Relative intensity influences the degree of correspondence of jump squats and push jerks to countermovement jumps

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ABSTRACT

The aim of this study was to determine the mechanical similarity between push jerk (PJ) and jump squat (JS) to countermovement jump (CMJ) and further understand the effect increasing external load may have on this relationship. Eight physically trained males (age 22 ± 3; height 176 ± 7 kg; weight 83 ± 8 kg) performed an unloaded CMJ followed by JS under a range of loads (10%, 25%, 35% and 50% 1RM back squat) and PJ (30%, 50%, 65% and 75% 1RM push jerk). A portable force platform and high speed camera both collecting at 250 Hz were used to establish joint moments and impulse during the propulsive phase of the movements. A standard inverse dynamics model was used to determine joint moment and impulse at the hip, knee and ankle. Significant correlations ($p<0.05$) were shown between CMJ knee joint moment and JS knee joint moment at 25% load and PJ knee joint moment at 30% and 50% load. Significant correlations were also observed between CMJ knee joint impulse and JS knee joint impulse at 10% load and PJ knee joint moment at 30% and 65% load. Significant correlation was also observed between CMJ hip joint impulse and PJ hip joint impulse at 30% load. No significant joint x load interaction was shown as load increased for either PJ or JS. Results from the study suggest partial correspondence between PJ and JS to CMJ, where a greater mechanical similarity was observed between the PJ and CMJ. This interaction is load and joint dependent where lower relative loads showed greatest mechanical similarity. Therefore utilising lower relative loads when programming may provide a greater transfer of training effect.

Key Words: inverse dynamics, jumping, joint moments, specificity

INTRODUCTION

When choosing exercises to enhance physical qualities, consideration of the correspondence between a training exercise and target sport skill is regarded and often results in the categorization of exercises from general to specific in regard to the mechanical similarity to a specific sport skill. Choosing the most appropriate exercises for training to enhance sport specific motor qualities, by the assessment of the similarities in kinetic and kinematic qualities between the training exercises and the sporting skills may allow for more direct transfer (8).

A sporting skill that is of importance in many sports is the vertical jump. Although the vertical jump is a valuable training exercise in its own right, coaches will often use modalities such as Olympic weightlifting and lower limb ballistic exercises to enhance vertical jump ability. This is based upon the contention that these movements are mechanically similar to vertical jumping, mainly due to the triple extension pattern that is displayed, their similar movement velocities and rate of force development (3,5,15). Despite the prevalence of this common assumption, there is a lack of conclusive evidence of a mechanical similarity. In particular, there is a body of previous work that has compared the external kinetics (e.g. ground reaction force; GRF) of these movements, however comparisons of the internal kinetics (e.g. individual joint moments) are reported to a much lesser extent (2,5,6,17,20,27,30,31). Specifically, joint moment analysis is a commonly used description of internal kinetics and describes joint specific loading in a given movement. Due to the time constraints in many sporting actions, the assessment of joint impulse (integral of moment with respect to time) may provide further insight into the strategies used to complete specific movements. Studies investigating internal kinetics have been shown to be important for understanding the mechanical similarities between skills such as sprinting, lunging and squatting (e.g. 7,33,34). However, there is still limited research in this area, warranting further investigation.

There is some recent evidence that suggests that the joint kinetics of common training movements like Olympic weightlifting may not be as similar to vertical jumping as it is commonly assumed. For instance, Cleather, Goodwin and Bull (9) have shown that the joint moments in a countermovement jump (CMJ) can be variable, with some athletes showing a knee dominance (i.e. greater amount of knee moment production), some showing a hip dominance (greater hip moment production) and some showing a more balanced strategy. In contrast, they found that the pattern of joint moments in the push jerk (PJ) were more consistent, showing a clear knee dominant strategy. Thus, when considering the internal (joint) kinetics, the PJ is more similar in those athletes who are knee dominant jumpers. Taking into regard the continuum of general to specific exercises for sports performance, for those athletes who adopted more hip dominant strategies the PJ may be a more general exercise and movements considered to produce more hip moment, such as jump squats (28), could instead be used as a more specific exercise for these athletes. Further research in various movements may add further insight into this matter.

Another open question is the effect of external load on the internal kinetics (and hence the mechanical similarity) of exercises and sports skills. Again, the effect that an increase in load has on movement has been subject to analysis by a number of studies (19,22,23,32,33). A recent study by Moir, Gollie, Davis, Guers and Witmer (28) showed that during a jump squat (JS) there was a linear increase in the joint moments at the hip, knee and ankle as the load was increased. Conversely, a number of similar studies, reporting on internal joint kinetics in other movement skills, have shown a nonlinear increase in kinetic variables (e.g. joint power, joint moment) at the hip, knee and ankle as load increases (13,19). Therefore, it is entirely plausible that in different movements, the relative moment contribution of the ankle, knee and hip might change as the loading increases (representing a changing movement strategy with increased load). For example, as load increases within a given movement, there may be a change in joint moment contribution from greater knee to greater hip moment. Given the potential change in movement production with increasing load this may have ramifications in regards to the mechanical similarities between movements and it is certainly an area that deserves further investigation.

This review has therefore identified the possibility that some training movements may not share as strong a mechanical similarity to vertical jumping as is commonly portrayed or that the similarity may vary with increasing load. This in turn could impact the decision on whether to use the training modalities as general or specific exercises and thus impact the adaptations attained. Therefore, the aim of this study was to evaluate the mechanical similarity (based upon internal kinetics, joint moment and joint impulse) between two common training movements and the CMJ. A secondary aim was to determine if the similarity altered with increasing load in the training activities. It was hypothesised based on previous research (9, 26) the PJ would display greater mechanical similarities to CMJ at hip and knee joint compared to JS at hip joint. It was also hypothesised increasing load would decrease the mechanical similarity between both lifts and CMJ based on alterations in movement strategies that may occur.

