DECONSTRUCTING THE POWER-RESISTANCE RELATIONSHIP FOR SQUATS: A JOINT-LEVEL ANALYSIS

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A JOINT-LEVEL ANALYSIS

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Running Title: **Joint-level Power-Resistance in Squatting**

1 **ABSTRACT**

2 Generating high leg power outputs is important for executing rapid movements. Squats are

3 commonly used to increase leg strength and power. Therefore, it is useful to understand

4 factors affecting power output in squatting. We aimed to deconstruct the mechanisms behind

5 why power is maximised at certain resistances in squatting. Ten male rowers (age = 20 ± 2.2

6 years; height = 1.82 ± 0.03 m; mass = 86 ± 11 kg) performed maximal power squats with

7 resistances ranging from body weight to 80% of their one repetition maximum (1RM). Three-

8 dimensional kinematics were combined with ground reaction force (GRF) data in an inverse

9 dynamics analysis to calculate leg joint moments and powers. System centre of mass (COM)

10 velocity and power were computed from GRF data. COM power was maximised across a

11 range of resistances from 40-60% 1RM. This range was identified because a trade-off in hip

12 and knee joint powers existed across this range, with maximal knee joint power occurring at

13 40% 1RM and maximal hip joint power at 60% 1RM. A quasi-linear system force-velocity

14 relationship was observed that dictated large reductions in COM power below 20% 1RM and

15 above 60% 1RM. These reductions were due to constraints on the control of the movement.

16 **Keywords:** Joint power; Weightlifting; Biomechanics; Force-Velocity.

INTRODUCTION

Developing greater capacity for muscular power output is often a key goal of athletic training and rehabilitation programmes. Typically, a part of this programme will include resistance training in the form of weightlifting exercises. It has been reported that to achieve the greatest improvements in muscular power output, the training task should be performed against the resistance that maximises power output (Cormie et al. 2011). Therefore it is desirable to know what level of resistance will result in maximal power production and as a result, this topic has received considerable attention in the literature. However, existing studies have produced greatly varied results, reporting maximal power production to occur anywhere between 0 and 60% of one-repetition maximum (1RM) dependent on the exercise (Baker et al. 2001; Cormie et al. 2007).

In terms of lower limb exercises, the most prevalently studied in the literature are the squat, jump squat and leg press, with maximal system (body plus added mass) power being developed at low resistances for the jump squat and higher resistances for the squat that are typically near 50-60% of 1RM (Cormie et al. 2007; Bevan et al. 2010). However, peak system power for the optimal resistance in these studies was not significantly different from peak system power for a large range of resistances surrounding the optimum. This indicates that there is actually a broad range of resistances over which maximal system power can be attained. It has been shown that this range of resistances for maximal power production is dictated by a trade-off in the resultant velocity of the system and net external forces acting on the system (Cormie et al. 2007). An individual's maximum external force, velocity and power generating capacity are all important in determining vertical squat jump performance (Yamauchi & Ishii 2007). Furthermore, Samozino and colleagues (2012) highlighted that, in addition to maximal power generating capacity of the leg, the slope of the leg extension force-velocity relationship was important in dictating what external load resulted in maximal

42 ==power output during ballistic leg extension==. However, these velocities and forces only

43 represent the overall net effect of all muscles that are acting in a coordinated fashion through

44 multiple joints to effect the movement. Although total system power reflects the sum total of

45 joint powers well for squats (Moir et al. 2012), maximal power for coordinated multi-joint

46 dynamic tasks such as leg extension is likely constrained by coordination rather than

47 simultaneously maximising power output of all contributing muscles and at all lower limb

48 joints (Wakeling et al. 2010). Therefore, the resistance at which system power is maximised

49 may not reflect the resistance at which each lower limb joint power output or individual

50 muscle power output is maximised. ==It has been shown through experiments and simulations==

51 ==that for isometric and concentric leg pressing, magnitudes of individual joint torques are not==

52 ==always correlated with that of external limb force (Hahn 2011) and that external force-==

53 ==velocity relationships are not reflective of joint or muscle-level force-velocity relationships==

54 ==(Bobbert 2012; Hahn et al. 2014)==. Breaking down squatting mechanics to a joint level could

55 reveal more about the mechanisms underpinning the optimal resistance for power production

56 and elicit why a singular optimal resistance has not been clearly identified. Furthermore,

57 understanding joint level power-resistance relationships may facilitate more tailored sport-

58 specific power-based training programmes and improve our understanding of the efficacy of

59 such programmes.

