

**TITLE**

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

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

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49 **ABSTRACT**

50 The aim of this study was to determine the mechanical similarity between push jerk (PJ) and  
51 jump squat (JS) to countermovement jump (CMJ) and further understand the effect increasing  
52 external load may have on this relationship. Eight physically trained males (age  $22 \pm 3$ ;  
53 height  $176 \pm 7$  kg; weight  $83 \pm 8$  kg) performed an unloaded CMJ followed by JS under a  
54 range of loads (10%, 25%, 35% and 50% 1RM back squat) and PJ (30%, 50%, 65% and 75%  
55 1RM push jerk). A portable force platform and high speed camera both collecting at 250 Hz  
56 were used to establish joint moments and impulse during the propulsive phase of the  
57 movements. A standard inverse dynamics model was used to determine joint moment and  
58 impulse at the hip, knee and ankle. Significant correlations ( $p < 0.05$ ) were shown between  
59 CMJ knee joint moment and JS knee joint moment at 25% load and PJ knee joint moment at  
60 30% and 50% load. Significant correlations were also observed between CMJ knee joint  
61 impulse and JS knee joint impulse at 10% load and PJ knee joint moment at 30% and 65%  
62 load. Significant correlation was also observed between CMJ hip joint impulse and PJ hip  
63 joint impulse at 30% load. No significant joint x load interaction was shown as load increased  
64 for either PJ or JS. Results from the study suggest partial correspondence between PJ and JS  
65 to CMJ, where a greater mechanical similarity was observed between the PJ and CMJ. This  
66 interaction is load and joint dependent where lower relative loads showed greatest mechanical  
67 similarity. Therefore utilising lower relative loads when programming may provide a greater  
68 transfer of training effect.

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

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74 **INTRODUCTION**

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

82

83 A sporting skill that is of importance in many sports is the vertical jump. Although the  
84 vertical jump is a valuable training exercise in its own right, coaches will often use modalities  
85 such as Olympic weightlifting and lower limb ballistic exercises to enhance vertical jump  
86 ability. This is based upon the contention that these movements are mechanically similar to  
87 vertical jumping, mainly due to the triple extension pattern that is displayed, their similar  
88 movement velocities and rate of force development (3,5,15). Despite the prevalence of this  
89 common assumption, there is a lack of conclusive evidence of a mechanical similarity. In  
90 particular, there is a body of previous work that has compared the external kinetics (e.g.  
91 ground reaction force; GRF) of these movements, however comparisons of the internal  
92 kinetics (e.g. individual joint moments) are reported to a much lesser extent  
93 (2,5,6,17,20,27,30,31). Specifically, joint moment analysis is a commonly used description of  
94 internal kinetics and describes joint specific loading in a given movement. Due to the time  
95 constraints in many sporting actions, the assessment of joint impulse (integral of moment  
96 with respect to time) may provide further insight into the strategies used to complete specific  
97 movements. Studies investigating internal kinetics have been shown to be important for  
98 understanding the mechanical similarities between skills such as sprinting, lunging and

99 squatting (e.g. 7,33,34). However, there is still limited research in this area, warranting  
100 further investigation.

101

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

116

117 Another open question is the effect of external load on the internal kinetics (and hence the  
118 mechanical similarity) of exercises and sports skills. Again, the effect that an increase in load  
119 has on movement has been subject to analysis by a number of studies (19,22,23,32,33). A  
120 recent study by Moir, Gollie, Davis, Guers and Witmer (28) showed that during a jump squat  
121 (JS) there was a linear increase in the joint moments at the hip, knee and ankle as the load  
122 was increased. Conversely, a number of similar studies, reporting on internal joint kinetics in  
123 other movement skills, have shown a nonlinear increase in kinetic variables (e.g. joint power,

124 joint moment) at the hip, knee and ankle as load increases (13,19). Therefore, it is entirely  
125 plausible that in different movements, the relative moment contribution of the ankle, knee  
126 and hip might change as the loading increases (representing a changing movement strategy  
127 with increased load). For example, as load increases within a given movement, there may be  
128 a change in joint moment contribution from greater knee to greater hip moment. Given the  
129 potential change in movement production with increasing load this may have ramifications in  
130 regards to the mechanical similarities between movements and it is certainly an area that  
131 deserves further investigation.