METHODS

Experimental approach to the problem

This study was designed to establish the degree of mechanical similarity that two commonly used resistance exercises (JS and PJ) shared with the CMJ. Further to this, it was the aim to assess how increasing external load in these lifts would affect this relationship. Subjects completed three repetitions of CMJ followed by three repetitions at each load for both JS and PJ. Kinetic and kinematic data were recorded via portable force plate and high speed camera. A 2- dimensional (2D) linked rigid segment model was used for an inverse dynamics analysis (IDA) to determine hip, knee and ankle joint moments and joint impulse. These data were then compared between each condition and load in order to test our hypotheses.

Subjects

Eight male subjects were recruited from a local university weightlifting club. Subjects characteristics were (mean ± SD): age 22±3, height (m) 1.76±0.7, mass (kg) 83±8. Only subjects who had 6 months prior experience in weightlifting, could back squat 1.5 × bodyweight (BW) and had no musculoskeletal injuries that would affect their ability to train were included (training years 2±1, back squat 1RM (kg) 157±18, push jerk 1RM (kg) 93±12). Prior to commencement of the study subjects were asked to refrain from exercise for the 24 hours preceding testing. All subjects were provided with details of the study which included an information sheet, verbal instructions and an informed consent form that was signed before testing could begin. Ethical approval was granted by the ethical review board of St Mary’s University College.

Procedure

At least one week prior to the main testing session all subjects took part in a 1 repetition maximum (1RM) testing session. This required subjects to complete both a 1RM back squat and a 1RM push jerk following the testing protocol of Winchester, Erickson, Blaak and McBride (38).

The main testing session began with a standardized warm up consisting of ten bodyweight squats, ten inchworms and barbell work including ten jumps squats and ten push jerks completed in their own time. Participants then performed an unloaded CMJ, followed by the loaded lifts. The order in which the participants completed testing of the loaded lifts (i.e. whether they performed the JS or the PJ first) was randomized. Test re-test reliability was not tested as previous studies have shown high degrees of reliability in loaded and unloaded jumping movements (29).

Countermovement Jump

Subjects performed three repetitions of the CMJ. It began with subjects in an upright position with hands akimbo. Subjects were instructed to jump maximally for each repetition with depth of the countermovement jump self-selected. Previous research (16) has established trained subjects show a high degree of reliability between repetitions when self-regulating rest periods. As athletes were experienced in training in the present study they were trusted in their judgement to self-select rest periods, this was also to ensure they felt adequately recovered between each repetition.

Jump Squat

The loaded JS began with subjects in an upright position with the barbell placed on the upper back. Subjects performed a maximal jump initiated with a countermovement where depth was again self-selected. Three repetitions of each load were performed with self- selected rest periods between each repetition.

Push Jerk

The loaded PJ began with subjects in an upright position with the barbell placed on the anterior deltoids. Subjects initiated the movement with a countermovement before extending the arms above the head and landing in a semi squat position. Three repetitions of each load were performed with self- selected rest periods between each repetition.

Loads for the lifts were as follows: jump squat - 10, 25, 35 and 50% of back squat 1RM; push jerk - 30, 50, 65 and 75% of PJ 1RM. Different loads were selected for each lift as they more closely reflect those which would be used in strength and conditioning practice. The greatest loads lifted (i.e. 50% of back squat 1 RM for jump squat or 75% of PJ 1RM for the PJ) were always completed last to ensure there was not a large increase in weight from the warm up. Both exercises and order of the three preceding loads (10, 25 and 35% of squat 1RM for jump squat, or 30, 50 and 65% of PJ 1RM for the PJ) were randomised. As subjects were well trained this protocol was deemed sufficient to minimise fatiguing effects, this was confirmed with statistical analysis, where no effect of order occurred ($p < 0.05$).

After all loads had been completed for the first exercise a 10 minute rest was provided. The same protocol then followed with the second lift. Due to the training status of these subjects (all performing weight training 5-6 times a week and five subjects regularly competing in weightlifting competitions) it was not deemed necessary for the two lifts to be tested in separate sessions.

Instrumentation

Markers were placed on bony landmarks of anatomical structures on the shoulder (acromioclavicular joint), hip (greater trochanter), knee (lateral ridge of tibial plateau), ankle (apex of the lateral malleolus) and distal end of the foot (metatarsus head) (39,40). Kinematic data were collected using a high speed video camera (Phantom V5.2, Vision

Research Inc, Wayne New Jersey, USA) sampling at 250 Hz. The camera was positioned perpendicular to the right hand side of the participant (sagittal plane view). The image was calibrated using two vertical poles of known height (1.70 m) which were placed 0.60 m apart in the centre of the field of view. Digitized co-ordinate data were filtered using a fourth order dual pass Butterworth filter with a cut off frequency of 6Hz in MATLAB (MatLab, The Mathworks, Inc, Natick, MA, USA). GRF data were collected using a portable force plate (Kistler Type 9286AA, 600mm x 400mm, Kistler Instruments AG, Wintherthur, Switzerland) sampling at 250 Hz, mounted within a portable lifting platform.

Kinetic and kinematic data were synchronised using an external synchronisation unit, which was linked to a bank of LEDs illuminating in series at 1000Hz. Data was combined for use within an IDA to determine joint moments. An average of the peak values determined from the first and last repetition of each lift were used for analysis, additionally only the propulsive phase of the lifts was used for analysis.

Inverse Dynamics Analysis

A rigid, linked, four segment model (Figure 1) was used for the IDA, where the foot was from the second metatarsal to the ankle joint centre, the shank was from the ankle joint centre to the knee joint centre, the thigh was from the knee joint centre to the hip joint centre, and the trunk was from the hip joint centre to the shoulder joint centre. It was assumed that the centre of joints and segment ends would lie on the midlines of the body segments (21). The combination of filtered co-ordinate data, external ground reaction force and anthropometric data (sourced from de Leva (12)) were used to solve the 2D equations of motion using standard IDA procedures (11). Firstly, kinematic data representing the movement of the segments was calculated from the co-ordinate data. Next, the force and moment acting upon the distal end of the foot segment were determined from the force plate data. Finally, the

Newton-Euler equations of motion were solved in turn for each segment, working from proximal to distal, in order to establish inter-segmental forces and moments. Equations to solve IDA are displayed below: 1- centre of mass (COM) 2- acceleration at COM and 3 - velocity at COM 4- Segment velocity 5- Segment acceleration.

