-way interactions were significant: load x exercise (p = 0.009), joint x exercise ($p = 0.002$), joint x load ($p = 0.001$ – Greenhouse-Geisser corrected). Post-hoc testing for the load x exercise interaction indicated that, when averaged across joints, the NJM differed at 30% and 50%, but not at 70% of 1-RM (Figure 1A). Post-hoc testing for the joint x exercise interaction indicated that load-averaged NJM of the HPC and JS differed only at the knee and ankle joints (Figure 1B). Post-hoc testing for the joint x load interaction indicated that, when averaged across exercises, only the hip and ankle joints exhibited load-dependent behavior in NJM

(Figure 2). More specifically, the exercise-averaged NJM at the hip and ankle differed across all loads.

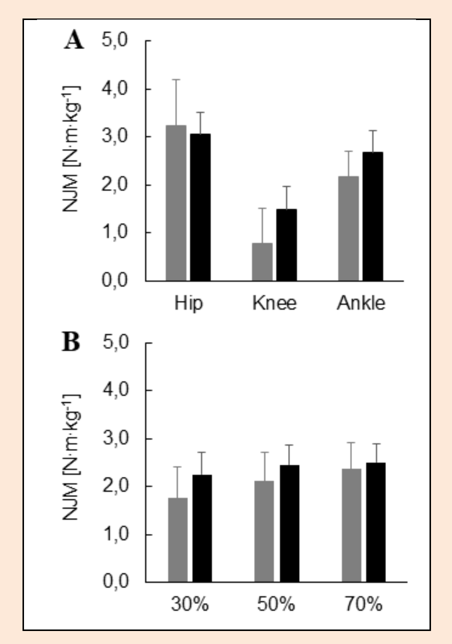

Figure 1. Mean±SD for A) load-averaged and B) joint-averaged net joint moments (NJM [N·m·kg^{-1}]). Grey bars = Hang Power Clean, Black bars = Jump Shrug.

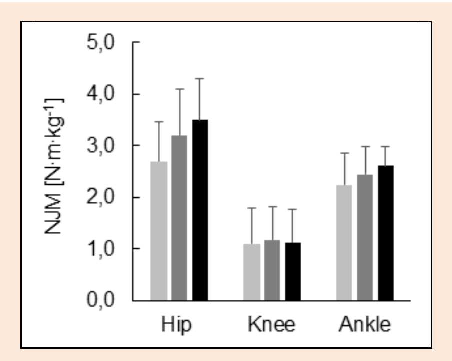

Figure 2. Mean±SD for lift-averaged net joint moments (NJM [N·m·kg^{-1}]) for all joints and loads. Light grey bars = 30%, dark grey bars = 50%, black bars = 70% of 1-RM Hang Power Clean.

The one-way main effect for exercise indicated that when pooled across joints and loads, the NJM did not differ between the HPC and JS ($p = 0.191$). The one-way main effect for load indicated that when pooled across joints and exercises, the NJM differed across load ($p = 0.001$ – Greenhouse-Geisser corrected). Post-hoc testing for the load main effect indicated that NJM were greater with each respective increase in load. The one-way main effect for joint indicated that when pooled across loads and exercises, the NJM differed across joints ($p = 0.001$). Post-hoc testing for the joint main effect indicated that all NJM differed from each other, and that hip NJM were the greatest, followed by ankle NJM, followed by knee NJM.

Discussion

The results of the current study suggest that performing the HPC and JS can be used to match the mechanical demands of the CMJ. In addition, and unsurprisingly, increasing the external load lifted during the HPC and JS effectively overloads the lower extremity extensor muscles beyond the levels required to execute a maximal effort CMJ. Although load-dependent increases in NJM are well documented across resistance training and weightlifting exercises, none have made joint kinetic comparisons between these tasks and the CMJ (Bryanton et al., 2012; Kipp et al., 2011; 2012; 2018). The results of the current study showed that the peak lower-extremity extensor NJM during the execution of the HPC at 30% 1-RM were equal to those of the CMJ. Furthermore, an increase in the external load of the HPC to 50% of 1-RM or above resulted in all NJM of the lower extremity during the HPC being greater than during the CMJ. For the JS, the NJM of the knee and ankle were greater than the NJM of the CMJ regardless of the external load. In addition, the hip NJM during the JS exceeded the hip NJM of the CMJ once the JS load exceeded 50% of 1-RM.

Although previous research showed that increases in external loads lead to increases in the magnitude of lower extremity joint work performed during the execution of the HPC and JS (Kipp et al. 2018), no previous studies have made direct statistical comparisons between the mechanical demands of the lower extremity extensor muscles during CMJ and the HPC or JS. While Cushion et al. (2016) reported NJM for the CMJ, push jerk, and jump squat, these authors did not compare joint kinetics between these exercises. However, brief examination of their data suggests similar load-dependent increases in NJM that lead to the knee and ankle NJM exceeding those during the CMJ (Cushion et al. 2016). It therefore appears that performing these weightlifting derivatives at 50% of 1-RM or greater increases the NJM demands enough to overload the lower extremity extensor muscles beyond the mechanical requirements of the CMJ. Notably, however, the mechanical outputs at the knee and ankle joint during the JS already exceed the mechanical demand of the CMJ, even if the JS is performed with only 30% of 1-RM. Although these findings may justify the use of weightlifting derivatives, such as the HPC and JS, in efforts to improve CMJ performance, an intervention study would be required to test this assertion.