132

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

145

146 **METHODS**

147 **Experimental approach to the problem**

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

156 **Subjects**

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

167 **Procedure**



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

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

#### 179 *Countermovement Jump*

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

#### 187 *Jump Squat*

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

192 *Push Jerk*

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

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

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

211 **Instrumentation**

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

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

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

### 229 **Inverse Dynamics Analysis**

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

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

244 (1)  $COM_x = X_p + (\% \text{ length of segment for COM}) * (X_d - X_p)$

245

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

247

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

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

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

251

252 Where  $\omega$  = angular velocity,  $d\phi$  = rate of change in angular displacement,  $dt$  = rate of change  
253 in time,  $\alpha$  = angular acceleration,  $d\omega$  = rate of change in angular velocity, p = proximal, d =  
254 distal,  $a_{com}$  = acceleration of COM,  $v_{com}$  = velocity of COM and T = time.

255

*Figure 1 here*

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

## 260 **Statistical Analysis**

261 Descriptive data are presented as means  $\pm$  SD for all data. A post hoc power analysis was  
262 carried out with sample size of eight. Power analysis indicated appropriate statistical power  
263  $>0.80$  was achieved. To assess order effect participants were split into three groups based on  
264 the order they performed the lifts. A repeated measures analysis of variance (ANOVA) was  
265 performed to determine the interaction between group  $\times$  trial. After assessing linearity of  
266 data a Pearson's correlation coefficient was used to determine the relationship between joint  
267 moment and joint impulse across different joints between the CMJ, PJ and SJ data.  
268 Additionally, Pearson's correlation was used to determine the relationship between joint  
269 moment and joint impulse as load increased between CMJ, PJ and JS. For analysis of the  
270 kinetic data two repeated measures ANOVA were used for the joint  $\times$  load interaction for  
271 each lift. Greenhouse Geisser (GC) corrections were used when Mauchly's Test of Sphericity  
272 was violated. Bonferroni adjusted t-tests were used for post hoc testing when ANOVA  
273 produced significant results. Significance level was set at  $p < 0.05$  for all data. Data was  
274 analysed using Windows Microsoft Excel 2007 (Microsoft Corporation: Redmond, WA) and  
275 IBM SPSS Statistics (Version 21, IBM Corp: Armonk, NY).

## 276 **RESULTS**

277 The relationship between joint impulse and joint moment between CMJ and JS (Table 1)  
278 highlighted a significant strong positive correlation between knee joint moment at 25% 1RM  
279 load ( $r=0.920$ , 95% CI [0.612-0.986]) and knee joint impulse at 10% 1RM load ( $r=0.804$ ,  
280 95% CI [0.229-0.963]) during the JS. As load increased above this point there were no further  
281 statistically significant correlations between CMJ and JS across all loads or joints.

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

285 Strong positive correlations were also observed between knee joint impulse in the CMJ and  
286 PJ at 30% 1RM load ( $r=0.708$ , 95% CI [0.007-0.942]) and between hip joint impulse at 30%  
287 1RM load ( $r=0.871$ , 95% CI [0.431-0.946]) and 65% 1RM load ( $r=0.797$ , 95% CI [0.211-  
288 0.962]). No further significant correlations were observed for joint impulse in the CMJ and  
289 PJ.

290 *Table 1-2 here*

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

298 *Table 3 here*

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

307 *Table 4 here*

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

311 *Figures 2-3 here*

## 312 **DISCUSSION**

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

317

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

333 understanding training modalities with similar movement sequences to that of vertical  
334 jumping. However, further analysis from this present research suggests that despite the  
335 apparent similarity between these exercises there are differences when considered at this  
336 internal level.