(1) COM_x= Xp + (% length of segment for COM) * (Xd – Xp)

(2) $a_{COM} = \frac{COM_3 - COM_1}{T_3 - T_1}$

(3) $v_{COM} = \frac{a_{com3} - a_{com1}}{T_3 - T_1}$

(4) $\omega = \frac{d\emptyset}{dt}$

(5) $\alpha = \frac{d\omega}{dt}$

Where ω = angular velocity, $d\emptyset$ = rate of change in angular displacement, dt = rate of change in time, α = angular acceleration, $d\omega$ = rate of change in angular velocity, p = proximal, d = distal, a_{com}= acceleration of COM, v_{com}= velocity of COM and T = time.

Figure 1 here

Net joint moments which combine the net intersegmental moments across joints were integrated to attain joint moment impulse values, which reflect total joint moment production with respect to time. All moment values were normalised to subject mass so comparisons between subjects could be made.

Statistical Analysis

Descriptive data are presented as means ± SD for all data. A post hoc power analysis was carried out with sample size of eight. Power analysis indicated appropriate statistical power >0.80 was achieved. To assess order effect participants were split into three groups based on the order they performed the lifts. A repeated measures analysis of variance (ANOVA) was performed to determine the interaction between group x trial. After assessing linearity of data a Pearson's correlation coefficient was used to determine the relationship between joint moment and joint impulse across different joints between the CMJ, PJ and SJ data. Additionally, Pearson's correlation was used to determine the relationship between joint moment and joint impulse as load increased between CMJ, PJ and JS. For analysis of the kinetic data two repeated measures ANOVA were used for the joint × load interaction for each lift. Greenhouse Geisser (GC) corrections were used when Mauchly's Test of Sphericity was violated. Bonferroni adjusted t-tests were used for post hoc testing when ANOVA produced significant results. Significance level was set at $p < 0.05$ for all data. Data was analysed using Windows Microsoft Excel 2007 (Microsoft Corporation: Redmond, WA) and IBM SPSS Statistics (Version 21, IBM Corp: Armonk, NY).

RESULTS

The relationship between joint impulse and joint moment between CMJ and JS (Table 1) highlighted a significant strong positive correlation between knee joint moment at 25% 1RM load (r=0.920, 95% CI [0.612-0.986]) and knee joint impulse at 10% 1RM load (r=0.804, 95% CI [0.229-0.963]) during the JS. As load increased above this point there were no further statistically significant correlations between CMJ and JS across all loads or joints.

The relationship between joint impulse and joint moment between CMJ and PJ (Table 2) highlighted a strong positive correlation between knee joint moment at 30% 1RM load (r=0.750, 95% CI [0.096-0.952]) and 50% 1RM load (r=0.808, 95% CI [0.240-0.964]).

Strong positive correlations were also observed between knee joint impulse in the CMJ and PJ at 30% 1RM load (r =0.708, 95% CI [0.007-0.942]) and between hip joint impulse at 30% 1RM load (r=0.871, 95% CI [0.431-0.946]) and 65% 1RM load (r=0.797, 95% CI [0.211-0.962]). No further significant correlations were observed for joint impulse in the CMJ and PJ.

Table 1-2 here

Peak joint moments for all lifts and across all loads are shown in Table 3. Significant main effect was observed for joint (F[2,14] = 9.093, p = .003) for the JS. There were significant differences between the knee and hip joint moments at 25% 1RM and between the ankle and knee and the knee and hip at 35% 1RM ($p < 0.05$). Significant mean effect was observed for load (F[3,21] = 14.473, p = .000) for PJ. There were significant differences between the hip and knee joint moments at loads of 30, 50 and 75% 1RM. Hip, knee and ankle joint moments were significantly greater as load increased from 30% to 75% 1RM ($p < 0.05$) in the PJ.

Table 3 here

Table 4 shows the variation of joint impulse values across all lifts and loads. A significant main effect for load (F[3,14] = 7.452, $p < 0.05$) was observed for the JS. For all lifts of the JS, except at 25% 1RM, hip joint impulse was greater than knee joint impulse. However, there were no statistically significant differences in joint impulse during the JS as load increased ($p > 0.05$). Significant main effects for joint (F[2,14] = 6.489, $p < 0.05$) and load (F[3,21] = 4.89, $p < 0.05$) were observed for PJ. For the PJ, ankle and hip joint impulse were significantly different from each other across all loading schemes ($p < 0.05$). Knee and hip joint impulse were significantly different between each other at all loads except 65% 1RM.

Table 4 here

Figures 2-3 provide representative data at lightest relative loads for JS (30%) and PJ (35%) to highlighting the proximal to distal joint moment pattern that was displayed across all jumping movements.

Figures 2-3 here

DISCUSSION

The present study aimed to evaluate the mechanical similarity of the PJ and JS to the CMJ and to further evaluate the effect increases in external loading had on the mechanical similarity. This study showed that there was a partial correspondence between both lifts and CMJ, which exhibited a load and joint dependent relationship.

Traditionally movements are compared based solely on external mechanics. As discussed previously, this approach gives a global representation of the movement but does not explain the internal kinetics. When analysing movement in the more traditional manner, all participants within the present study presented a proximal to distal pattern of moment production from hip, knee and ankle during all three lifts and load (see Figures 2 and 3 for representative data). This patterning of movement is characteristic of jumping based activities and has been described by Bobbert and Van Soest (4). This sequence allows the attainment of greater jump heights, through the action of hip, knee and ankle extension, allowing more optimal transfer of energy between joints. Even though the demands of movement were slightly different between JS and PJ, with the bar positioned either posteriorly (JS) or anteriorly (PJ), the goal of the movements was still to move the system mass vertically. It then seems that the proximal to distal pattern of peak moment production is stable with respect to the addition of loading or the vertical projection tasks considered here. Additionally, this proximal to distal patterning has been observed during other sporting movements such as sprinting (10). Collectively this information is useful for coaches in understanding training modalities with similar movement sequences to that of vertical jumping. However, further analysis from this present research suggests that despite the apparent similarity between these exercises there are differences when considered at this internal level.