60 Flanagan and Salem (2008) quantified lower limb net joint moments and the work done by

61 those moments during back squats with varied resistance, but without the aim of maximising

62 power. These authors showed that the proportion of total work contributed at each joint

63 varied with level of resistance. As added weight increased, a greater proportion of work was

64 provided at the hip with a lesser contribution at the knee. The contribution of the ankle was

65 never more than 10%. For jump squats, Moir et al. (2012) and Jandacka et al. (2014) have

66 both shown that maximal system power is achieved at a different resistance from individual

67 joint powers. This highlights that the relationship between total work or power output and

68 external resistance is not necessarily constrained by the force-velocity properties of lower

69 limb muscles, but is also influenced by a control strategy that changes with the external

70 resistance. Therefore, it is important to investigate the contributions made at individual lower

71 limb joints to power output during maximal power squatting to explain the relationship

72 between resistance and system power output.

73 The aim of this study was to understand trends in mechanical power output during weighted

74 back squats performed over a range of resistances by breaking it down to the level of

75 individual lower limb joint mechanics in order to provide new insights into power-based

76 resistance training methods. We hypothesised that total power output would be maximised

77 over a broad range of intermediate resistances, surrounding 50% 1RM. Furthermore, we

78 hypothesised that this broad range of optimal resistances would be a result of hip and knee

79 joint powers being maximised at different resistances from one another - knee power at lower

80 resistances and hip power at higher resistances.

81 **MATERIALS & METHODS**

82 **Participants & Protocol** - Ten male sub-elite rowers (mean age = 20 ± 2.2 years; height =

83 1.82 ± 0.03 m; mass = 86 ± 11 kg) experienced in performing weighted back-squats

84 participated in the study. A strength and conditioning professional had assessed all

85 participants' three-repetition maximum (3RM) no more than one month prior to their

86 participation. Each participant gave written informed consent and an institutional ethics

87 committee approved the study. Participants' 1RM was estimated as their 3RM multiplied by

88 1.08 (Baker et al. 2001) and they refrained from high intensity exercise for the 24-hours

89 preceding data collection. Prior to commencing the protocol, participants performed a warm

90 up on a bicycle ergometer and two warm up back squat sets at a weight of their choosing, all

91 <mark>supervised by their coach</mark>. The participants then performed two sets of three back squats with

92 0, 20, 40, 60 and 80% of their 1RM using an Olympic barbell and additional weights as

93 necessary. The 0% condition was body weight only and performed with the arms raised as if

94 holding the barbell. All squats were performed with a depth that corresponded to a knee angle

95 of 90° <mark>and five minutes rest was allowed between sets to avoid fatigue, although most sets</mark>

96 <mark>were performed at resistances unlikely to cause neuromuscular fatigue responses</mark> (Brandon et

97 al. in press). Participants lowered to the height of a horizontally oriented wooden pole that

98 they could feel touch their buttocks but would not support any weight. The height of the pole

99 was set prior to testing by having participants squat to an internal knee angle of 90 degrees

100 (shank relative to thigh), measured with a manual goniometer. For the experimental squats,

101 participants lowered at a steady controlled speed then were instructed to hold their position at

102 the bottom of the squat for two seconds prior to maximising velocity (and therefore power)

103 during the upward phase of the movement. However, participants were not permitted to lose

104 contact with the ground at the end of extension so as to keep a comparable movement across

105 all resistances.