337

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

356



357 Similarly, significant positive correlations were observed between CMJ and PJ at 30 and 50%  
358 knee joint moment, this is in line with the original hypothesis. To the authors' knowledge  
359 there is only one previous study that has examined joint kinetics between the CMJ and PJ. In  
360 partial agreement with the present studies results, Cleather et al. (9) found strong correlations  
361 between hip and knee moments between the PJ and CMJ. However, a point to consider  
362 within the work of Cleather et al. (9) is that an absolute load of 40 kg was used for all  
363 subjects. This makes direct comparison between studies more challenging, nevertheless 40 kg  
364 corresponds to loads between 30 and 50% 1RM PJ for subjects tested within the present  
365 study. The slight differences observed between these two studies could in part be attributed to  
366 individual's movement strategies, where previous research has established individuals  
367 performing the same skill use varying strategies (14,34,35,37). In particular, analysis of a  
368 CMJ has highlighted varying contributions from the hip, knee and ankle from joint moment  
369 data. For example Vanezis and Lees (35) demonstrate that for good jumpers (based on the top  
370 9 subjects determined by the mean jump data from three trials) the contribution from hip,  
371 knee and ankle is as follows: hip 43%, knee 29% and ankle 28%. Contrastingly, Hubley and  
372 Wells (18) reported 49% of the total work performed at the knee followed by 28% at the hip  
373 and 23% at the ankle. Similarly, Cleather et al. (9) showed a greater percentage contribution  
374 from the knee at 35%, hip 33%, and ankle 33% compared to 39% hip, 29% knee and 32%  
375 ankle in the current study. This suggests within the present study a greater hip dominant  
376 strategy was used compared to a knee dominant strategy used by participants in Cleather et  
377 al. (9) study. In comparison both studies highlighted greater knee joint moments compared to  
378 hip joint moments in the PJ, with significant increases in knee joint moment compared to hip  
379 joint moment at 30% and 50% 1 RM in the current study (30% knee 1.77 Nm/kg, hip 1.20  
380 Nm/kg; 50% knee 2.07 Nm/kg, hip 1.39 Nm/kg in the current study). This would indicate for  
381 the current subjects the addition of load provided a constraint on their movement, resulting in

382 a change in demand at each joint compared to a CMJ. In addition with significant correlations  
383 at hip and knee joint and significant increases in knee joint moment, it seems loads of 30%  
384 and 50% may be used as a specific training modality for increasing vertical jump  
385 performance.

386

387 In addition to significant correlations observed with joint moment data, significant positive  
388 correlations with CMJ were detected at 30% and 65% hip joint impulse and at 30% knee joint  
389 impulse during the PJ. The current results again indicate at lighter relative loads there is  
390 greater similarity in joint impulse generation between CMJ and PJ. Joint impulse is a product  
391 of joint moment and the time over which it is produced. The ability to produce joint moments  
392 over short periods of time has been highlighted as an important factor for improving  
393 performance in rapidly performed movements (1). This is important for coaches and trainers  
394 looking for training modalities that provide similar demands on impulse generation.  
395 Interestingly, these significant correlations were observed at 30% and 65% 1 RM but not at  
396 50% and 75% 1 RM for hip joint impulse in the PJ. At this stage, the exact reason for this  
397 lack of correlation at 50% and 75% load is not fully understood; however it might be  
398 speculated that just as the degree of correspondence is movement dependant, it may also be  
399 load dependent. With limited information within this area, further study would be able to  
400 expand on these results and so provide a more robust explanation of the present findings.

401

402 A secondary aim of this study was to ascertain the impact increasing loading had on  
403 mechanical similarity between CMJ, PJ and JS. In agreement with previous research,  
404 increasing load resulted in increased joint moments (14,19,24) for both lifts. Additionally,  
405 previous groups have also demonstrated that the peak moment for each joint occurred at  
406 varying relative loads during a given movement. Specifically, Flanagan and Salem (14)

407 compared joint moment production during a back squat movement, showing a concomitant  
408 increase in hip joint moment but a decrease in knee joint moment with increased loading.  
409 Likewise Kipp et al. (24) compared joint moments during a clean pull movement and  
410 observed peak joint moments occurring at different relative intensities (hip: 75%, knee: 75%:  
411 ankle: 85% 1RM). Equally Kipp et al. (24) determined joint impulse values across loads and  
412 joints, showing a similar trend to the present study. Peak joint impulse occurred at a higher  
413 intensity (85% 1RM) for the hip joint compared to peak joint moment (75% 1RM). In the  
414 current study peak joint moments for the JS occurred at 25% 1 RM for hip joint, 50% 1 RM  
415 for knee joint and 50% for ankle joint and during the PJ peak hip joint moment occurred at  
416 65% 1 RM, 75% 1 RM for knee joint and 65% for ankle joint. In partial agreement with the  
417 original hypothesis, as load increased correlations between JS and PJ decreased. The JS  
418 seemed to be most affected by this with no further significant correlations beyond 25% loads  
419 whereas at 65% load in the PJ a significant correlation was observed at the knee joint  
420 impulse. Consequently, it seems that both joint moment and joint impulse both represent a  
421 load and joint dependent relationship. In addition the position of loading seems to impact the  
422 degree of correspondence to the CMJ. This should be considered when programming with  
423 these exercises.