Correlational analysis showed significant strong positive correlations between the CMJ and JS at 10% 1RM for knee joint impulse (r = 0.80, 95% CI [0.229-0.963]), and 25% 1RM for knee joint moment (r = 0.920, 95% CI [0.612-0.986]). However no other significant correlations were found between CMJ and JS across load or joints. This indicates only a partial correspondence between the CMJ and JS which occurs at lighter relative loads. This is not in line with the original hypothesis, where it was postulated JS would show correlations between CMJ at the hip joint. The lack of greater mechanical similarity between the hip and ankle could be explained from previous research establishing trunk inclination role on jumping performance (25, 36). In particular Vanrenterghem, Lees and de Clercq (36) showed when the trunk is held in a vertical position (as would be the case during a loaded jump squat) there is greater knee joint moment developed, whereas this decreases by 13% when trunk inclination is not restricted. It would seem that during a JS at lighter loads (<25% 1RM) due to the position of the bar on the upper back, this increases the trunk angle reducing the demand at the hip joint compared to an unloaded CMJ, subsequently increasing the involvement of knee extension in vertical translation (25). Therefore, despite more traditional analysis highlighting similarity in movement patterns between CMJ and JS, further analysis indicates JS may alter the loading at joints based on the added constraints of the loaded bar which limit trunk movement compared to a CMJ.

Similarly, significant positive correlations were observed between CMJ and PJ at 30 and 50% knee joint moment, this is in line with the original hypothesis. To the authors' knowledge there is only one previous study that has examined joint kinetics between the CMJ and PJ. In partial agreement with the present studies results, Cleather et al. (9) found strong correlations between hip and knee moments between the PJ and CMJ. However, a point to consider within the work of Cleather et al. (9) is that an absolute load of 40 kg was used for all subjects. This makes direct comparison between studies more challenging, nevertheless 40 kg corresponds to loads between 30 and 50% 1RM PJ for subjects tested within the present study. The slight differences observed between these two studies could in part be attributed to individual's movement strategies, where previous research has established individuals performing the same skill use varying strategies (14,34,35,37). In particular, analysis of a CMJ has highlighted varying contributions from the hip, knee and ankle from joint moment data. For example Vanezis and Lees (35) demonstrate that for good jumpers (based on the top 9 subjects determined by the mean jump data from three trials) the contribution from hip, knee and ankle is as follows: hip 43%, knee 29% and ankle 28%. Contrastingly, Hubley and Wells (18) reported 49% of the total work performed at the knee followed by 28% at the hip and 23% at the ankle. Similarly, Cleather et al. (9) showed a greater percentage contribution from the knee at 35%, hip 33%, and ankle 33% compared to 39% hip, 29% knee and 32% ankle in the current study. This suggests within the present study a greater hip dominant strategy was used compared to a knee dominant strategy used by participants in Cleather et al. (9) study. In comparison both studies highlighted greater knee joint moments compared to hip joint moments in the PJ, with significant increases in knee joint moment compared to hip joint moment at 30% and 50% 1 RM in the current study (30% knee 1.77 Nm/kg, hip 1.20 Nm/kg; 50% knee 2.07 Nm/kg, hip 1.39 Nm/kg in the current study). This would indicate for the current subjects the addition of load provided a constraint on their movement, resulting in a change in demand at each joint compared to a CMJ. In addition with significant correlations at hip and knee joint and significant increases in knee joint moment, it seems loads of 30% and 50% may be used as a specific training modality for increasing vertical jump performance.

In addition to significant correlations observed with joint moment data, significant positive correlations with CMJ were detected at 30% and 65% hip joint impulse and at 30% knee joint impulse during the PJ. The current results again indicate at lighter relative loads there is greater similarity in joint impulse generation between CMJ and PJ. Joint impulse is a product of joint moment and the time over which it is produced. The ability to produce joint moments over short periods of time has been highlighted as an important factor for improving performance in rapidly performed movements (1). This is important for coaches and trainers looking for training modalities that provide similar demands on impulse generation. Interestingly, these significant correlations were observed at 30% and 65% 1 RM but not at 50% and 75% 1 RM for hip joint impulse in the PJ. At this stage, the exact reason for this lack of correlation at 50% and 75% load is not fully understood; however it might be speculated that just as the degree of correspondence is movement dependant, it may also be load dependent. With limited information within this area, further study would be able to expand on these results and so provide a more robust explanation of the present findings.

A secondary aim of this study was to ascertain the impact increasing loading had on mechanical similarity between CMJ, PJ and JS. In agreement with previous research, increasing load resulted in increased joint moments (14,19,24) for both lifts. Additionally, previous groups have also demonstrated that the peak moment for each joint occurred at varying relative loads during a given movement. Specifically, Flanagan and Salem (14) compared joint moment production during a back squat movement, showing a concomitant increase in hip joint moment but a decrease in knee joint moment with increased loading. Likewise Kipp et al. (24) compared joint moments during a clean pull movement and observed peak joint moments occurring at different relative intensities (hip: 75%, knee: 75%: ankle: 85% 1RM). Equally Kipp et al. (24) determined joint impulse values across loads and joints, showing a similar trend to the present study. Peak joint impulse occurred at a higher intensity (85% 1RM) for the hip joint compared to peak joint moment (75% 1RM). In the current study peak joint moments for the JS occurred at 25% 1 RM for hip joint, 50% 1 RM for knee joint and 50% for ankle joint and during the PJ peak hip joint moment occurred at 65% 1 RM, 75% 1 RM for knee joint and 65% for ankle joint. In partial agreement with the original hypothesis, as load increased correlations between JS and PJ decreased. The JS seemed to be most affected by this with no further significant correlations beyond 25% loads whereas at 65% load in the PJ a significant correlation was observed at the knee joint impulse. Consequently, it seems that both joint moment and joint impulse both represent a load and joint dependent relationship. In addition the position of loading seems to impact the degree of correspondence to the CMJ. This should be considered when programming with these exercises.