The correlation analyses showed several significant positive correlations between the NJM of the CMJ and weightlifting derivatives. More specifically, one the major finding of this analysis was that at 70% of 1-RM all the NJM of both weightlifting derivatives were highly correlated with their respective counterparts during the CMJ. In addition, at 50% of 1-RM all NJM of the JS were also highly correlated with those of the CMJ. The fact that the NJM correlation coefficients between the CMJ and the two weightlifting derivatives differed across loads indicated that the mechanical similarity changed as the external load increased. Cushion et al. (2016) similarly reported that the NJM correlations between CMJ and the push jerk and jump squat changed across load. It is perhaps not surprising that the correlations between CMJ and JS NJM were more consistent across a broader range of loads and joints because the JS is executed with an emphasis on jumping as high as possible with the barbell whereas the HPC is executed with an emphasis on catching the barbell in a front rack, semi-squat position (Suchomel et al. 2017). Even though the execution of weightlifting derivatives is often described as "jumping with weights," the current results suggest that this comparison becomes more valid when the HPC is performed with relatively high loads. In contrast, it appears that the comparison between the CMJ and JS NJM are valid across all loads. Depending on this joint-load combination, the JS therefore appears to provide an effective lower extremity overload stimulus. This finding, however, should be considered in light of previous research that indicated that the JS may be best implemented with lighter loads, while the HPC may be best implemented with moderate to heavy loads (Kawamori et al., 2005; Kilduff et al., 2007; Kipp et al., 2018; Suchomel et al., 2017).

Analyses of the joint- and load-based interactions between the NJM of the HPC and JS suggest that differences were most apparent at the knee and ankle joint, and at 30% and 50% of 1-RM. More specifically, the joint-averaged NJM at 30% and 50% were greater for the JS than the HPC, while at 70% there were no differences. In addition, the difference in load-averaged NJM between the HPC and JS existed only at the knee and ankle joints, but not for the hip joint. Furthermore, only the hip and ankle exercise-averaged NJM joints exhibited load-dependent behavior across the range of 1-RM conditions. Collectively, these results thus indicate that the JS is associated with greater mechanical demands of the knee and ankle joints, especially at lighter loads. These results agree with previous research that showed greater knee and ankle joint power during the JS than the HPC, especially at 30% and 50% of 1-RM (Kipp et al. 2018). Given that load-dependent differences between the HPC and JS disappear at 70%, it could be surmised that the two weightlifting derivatives become more mechanically similar, perhaps because it is possible to execute the HPC and JS with several different movement strategies and still complete each task at lower loads.

The results from this study should be interpreted in light of several limitations. First, the focus of the current manuscript was on investigating the mechanical similarity between CMJ and weightlifting derivatives. The findings therefore do not hold much direct insight into performance for the sport of weightlifting. Second, the current study used only a cross-sectional research design, which precludes making ultimate conclusions about which weightlifting derivative would lead to the greatest increase in CMJ performance if used as part of a longitudinal research study. For example, limited longitudinal evidence suggests that training programs that implement weightlifting derivatives that either include or exclude the catch phase have similar positive effects on CMJ performance (Comfort and Suchomel, 2018). Similarly, one other study indicated that training with either loaded hexagonal barbell jumps or high pulls performed from the hang position produce similar adaptations in CMJ performance after 10 weeks of training (Oranchuk et al., 2019). Lastly, the small sample size of the current study likely increased the uncertainty in the calculation of the correlation coefficient, which led to the large range of confidence intervals. Given the spread in the confidence intervals it is difficult to reliably distinguish between the strengths of the correlation coefficients aside from either significant or not, and the results from the correlation analyses should therefore be interpreted accordingly.

Conclusion

Peak lower-extremity NJM during the HPC and JS, across all loads, were at least equal to or greater than the NJM during the CMJ. In addition, the peak lower-extremity NJM during the HPC and JS were significantly correlated with NJM during the CMJ across a range of loads. Interestingly, these correlations differed between the respective weightlifting derivatives. All peak NJM during the execution of the JS at 50% and 70% correlated with NJM during the CMJ. In contrast, only hip and knee NJM during execution of the JS at 70%, and only the ankle NJM at 50% correlated with the respective NJM during the CMJ. Lastly, the results suggest that the HPC and JS exhibit joint- and load-dependent mechanical differences that were most apparent at the knee and ankle joint, and at 30% and 50%. Collectively, these results therefore suggest that the mechanical similarity between the CMJ and the two weightlifting derivatives varies with load and across joints.

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Key points

- JS loads greater than 50% exceed the peak NJM demands of the CMJ, and correlate with all NJM during the CMJ.
- While HPC loads greater than 50% exceeded the peak NJM demands of the CMJ, at 50% only ankle HPC NJM correlated with ankle CMJ NJM and at 70% only hip and knee HPC NJM correlated with the respective NJM during the CMJ.
- The greatest training stimulus and degree of mechanical similarity between weightlifting derivatives and the CMJ is likely achieved when performing the JS at 50% and 70% and the HPC at 70%.

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