424

425 The results of this study suggest a partial correspondence between the PJ and JS to the CMJ,  
426 with greatest correspondence occurring at lower relative intensities. Based on correlation  
427 analysis, as load increased similarities between lifts and CMJ decreased. It would seem that  
428 as load changes subjects are required to alter the way in which they carry out the movement  
429 such that the similarity to CMJ characteristics is affected. The PJ seems to offer the greatest  
430 mechanical similarity to that of the CMJ when using loads of 30% 1RM. These results  
431 suggest that establishing similarity and therefore transferability of movements based solely

432 on external movement analysis may not provide a complete reflection of the correspondence  
433 between two skills. Therefore, determining internal mechanical characteristics of both  
434 sporting skills and training modalities can aid in a further understanding of how to create a  
435 positive adaptation for the most optimal transfer of training ability.

436

## 437 **PRACTICAL APPLICATIONS**

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

443 From a practical standpoint the results suggest the PJ shows greatest mechanical similarity to  
444 that of a CMJ, compared to the JS. This occurred at the lowest relative intensities of 30% and  
445 50% 1RM. For optimal transfer of training effect training modalities should offer mechanical  
446 overload. Thus, as mechanical similarities were observed at the knee joint at both 30% and  
447 50% 1RM with significant increases in knee joint moment, this would indicate these  
448 represent loads which may aid in providing an environment for optimal transfer adaptations.  
449 Therefore, due to the similarities in movement PJ could be used as a specific training  
450 modality for developing vertical jump performance. In contrast the JS may be more  
451 appropriately applied as a general exercise to develop lower limb explosive strength.

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591 **FIGURE LEGENDS**

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

594 **Figure 2.** Proximal to distal joint moment pattern from representative participant at 30%  
595 1RM PJ.

596 **Figure 3.** Proximal to distal joint moment pattern from representative participant at 35%  
597 1RM JS.

598 **TABLE LEGENDS**

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

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

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

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

Figure 1.

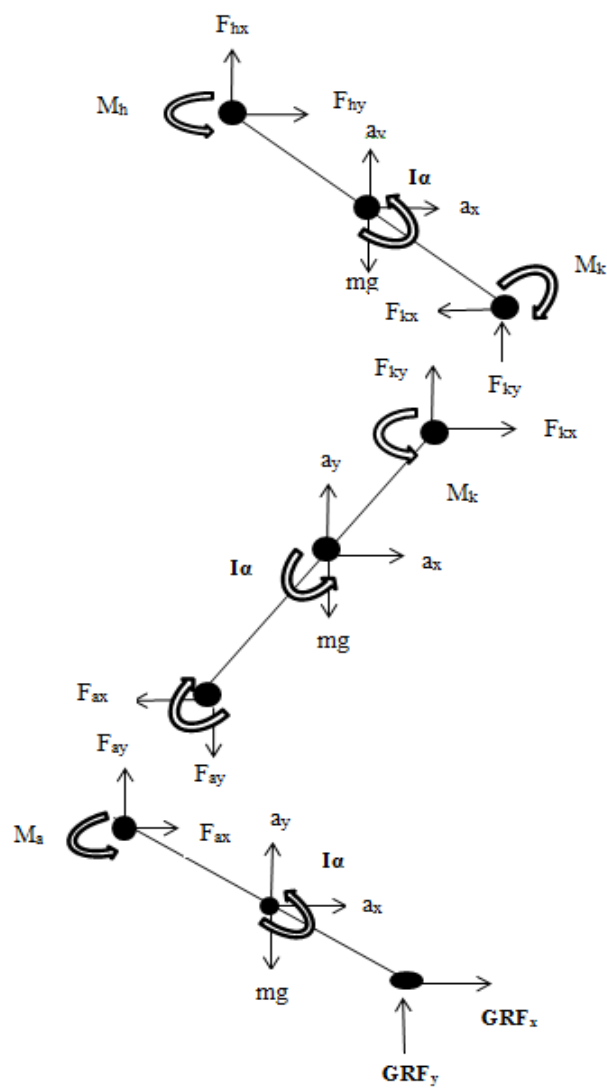


Figure 2.