The results of this study suggest a partial correspondence between the PJ and JS to the CMJ, with greatest correspondence occurring at lower relative intensities. Based on correlation analysis, as load increased similarities between lifts and CMJ decreased. It would seem that as load changes subjects are required to alter the way in which they carry out the movement such that the similarity to CMJ characteristics is affected. The PJ seems to offer the greatest mechanical similarity to that of the CMJ when using loads of 30% 1RM. These results suggest that establishing similarity and therefore transferability of movements based solely on external movement analysis may not provide a complete reflection of the correspondence between two skills. Therefore, determining internal mechanical characteristics of both sporting skills and training modalities can aid in a further understanding of how to create a positive adaptation for the most optimal transfer of training ability.

PRACTICAL APPLICATIONS

The findings of this study provide insight into the mechanical similarity between two common training modalities JS and PJ to a vertical jump movement. Of particular importance is to not only consider the inherent task constraints of exercises but also the added constraints imposed by loading strategies within a given exercise, and how an individual athlete may optimise their movement based on their musculoskeletal constraints.

From a practical standpoint the results suggest the PJ shows greatest mechanical similarity to that of a CMJ, compared to the JS. This occurred at the lowest relative intensities of 30% and 50% 1RM. For optimal transfer of training effect training modalities should offer mechanical overload. Thus, as mechanical similarities where observed at the knee joint at both 30% and 50% 1RM with significant increases in knee joint moment, this would indicate these represent loads which may aid in providing an environment for optimal transfer adaptations. Therefore, due to the similarities in movement PJ could be used as a specific training modality for developing vertical jump performance. In contrast the JS may be more appropriately applied as a general exercise to develop lower limb explosive strength.

REFERENCES

1. Aagard, P. Simonsen, E.B., Anderson, J.L., Magnusson, P. and Dyhre-Poulsen, P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol,* 93: 1318-1326, 2002.

2. Arabatzi, F, and Kellis, E. Biomechanical analysis of snatch movement and vertical jump: similarities and differences. *Hellenic J Phys Educ Sport Sci*, 29: 185-199, 2009.
3. Baumann, W, Gross, V, Quade, K, Galbierz, P, and Shwirtz, A. The snatch technique of world class weightlifters at the 1985 World Champions. *Int J Sport Biomech*, 68: 68-89, 1988.
4. Bobbert, MF, and van Soest, AK. Why do people jump the way they do? *Exerc Sport Sci Rev*, 29: 95-102, 2001.
5. Canavan, PK, Garret, GE, and Armstrong, LE. Kinematic and kinetic relationships between an Olympic style lift and the vertical jump. *J Strength Cond Res*, 10: 127-130, 1996.
6. Carlock, JM, Smith, SL, Hartman, MJ, Morris, RT, Ciroslan, DA, Pierce, KC, Newton, RU, Harman, EA, Sands, WA, and Stone, MH. The relationship between vertical jump power estimates and weightlifting ability: a field test approach. *J Strength Cond Res,* 18: 534-539, 2004.
7. Charalambous, L, Irwin, G, Bezodis, IN and Kerwin, D. Lower limb joint kinetics and ankle joint stiffness in the sprint start push off. *J Sports Sci*, 30: 1-9, 2012.
8. Chiu, LZ, and Schilling B. A Primer on Weightlifting: From Sport to Sports Training. *Strength Cond J*. 27:42-48, 2005.
9. Cleather, DJ, Goodwin, JE, and Bull, AMJ. Intersegmental moment analysis characterizes the partial correspondence of jumping and jerking. *J Strength Cond Res*, 27: 89-100, 2013.
10. Coh, M, and Mackala, K. Differences between the elite and subelite sprinters in kinematic and dynamic determinations of countermovement jump and drop jump. *J Strength Cond Res*, 27: 3021-3027, 2013.

11. Davis, RB, Ounpuu, S., Tyburski, D, and Gage,JR. A gait analysis data collection and reduction technique. *Hum Movement Sci*, 10: 575-578, 1991.

12. de Leva, P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal Biomech*, 29: 1223-1230, 1996.

13. Driss, T, Vandewalle, H, Quievre, J, Miller, C, and Monad, H. Effects of external loading on power output in a squat jump on a force platform: A comparison between strength and power athletes and sedentary individuals. *J Sports Sci*, 19: 99-105, 2001.

14. Flanagan, SP, and Salem, GJ. Lower extremity joint kinetic responses to external resistance variations. *J Appl Biomech*, 24: 58-68, 2008.

15. Garhammer, J, and Gregor, R. Propulsion forces as a function of intensity for weightlifting and vertical jumping. *J Appl Sport Sci Res*, 6: 129-134, 1992.

16. Glaister, M, Witmer, C, Clarke, DW, Guers, JJ, Heller, JL. and Moir, G. Familiarization, reliability and evaluation of a multiple sprint running test using self-selected recovery periods. *J Strength Cond Res*, 24: 3296-3301, 2010.

17. Hori, N, Newton, RU, Andrews, WA, Kawamori, N, McGuigan, MR, and Nosaka, K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? *J Strength Cond Res*, 22: 412-418, 2008.

18. Hubley, CL. and Wells, RP. A work energy approach to determine individual joint contributions to vertical jump performance. *Eur J Appl Physiol*, 50: 247-254, 1983.

19. Jandacka, D, Uchytil, J, Farana, R, Zahradnik, D, and Hamill, J. Lower extremity power during the squat jump with various barbell loads. *Sports Biomec*, 13: 75-86, 2014.

20. Jidovtseff, B, Cronin, J, Harris, N, and Quievre, J. Mechanical comparison of eight vertical jump exercises. *CompMet Biomec Biomed Eng*, 13: 77-78, 2010.

21. Johnson, MD, and Buckley, JG. Muscle power patterns in the mid-acceleration phase of sprinting. *J Sports Sci*, 19: 263-272, 2001.

22. Kawamori, N, Crum, AJ, Blumert, PA, Kulick, JR, Childers, JT, Wood, JA, Stone, MH, and Haff, GG. Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. *J Strength Cond Res*, 19: 698-708, 2005.

23. Kellis, E, Arambatzi, F, and Papadopoulos, C. Effects of load on ground reaction force and lower limb kinematics during concentric squats. *J Sports Sci*, 23: 1045-1055, 2005.

24. Kipp, K, Harris, C, and Sabick, MB. Lower extremity biomechanics during weightlifting exercise vary across joint and load. *J Strength Cond Res,* 25: 1229-1234, 2011.