106 **Data Collection & Processing** - An eight-camera motion capture system (Oqus, Qualisys,

107 Sweden) sampling at 200 Hz was used to record three-dimensional positions of thirty-seven

108 reflective markers attached to the lower limbs and pelvis of each participant. Marker

109 positions were used to generate the kinematics for a seven-segment rigid body model of the

110 lower limbs and pelvis (feet, shanks, thighs and pelvis). The lower limb model developed by

111 Arnold et al. (2010) was used in OpenSim software v3.0 (Delp et al. 2007). The model was

112 calibrated using static and dynamic calibration trials. In the static trial participants stood in a

113 comfortable stance with hands on hips and the same pose was adopted for the dynamic trial

114 where the participant performed several pelvic rotations that utilised the full range of

115 circumduction at the hip joints. The dynamic trial was used to compute the location of

116 functional hip joint centres in Visual 3D software (C-Motion Inc., USA) using an adaptation

117 of the methods of Schwartz and Rozumalski (2005). Static trials were used to scale the

118 generic skeletal model and generate an individually scaled model for each participant. This

119 scaling was based on pairs of calibration markers on each segment. A scale factor for each

120 segment was calculated as the distance between two calibration markers on that segment on

121 the participant divided by the distance between the same markers on the generic model. The

122 pelvis was scaled based on the distances between markers placed on the left and right

123 anterior-superior iliac spines and the posterior superior iliac spines. An additional marker on

124 the sacrum was used in addition to these markers to track the orientation of the pelvis during

125 subsequent trials. The distances between the calculated hip joint centres and markers placed

126 on the lateral and medial aspects of the knee joint line were used to scale the femurs. For the

127 shank, the distance between the knee joint markers and markers on the medial and lateral

128 malleoli were used. The feet were scaled by the distance between markers on the calcanei and

129 distal phalanxes of the second toes. Segment masses were scaled to sum to the mass of the

130 participant's lower body (61% total body mass) and keep the distribution of mass among

131 segments the same as is in the generic model. To track segment motion during squatting

132 trials, rigid clusters of four markers were taped securely to the lateral aspect of participants

133 thighs and shanks, and additional markers at the first and fifth metatarsal-phalangeal joints

134 were added to the foot to supplement the calibration markers. Participants wore tight-fitting

135 spandex shorts to minimise cluster motion relative to the thigh segment.

136 The scaled model for each participant was used in an inverse kinematics analysis in OpenSim

137 software v3.0 (Delp et al. 2007) using filtered three-dimensional marker positions recorded

138 during squatting trials. The filter was a second order low-pass Butterworth digital filter with a

139 cut-off of 10 Hz. Inverse kinematics analysis allows instantaneous joint angles for the ankle,

140 knee and hip to be computed at each point in time. Half of the squat trials at each resistance

141 were performed with only the right foot in contact with an in-ground force platform (OR6-5-

142 2000, AMTI, USA). For these trials we combined the model kinematics with measured

143 ground reaction force (GRF) data (sampled at 2000 Hz) in an inverse dynamics analysis to

144 compute net muscle moments at the ankle, knee and hip joints of the right leg. These

145 moments were multiplied by joint velocities (the first derivative of joint angles) to obtain

146 instantaneous joint powers for the ankle, knee and hip. Positive joint moments and powers

147 represent moments acting to extend the joint and work being done to extend the joint. For the

148 other half of the squat trials, participants had both feet in contact with the force platform.

149 These trials were used to calculate system centre of mass (COM) velocity and power via the

150 following steps. First, system weight was subtracted from the vertical component of GRF to

151 determine net GRF. The net GRF was divided by system mass to determine system

152 acceleration. Acceleration was then integrated to calculate system COM velocity, and power

153 was calculated as the dot product of COM velocity and GRF. Prior to any inverse dynamic

154 analyses or COM power calculations, GRF data were filtered with a second order low-pass

155 Butterworth digital filter with a cut-off of 25 Hz.

156 **Data Reduction & Statistics -** All further analyses were conducted on data from the onset of

157 upward motion (detected as onset of positive vertical velocity of the sacral marker) to the end

158 of the upward motion (detected as the end of positive vertical velocity of the sacral marker)

159 and this will be referred to as upward motion from hereafter. During upward motion we

160 calculated the average velocity ($\bar{v}$), moment ($\bar{M}$) and power ($\bar{P}$) at the ankle knee and hip

161 joints as the integral of the respective instantaneous signals, divided by the time taken

162 [similar to the methods of Farris and Sawicki (2012; 2012)]. Peak positive joint velocity

163 (v_{pk}) moment (M_{pk}) and power (P_{pk}) were also calculated during upward motion. For trials

164 where COM power was computed, average and peak velocities, GRF and powers were

165 computed similarly. Normalised values for most metrics were computed by division by body

166   mass and are reported in units per kilogram. All metrics were averaged within each resistance

167   to provide group means and standard deviations. To test for statistical differences in COM

168   metrics between resistances, a one-way repeated measures ANOVA and a Bonferroni

169   adjustment was employed with the alpha level set to $P \leq 0.05$. For joint metrics a two-way

170   (joint x resistance) repeated measures ANOVA with a Bonferroni adjustment was used.