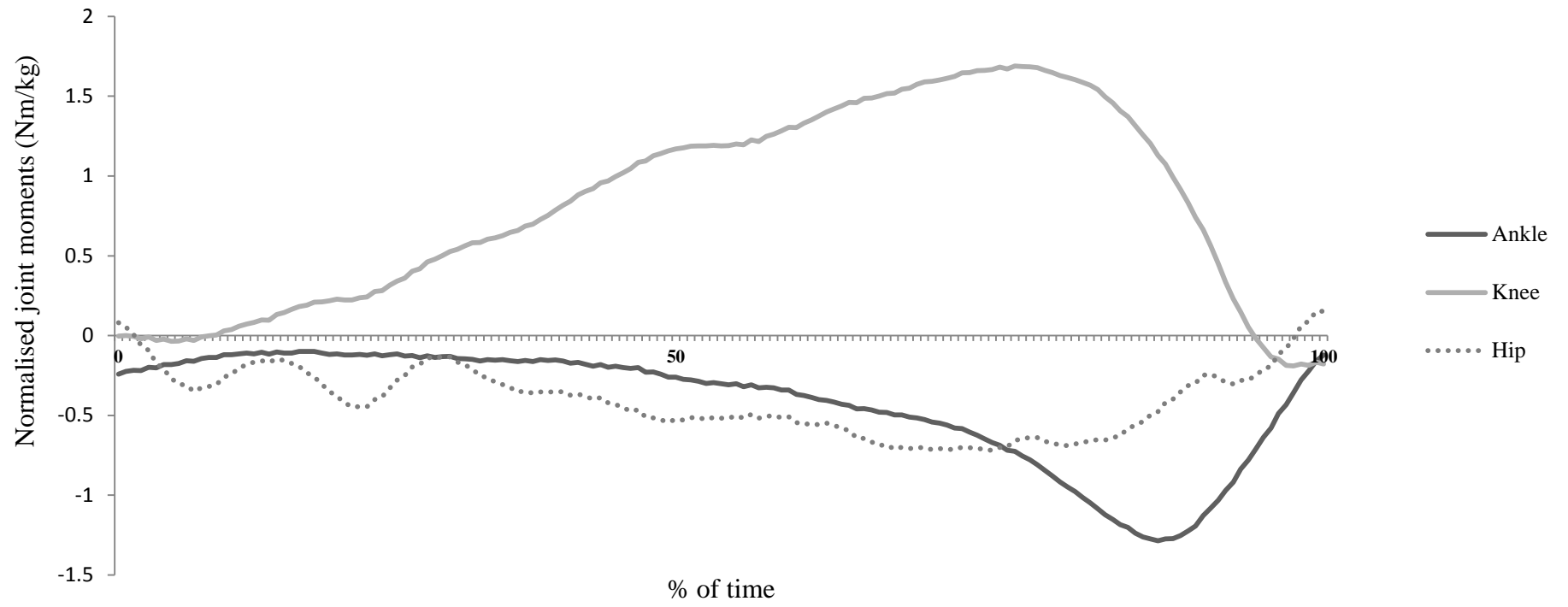
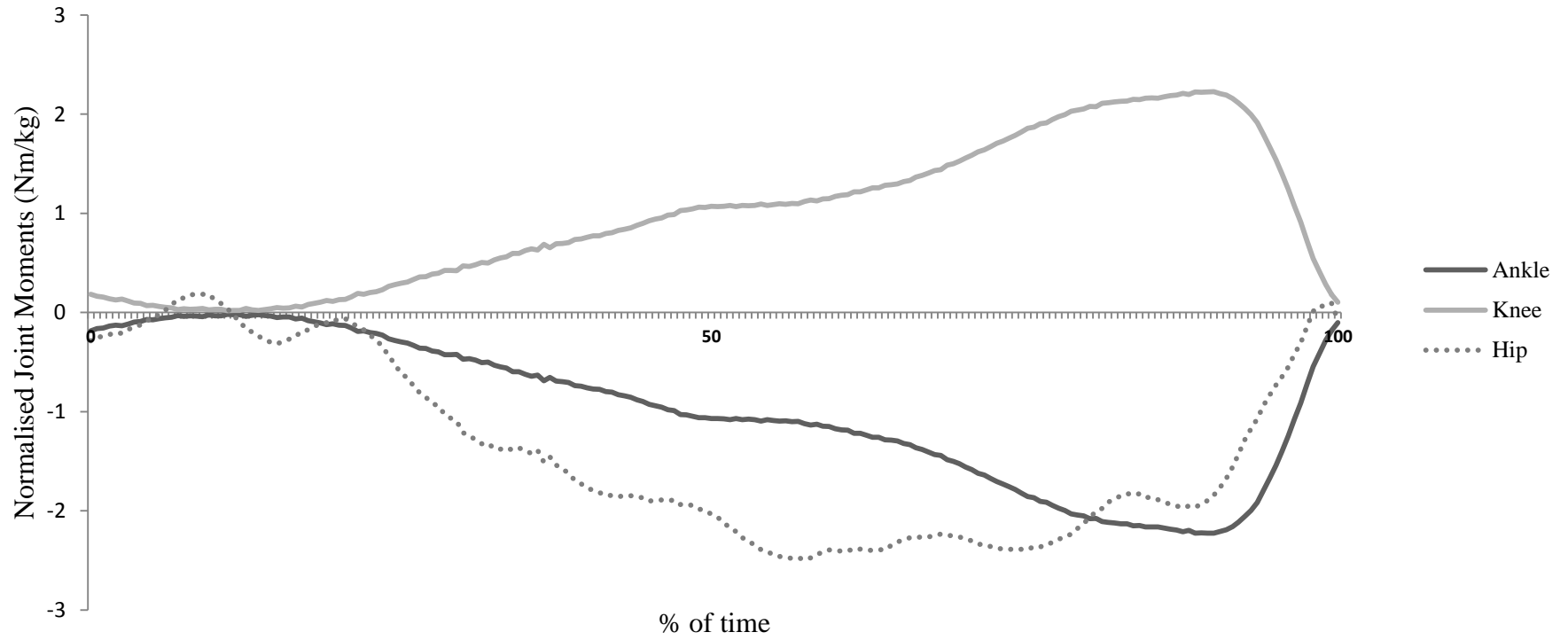