25. Kopper, B, Ureczky, D, and Tihanyi, J. Trunk position influences joint activation pattern and physical performance during vertical jumping. *Acta, Physiol Hung*, 99: 194-205, 2012.

26. Laffaye, G, Wagner, P. and Tombleson, T. Countermovement jump height: gender and sport specific differences in the force time variables. *J Strength Cond Res,* 28: 1096-1105.

27. Lake, J, Lauder, M, and Dyson, R. Exploring the biomechanical characteristics of the weightlifting jerk. *ISBS*, 24: 1-4, 2006.

28. Moir, GL, Gollie, JM, Davis, SE, Guers, JJ, and Witmer, CA. The effects of load on system and lower body joint kinetics during jump squats. *Sports Biomec*, 11: 492-506, 2012.

29. Moir, G, Sanders, R., Button, C, and Glaister, M. The influence of familiarisation on reliability of force variables measured during unloaded and loaded vertical jump. *J Strength Cond Res,* 1: 140-145, 2005.

30. Moolyk, AN, Carey, JP, and Chiu, LZF. Characteristics of lower extremity work during the impact phase of jumping and weightlifting. *J Strength Cond Res*, 27: 3225-3232, 2013.

31. Nuzzo, JL, McBride, JM, Cormie, P, and McCaulley, GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res*, 22: 699-707, 2008.

32. Pazin, N, Bozic, P, Bobana, B, Nedeljikovic, A, and Jaric, S. Optimum loading for maximising muscle power output: The effect of training history. *Eur J Appl Physiol*, 9: 2123-2130, 2011.

33. Rao, G, Amarantini, D, and Berton, E. Influence of additional load on the moments of the agonist and antagonist muscle groups at the knee joint during closed chain exercise. *J Electro Kines*, 19: 459-466, 2009.

34. Riemann, B, Congleton, A, Ward, R, and Davies, GJ. Biomechanical comparison of forward and lateral lunges at varying step lengths. *J Sports Med Phys Fitness*, 53: 130-138, 2013.

35. Vanezis, A, and Lees, A. A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics,* 48: 1594-1603, 2005.

36. Vanrenterghem, J, Lees, A, and De Clercq, D. Effect of forward trunk inclination on joint power output in vertical jumping. *J Strength Cond Res*, *22*: 708-714, 2008.

37. Vuk, S, Markovic, G, and Jaric, S. External loading and maximum dynamic output in vertical jumping: The role of training history. *Hum Movement Sci*, 31: 139-151, 2012.

38. Winchester, JB, Erikson, TM, Blaak, JB, and McBride, JM. Changes in bar path kinematics and kinetics after power clean training. *J Strength Cond Res*, 22: 708-714, 2005.

39. Wu, G, Siegler, S, Allard, P, Kirtley, C, Leardini, A, Rosenbaum, D, Whittle, MD,Lima, D, Cristofolini, L, Witte, H, Schmid, O, and Stokes, I. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part I: Ankle, hip, spine. *J. Biomech*. 35: 543– 548, 2002.

40. Wu, G, van der Helm, FC, Veeger, H, Makhsous, M, Van Roy, P, Anglin, C, Nagels, J, Karduna, A, McQuade, K, Wang, X, Werner, F, and Buchholz, B. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion-Part II: Shoulder, elbow, wrist and hand. *J. Biomech*, 38: 981-982, 2005.

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FIGURE LEGENDS

Figure 1. Free body diagram for inverse dynamics analysis, detail included is for the foot segment adapted from Johnson and Buckley (19).

Figure 2. Proximal to distal joint moment pattern from representative participant at 30% 1RM PJ.

Figure 3. Proximal to distal joint moment pattern from representative participant at 35% 1RM JS.

TABLE LEGENDS

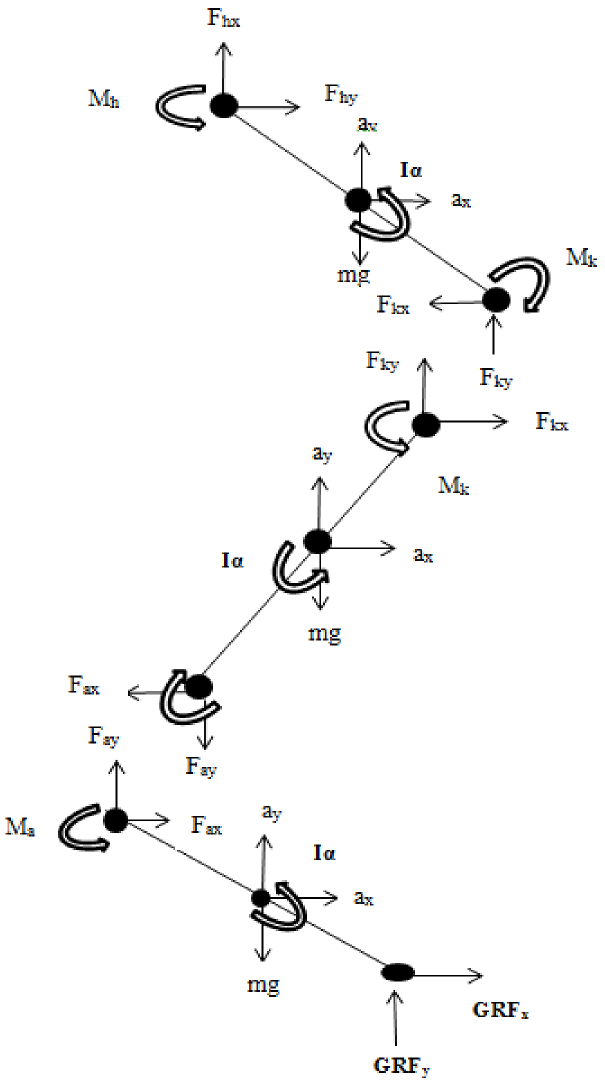
Table 1. Correlations between CMJ and JS across all loads and joints. (Pearson's r and 95% confidence intervals). *Indicates significant correlation ($p < 0.05$).