171   Where a significant main effect was detected for a variable, Tukey's post-hoc test was used to

172   elicit between which pairs of resistances and joints significant differences existed. All

173   hypothesis testing was performed in Prism software v6.0 (GraphPad Software Inc.).

174   **RESULTS**

175   **COM mechanics -** There was a significant ($F = 20.9$, $P < 0.0001$) main effect of resistance

176   on average COM power ($\bar{P}_{COM}$). $\bar{P}_{COM}$ was significantly ($P < 0.05$) greater at resistances of

177   20, 40 and 60% 1RM than for 0% and 80% 1RM resistances (Figure 1A). However, the 20,

178   40 and 60% conditions were not significantly different from one another ($P > 0.05$),

179   indicating a broad range of resistances (20-60% 1RM) over which $\bar{P}_{COM}$ was maximised.

180   When $\bar{P}_{COM}$ was plotted against average COM velocity ($\bar{v}_{COM}$) for each resistance (Figure

181   1B), $\bar{P}_{COM}$ was greatest at resistances that produced intermediate velocities (20-40% 1RM).

182   Notably, when moving from 20% to 0% 1RM and from 60% to 80% 1RM, there were large

183   reductions in $\bar{P}_{COM}$ (Figure 1B). Average vertical GRF ($\bar{F}_{GRFz}$) decreased with increasing

184   $\bar{v}_{COM}$ in non-linear fashion especially at the extremes of resistance values, where the

185   relationship deviated most from the linear fit provided for comparison (Figure 1B).

186   **Average Joint powers -** The two-way ANOVA results indicated a significant effect of

187   resistance ($F = 8.3$, $P < 0.0001$), joint ($F = 97.3$, $P < 0.0001$) and their interaction ($F = 21.9$, P

188   < 0.0001) on $\bar{P}$. Average ankle power output ($\bar{P}_A$) was the smallest contributor to total $\bar{P}$ at all

189   resistances, never providing more than 16% (Figure 2A). The magnitude of $\bar{P}_A$ was

190 significantly greater (P < 0.05) at 40, 60 and 80% 1RM resistances than at 0%. The

191 magnitude of knee joint average power output ($\bar{P}_K$) exhibited a significant (P < 0.05) decline

192 as resistance increased above 20% 1RM (Figure 2A). Furthermore, the knee joint contributed

193 50% of the total power output at the 20% 1RM resistance but only 34% at a resistance of

194 80% 1RM. Conversely, hip joint average power output ($\bar{P}_H$) significantly increased as

195 resistance increased from 20% to 40% 1RM and reached a maximum at 60% 1RM before

196 falling again at 80% 1RM (Figure 2A). This meant that $\bar{P}_H$ contributed a greater proportion of

197 total power at high resistances.

198 **Average Joint moments -** The two-way ANOVA results indicated a significant effect of

199 resistance (F = 220.8, P < 0.0001), joint (F = 29.7, P < 0.0001) and the interaction (F = 23.4,

200 P < 0.0001) on $\bar{M}$. Average ankle moment ($\bar{M}_A$) and average hip moment ($\bar{M}_H$) increased

201 significantly (P < 0.01) with each increment in resistance, excepting the final increment (60-

202 80% 1RM) for $\bar{M}_A$ (Figure 2B). The average knee moment ($\bar{M}_K$) significantly increased from

203 0-20% 1RM but did not significantly increase for subsequent increments in resistance (Figure

204 2B).