Figure 3.



External loading affects joint similarities in loaded jump training movements

Table 1.

CMJ						
	Joint Moment			Joint Impulse		
	Hip	Knee	Ankle	Hip	Knee	Ankle
HIP <sub>10%</sub>	0.438 [-0.386-0.873]			0.530 [-0.279-0.899]		
KNEE <sub>10%</sub>		0.091 [-0.656-0.748]			0.804* [0.229-0.963]	
ANKLE <sub>10%</sub>			0.438 [-0.386-0.873]			-0.025 [-0.717-0.692]
HIP <sub>25%</sub>	0.159 [-0.615-0.777]			0.628 [-0.138-0.924]		
KNEE <sub>25%</sub>		0.920* [0.612-0.986]			0.704 [-0.001-0.942]	
ANKLE <sub>25%</sub>			0.321 [-0.496-0.836]			-0.109 [-0.756-0.645]
HIP <sub>35%</sub>	-0.188 [-0.788-0.596]			-0.023 [-0.716-0.693]		

External loading affects joint similarities in loaded jump training movements

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

---



External loading affects joint similarities in loaded jump training movements

Table 2.

CMJ						
	Joint Moment			Joint Impulse		
	Hip	Knee	Ankle	Hip	Knee	Ankle
HIP <sub>30%</sub>	0.457			0.871*		
	[-0.365-0.879]			[0.431-0.976]		
KNEE <sub>30%</sub>		0.750*			0.708*	
		[0.096-0.952]			[0.007-0.942]	
ANKLE <sub>30%</sub>			0.073			-0.156
			[-0.666-0.740]			[-0.775-0.616]
HIP <sub>50%</sub>	0.345			-0.172		
	[-0.475-0.844]			[-0.782-0.606]		
KNEE <sub>50%</sub>		0.808*			0.505	
		[0.240-0.964]			[-0.310-0.892]	
ANKLE <sub>50%</sub>			0.305			-0.280

External loading affects joint similarities in loaded jump training movements

			[-0.509-0.831]			[-0.822-0.529]
	0.293			0.797*		
HIP <sub>65%</sub>				[0.211-0.962]		
	[-0.519-0.827]					
		0.547			0.618	
KNEE <sub>65%</sub>						
		[-0.257-0.903]			[-0.154-0.921]	
			0.030			0.211
ANKLE <sub>65%</sub>						
			[-0.689-0.719]			[-0.580-0.797]
	-0.096			0.314		
HIP <sub>75%</sub>						
	[-0.750-0.653]			[-0.502-0.834]		
		0.666			0.471	
KNEE <sub>75%</sub>						
		[-0.084-0.931]			[-0.350-0.883]	
			0.060			-0.150
ANKLE <sub>75%</sub>						
			[-0.673-0.734]			[-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
	30%	1.20±0.25*	1.77± 0.59*	1.55 ± 0.58
PJ	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
	30%	0.42±0.15†*	0.65±0.26†	0.63±0.18*
PJ	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±0.14
	50%	1.12±0.26	0.95±0.32	0.90±0.32