Table 2. . Correlations between CMJ and PJ across all loads and joints. (Pearson's r and 95% confidence intervals). * Indicates significant correlation ($p< 0.05$).

Table 3. Mean ± SD normalized peak hip, knee and ankle joint moments (Nm/kg) across loading conditions and movements during the propulsive phase of the movements. CMJ = countermovement jump, PJ = push jerk, JS = jump squat, 1RM = 1 repetition maximum. *Denotes significant difference from knee joint ($p< 0.05$). † Denotes significant difference from 30% 1RM ($p<0.05$).

Table 4. Mean ± SD normalized peak hip, knee and ankle joint impulse (Nm/s/kg) across loading conditions and movements during the propulsive phase of the movements. CMJ = countermovement jump, PJ = push jerk, JS = jump squat, 1RM = 1 repetition maximum. *Denotes significant difference from ankle joint ($p< 0.05$). † Denotes significant difference from knee joint ($p< 0.05$).

Figure 1.



Fhx
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Figure 2.

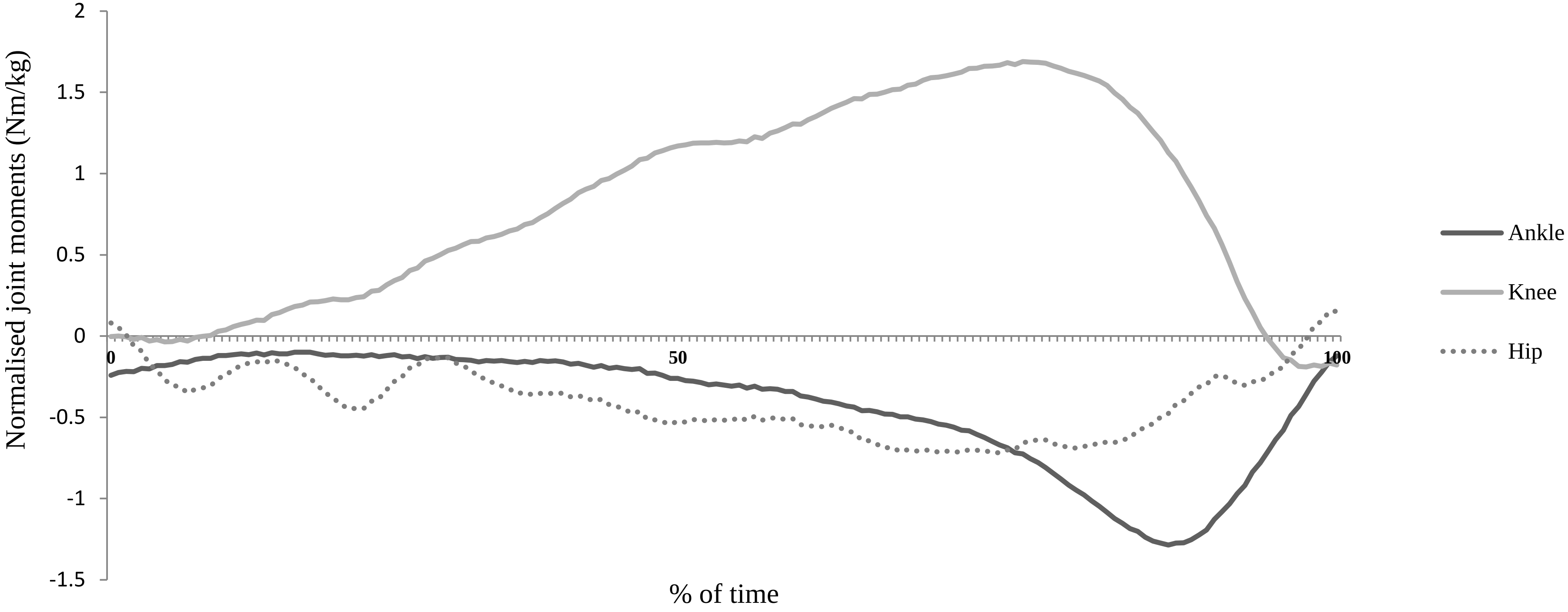
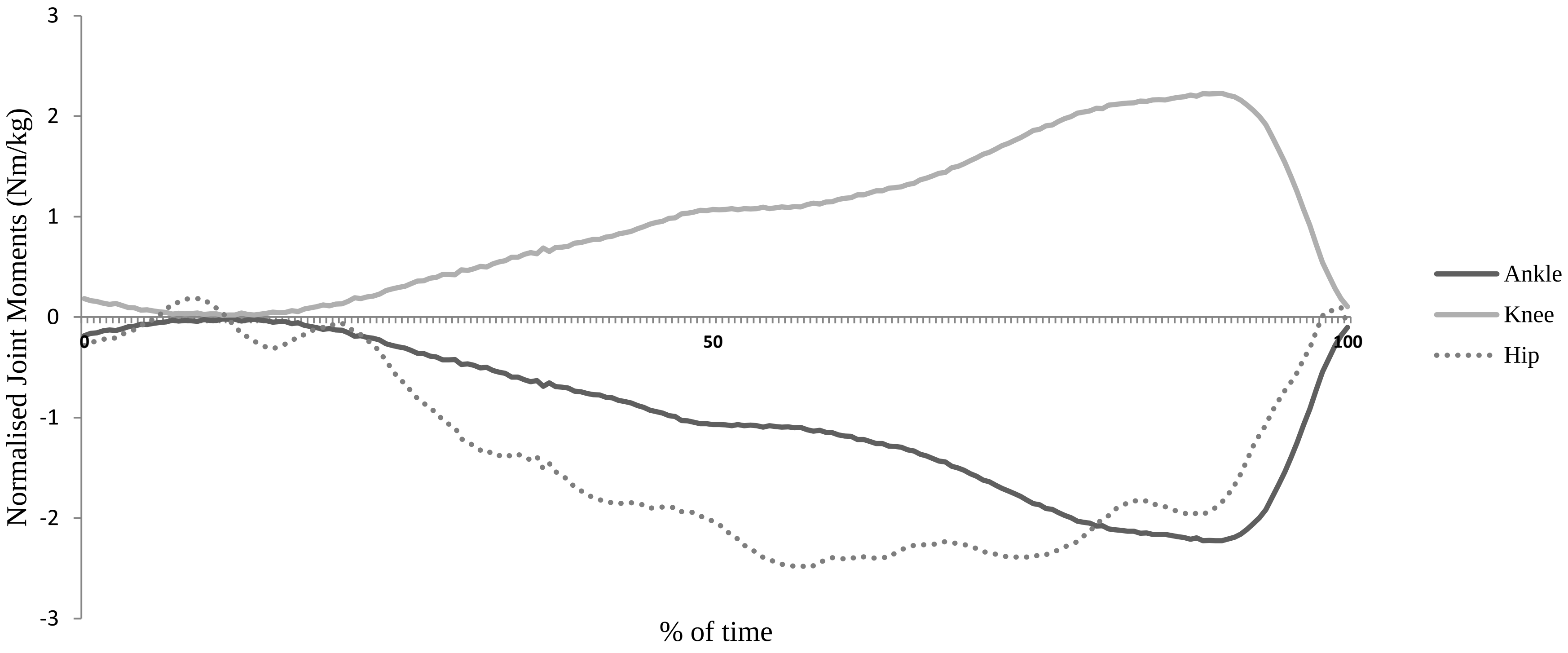