205 **Average Joint velocities -** The two-way ANOVA results indicated a significant effect of

206 resistance (F = 28.7, P < 0.0001) and joint (F = 176.4, P < 0.0001) but no interaction (F = 1.5,

207 P = 0.18) on $\bar{v}$. Average ankle, knee and hip joint velocities ($\bar{v}_A$, v_K, $\bar{v}_H$) all significantly (P <

208 0.0001) declined with each increment in resistance (Figure 2C).

209 **Peak powers -** COM P_{pk} was significantly affected by resistance (F = 23.0, P < 0.0001),

210 increasing with each increment in resistance up to 40% 1RM, after which it did not

211 significantly change despite trending to a reduction at 80% 1RM (Figure 3). For joint P_{pk}

212 there was a significant effect of resistance (F = 11.7, P < 0.0001), joint (F = 61.1, P < 0.0001)

213 and their interaction (F = 9.6, P < 0.0001). Ankle P_{pk} increased from 0-40% 1RM (P < 0.05)

214   but did not significantly increase for any further increments in resistance (Figure 3). There

215   was a significant (P < 0.05) reduction observed in knee P_{pk} between the 0% 1RM and 80%

216   1RM resistances (Figure 3). Hip P_{pk} increased significantly (P < 0.05) from 0% 1RM

217   resistance to 20% 1RM but did not increase with further resistance increments (Figure 3).

218   **DISCUSSION**

219   This study sought to explain trends in system power output with varied resistance during

220   weighted back squats by analysing joint level mechanics. Our first hypothesis was that a

221   broad range of resistances surrounding 50% 1RM would provide equivocal maximal powers.

222   This was supported as $\bar{P}_{COM}$ was maximised for resistances from 20-60% 1RM. We also

223   hypothesised that this broad range would be observed because knee and hip joint powers

224   would be maximised at different resistances from one another. This was supported by our

225   observation of an apparent trade-off between $\bar{P}_H$ and $\bar{P}_K$ across the range of resistances from

226   20-60% 1RM.

227   **Joint powers -** The trade-off between contributions at the hip and knee to overall power was

228   evidenced by distinctly different trends in $\bar{P}_K$ and $\bar{P}_H$ with varying resistance. $\bar{P}_H$ was greatest

229   at 60% 1RM with a significant decrease in power occurring if the resistance was increased or

230   decreased from 60% (Figure 2A). However, $\bar{P}_K$ was greatest at 20% 1RM and was less at

231   greater resistances. The respective maximum values of $\bar{P}_K$ and $\bar{P}_H$ were similar in magnitude

232   and from Figure 2A it can be seen that the trends of $\bar{P}_K$ and $\bar{P}_H$ across different resistances are

233   almost a mirror image of one another. This explains the broad range of resistances over

234   which $\bar{P}_{COM}$ was maximised. At the lower end of this maximal range (20% 1RM) $\bar{P}_K$ was

235   maximised, but $\bar{P}_H$ was significantly below its maximum. The exact opposite was true for the

236   upper end of the range (60% 1RM) and at the intermediate resistance (40%) where both $\bar{P}_K$

237   and $\bar{P}_H$ were less than maximal but summed to a similar total power as at 20% and 60%

238   1RM. Thus, the broad range of resistances over which $\bar{P}_{COM}$ was maximised was dictated by a

239   trade-off between $\bar{P}_K$ and $\bar{P}_H$. $\bar{P}_A$ made such a minimal contribution to total power that we

240   considered it insignificant in this part of the discussion.

241   **Force and velocity -** While joint powers provide descriptive insight into the observed trends

242   in $\bar{P}_{COM}$, to gain insight into the underlying mechanisms we also reported forces, joint

243   moments and velocities. The force-velocity relations that exist for isolated skeletal muscle

244   were documented some time ago (Fenn & Marsh 1935; Hill 1938). An exponential decay in

245   force with increasing velocity was described by Hill's (1938) hyperbolic equation and this

246   relation results in a maximal power output at approximately one-third of maximal shortening

247   velocity. However, experiments that have characterised the external or joint force-velocity

248   relationships in multi-joint tasks such as leg extension generally report a quasi-linear force-

249   velocity relationship at the system or joint level (Perrine & Edgerton 1978; Rahmani et al.

250   2001; Macaluso & De Vito 2003; Pearson et al. 2004; Bobbert 2012) although Hahn et al.

251   (2014) showed that a linear fit underestimated maximum joint velocity. In our data, we

252   observed a system-level force-velocity relation for squatting that deviated from a linear fit

253   and was not hyperbolic (Figure 1B). The most notable deviations of this trend from linear and

254   hyperbolic relationships were at the extremes of the resistances tested. This indicates that leg

255   extension powers were limited at these resistances by factors other than the maximal force-

256   velocity properties at the level of muscle or the system.

257   For the change in $\bar{F}_{GRFz}$ that occurs between 60 and 80% 1RM, $\bar{v}_{COM}$ was decreasing to its

258   lowest value. If the only constraint on force production was that dictated by the force-velocity

259   relation of muscle we would expect $\bar{F}_{GRFz}$ to increase exponentially with decreasing velocity.

260   However, this was not the case as an increase in $\bar{F}_{GRFz}$ that was even slightly less than linear,

261   (as might be expected at the whole-limb level) was observed between 60 and 80% 1RM

262   (Figure 1B). At this time, $\bar{M}_H$ was significantly increasing with each increment in resistance

263   (Figure 2B) and so did not appear to indicate any constraints on muscle force or joint torque

264   production. However, $\bar{M}_K$ did not significantly increase for any increments in resistance

265   above 20% 1RM. Potentially this suggests an inability to produce a greater knee extensor

266   moment at high resistances and this could have been constraining force production at those

267   resistances. However, the intrinsic force-velocity relationship of knee extensor muscles or the

268   joint torque-velocity relationship would not dictate this, as both would predict that greater

269   forces could be generated at slow velocities. Alternatively, we propose that the inherent

270   mechanical constraints of the task would have prevented any further increases in knee

271   extensor moments at high resistances. Here we refer to the need to control the direction of the

272   GRF as described by van Ingen Schenau and colleagues (1992). To consider this we will

273   neglect inertial factors and consider the problem as a quasi-static scenario where the direction

274   of the reaction force is dictated by the magnitudes of the joint moments only. Figure 4A

275   schematically illustrates the current data, where the ground reaction force (black arrow) is

276   acting vertically through the COM and the hip and knee joint moments are balanced

277   accordingly. For the knee extensor joint moment to be larger, either the magnitude of the

278   GRF must be increased (Figure 4B) or the moment arm of the force about the knee joint must

279   be increased (Figure 4C). The former would involve a concomitant increase in the hip joint

280   moment, which may not be possible if the hip joint extensors are already maximally active.

281   The latter would involve reorienting the force vector away from the vertical in a posterior

282   direction (Figure 4C), with several negative consequences. First, the hip joint moment would

283   need to be reduced as the force vector passed closer to the hip joint centre. Second, the force

284   would generate a de-stabilising moment about the COM. Third, a large component of the

285   force would now be acting to accelerate the COM posteriorly not vertically, which is not

286   useful for the task. Therefore, we propose that at high forces the knee moment cannot be

287 increased to the limits dictated by muscle <mark>or joint-level</mark> force-velocity properties because of a

288 constraint imposed on knee joint extension moments by the need to control the direction of

289 the GRF vector. This, combined with a reduction in COM velocity, is why we observed a

290 large drop-off in $\bar{P}_{COM}$ when resistance increased to 80% 1RM. <mark>We did not measure muscle</mark>

291 <mark>activation but one would expect pre-activation of muscles before leg extension to have been</mark>

292 <mark>greater at higher resistances. However, if this were to have impacted the force-velocity</mark>

293 <mark>relationship, the forces and moments at high resistances should trend to be greater than linear</mark>

294 <mark>rather than less than linear as we observed.</mark>

295 At the other extreme, we examined the system force-velocity behaviour changes between

296 20% and 0% 1RM resistances. Here we observed that $\bar{P}_{COM}$ was considerably less at 0%

297 1RM than at 20% 1RM (Figure 1A & B). This was owing to a reduction in $\bar{F}_{GRFz}$ that was

298 accompanied by a relatively small increase in $\bar{V}_{COM}$. The small increase in $\bar{v}_{COM}$ was less than

299 a linear force-velocity relation would have predicted (Figure 1B) and therefore also less than