2
1.5
1
0.5
0
-0.5
-1
-1.5
Normalised joint moments (Nm/kg)
0
50
100
% of time
Ankle
Knee
Hip

Figure 3.



3
2
1
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-1
-2
-3
Normalised Joint Moments (Nm/kg)
0
50
100
% of time
Ankle
Knee
Hip

Table 1.

	CMJ					
	Joint Moment			Joint Impulse		
	Hip	Knee	Ankle	Hip	Knee	Ankle
$HIP_{10\%}$	0.438 [-0.386-0.873]			0.530 [-0.279-0.899]		
$KNEE_{10\%}$		0.091 [-0.656-0.748]			0.804* [0.229-0.963]	
$ANKLE_{10\%}$			0.438 [-0.386-0.873]			-0.025 [-0.717-0.692]
$HIP_{25\%}$	0.159 [-0.615-0.777]			0.628 [-0.138-0.924]		
$KNEE_{25\%}$		0.920* [0.612-0.986]			0.704 [-0.001-0.942]	
$ANKLE_{25\%}$			0.321 [-0.496-0.836]			-0.109 [-0.756-0.645]
$HIP_{35\%}$	-0.188 [-0.788-0.596]			-0.023 [-0.716-0.693]		

KNEE$_{35\%}$		0.481 [-0.338-0.886]			0.498 [-0.318-0.890]	
ANKLE$_{35\%}$			0.487 [-0.331-0.887]			-0.128 [-0.764-0.634]
HIP$_{50\%}$	-0.359 [-0.849-0.463]			-0.495 [-0.889-0.322]		
KNEE$_{50\%}$		0.340 [-0.480-0.843]			0.104 [-0.648-0.753]	
ANKLE$_{50\%}$			0.487 [-0.331-0.887]			-0.065 [-0.736-0.670]

Table 2.

	CMJ					
	Joint Moment			Joint Impulse		
	Hip	Knee	Ankle	Hip	Knee	Ankle
$HIP_{30\%}$	0.457 [-0.365-0.879]			0.871* [0.431-0.976]		
$KNEE_{30\%}$		0.750* [0.096-0.952]			0.708* [0.007-0.942]	
$ANKLE_{30\%}$			0.073 [-0.666-0.740]			-0.156 [-0.775-0.616]
$HIP_{50\%}$	0.345 [-0.475-0.844]			-0.172 [-0.782-0.606]		
$KNEE_{50\%}$		0.808* [0.240-0.964]			0.505 [-0.310-0.892]	
$ANKLE_{50\%}$			0.305			-0.280

			[-0.509-0.831]			[-0.822-0.529]
$HIP_{65\%}$	0.293 [-0.519-0.827]			0.797* [0.211-0.962]		
$KNEE_{65\%}$		0.547 [-0.257-0.903]			0.618 [-0.154-0.921]	
$ANKLE_{65\%}$			0.030 [-0.689-0.719]			0.211 [-0.580-0.797]
$HIP_{75\%}$	-0.096 [-0.750-0.653]			0.314 [-0.502-0.834]		
$KNEE_{75\%}$		0.666 [-0.084-0.931]			0.471 [-0.350-0.883]	
$ANKLE_{75\%}$			0.060 [-0.673-0.734]			-0.150 [-0.773-0.620]

Table 3.

Lift	Percentage of 1RM	Joint		
		Hip	Knee	Ankle
CMJ	0%	2.05 ± 0.41	1.52 ± 0.42	1.68 ± 0.20
PJ	30%	1.20±0.25*	1.77± 0.59*	1.55 ± 0.58
	50%	1.39± 0.43*	2.07± 0.5*	2.00 ± 0.44
	65%	2.00 ±0.69	1.99 ± 0.56	2.11 ± 2.00
	75%	1.53± 0.24*	2.19± 0.63*	2.11 ± 0.17
JS	10%	1.90± 0.32	1.47± 0.35	2.10 ± 0.59
	25%	2.28± 0.34*	1.74± 0.39*	2.10 ± 0.31
	35%	1.92± 0.51*	1.65± 0.45*	2.15± 0.33*
	50%	2.23± 0.29	1.87± 0.46	2.30 ± 0.30

Table 4.

Lift	Percentage of 1RM	Joint		
		Hip	Knee	Ankle
CMJ	0%	0.55±0.23	0.54±0.22	0.54±0.09
PJ	30%	0.42±0.15†*	0.65±0.26†	0.63±0.18*
	50%	0.46±0.19†*	0.65±0.33†	0.65±0.26*
	65%	0.68±0.26*	0.89±0.30	0.90±0.29*
	75%	0.58±0.15†*	0.97±0.40†	0.90±0.21*
JS	10%	0.72±0.21	0.62±0.28	0.84±0.27
	25%	0.80±0.35	0.83±0.28	0.85±0.13
	35%	0.84±0.35	0.82±0.35	0.89±014.
	50%	1.12±0.26	0.95±0.32	0.90±0.32