300 what would be expected based on the force-velocity relationship of isolated muscle <mark>or joints</mark>

301 at high velocities. An explanation for this may again rest within the apparent constraints of

302 the task. Because a squat exercise was used, participants were instructed not to leave the

303 ground for any of the resistances. However, to maximise power at low resistances one would

304 typically jump. Bobbert and van Ingen Schenau (1988) observed that an important

305 contributor to maximal power in vertical jumping was high velocity ankle extension late

306 before take-off. Magnitudes of ankle extension velocity in that study were similar to, or even

307 greater than, knee and hip extension velocities. However, in our data $\bar{v}_A$ and peak ankle

308 velocity were significantly (P < 0.0001) less than for the knee and hip at all resistances. This

309 is likely because of the imposed restriction to stay grounded that would have required our

310 participants to decelerate the upward motion of the COM at the end of the movement. Given

311 the apparent importance of ankle joint velocity in contributing to COM velocity, our

312   restricting it likely constrained the participants' capacity to generate large power outputs at

313   low resistances. At low resistance power will be more determined by COM velocity than

314   GRF. In order to make fair comparisons of a squat across resistances it was necessary to

315   restrict participants from jumping. Other studies investigating the power-resistance

316   relationship in squat jumping have revealed that $\bar{P}_{COM}$ was actually maximised when jumping

317   with no additional resistance above body mass (Cormie et al. 2007; Moir et al. 2012;

318   Jandacka et al. 2014). Therefore, the constraint to not jump likely limited velocity and power

319   production potential at low resistances.

320   **Average vs. Peak Power -** In the present study we have primarily focussed on average

321   powers as a metric of power output. This is because the average power produced during leg

322   extension reflects both the amount of mechanical work done and the rate at which it was

323   done. However, some similar existing studies report peak powers (Cormie et al. 2007; Bevan

324   et al. 2010). Our intention here is not to conclude which is more appropriate but to note that

325   findings may differ depending on the authors' choice of metric. A close inspection of Figures

326   1 and 3 reveals that although $\bar{P}_{COM}$ did not increase significantly from 20% 1RM to 40%

327   1RM, COM P_{pk} did. Also, the significant changes in $\bar{P}_H$ and $\bar{P}_k$ that occurred with

328   increments between 20% 1RM and 80% 1RM were not always evident in the P_{pk} values for

329   these joints. One explanation for the discrepancies between trends in average and peak

330   powers is the potential influence of interdependent torque-angle-angular velocity

331   relationships that have been documented in multi-joint tasks (Hahn et al. 2014). Because joint

332   velocities were different at different resistances, the optimum joint angle for producing torque

333   or power would likely be different too. Thus it was possible that for the different resistances,

334   the angle at which peak power was reached was less optimal for that velocity than was the

335   case at other resistances. However, this joint position effect should not have influenced

336   average powers, as setting the starting position controlled the range of motion. Therefore, we

337 recommend exercising caution when comparing results based on peak powers with those

338 from average powers and that careful thought should be given to which metric is most

339 appropriate for a given purpose.

340 **PERSPECTIVES**

341 Conventional paradigms for training the development of muscular power incorporate high

342 resistance exercises followed by a progression that includes lighter, more sport-specific

343 exercises (Cormie et al. 2011). Our data suggest that this progression can be achieved in

344 squatting without compromising on power production because heavier weights and somewhat

345 lighter resistances resulted in similar power output. Furthermore, joint level power profiling

346 such as we have shown might facilitate better matching of lighter weights to the sporting task

347 of an athlete. For example, choosing a resistance that has a similar breakdown of joint

348 contributions to total power as the task. In this study to make fair comparisons across

349 resistances we restricted our participants to remaining grounded and not performing a jump

350 squat. A more likely progression at lighter weights would be to jump and this might provide a

351 better match to many sporting tasks in terms of coordination and with fewer constraints,

352 result in greater power outputs than observed for squats (Bevan et al. 2010; Bobbert 2014).

353 However, our purpose was to illustrate the fundamental mechanical principles using squatting

354 as an example, not a comprehensive resource of power-resistance data which remains an

355 important future direction for the field.

356 **CONCLUSIONS**

357 In this study we sought to deconstruct the power-resistance relationship in a back-squat

358 exercise by examining system force-velocity relationships and joint-level mechanics. We

359 found a broad range of intermediate weights could maximise COM power. This range was

360 determined by trading-off knee and hip joint powers that were individually maximised at

361   different resistances. <mark>Based on theoretical considerations, it was considered that the limits of the range were dictated by a need to control the direction of forces at high resistances.</mark> At low

363   resistances power was less because participants were not permitted to jump and this limited

364   the capacity of the ankle joint to contribute to increasing the COM velocity late in the

365   movement. Our findings provide new perspectives and support for power-based training

366   programmes that employ a progression through a range of resistances and incorporate sport-

367   specific exercises.

368   **ACKNOWLEDGEMENTS**

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433

FIGURE LEGENDS

Figure 1. A - Group mean (± s.e.m.) COM average power at each resistance. *Denotes a significant difference from 0% 1RM and † denotes a significant difference from the next lightest resistance. **B** - Group mean system force-velocity (solid line, left vertical axis) and power-velocity (dashed line, right vertical axis) with resistances labelled. The dotted line is a linear fit to the force-velocity data.

Figure 2. Group mean (± s.e.m.) average joint power (**A**), average joint moment (**B**) and average joint velocity (**C**) for the ankle (black), knee (grey) and hip (white). For joint powers, the percentage of total average power (sum of the three joint powers) provided by each joint at each resistance is labelled on the respective bars. *Denotes a significant difference from 0% 1RM and † denotes a significant difference from the next lightest resistance.

Figure 3. Group mean (± s.e.m.) peak COM (black), ankle (dark grey), knee (light grey) and hip (white) powers. *Denotes a significant difference from 0% 1RM and † denotes a significant difference from the next lightest resistance.
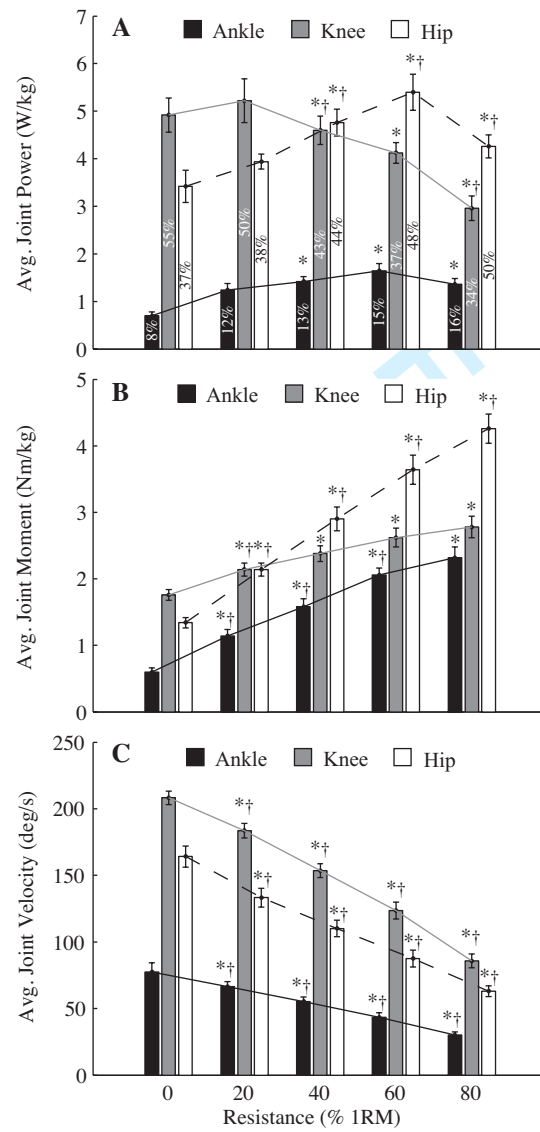
Figure 4. Schematic illustration of how the distribution of joint moments affects the direction and magnitude of the ground reaction force vector in a quasi-static case. **A** - represents the scenario from the current data at high resistances where the hip joint extension moment is larger than the knee joint extension moment and the GRF vector is oriented vertically through the COM. **B** - For the magnitude of the knee joint moment to increase and the GRF vector remain vertically aligned, the GRF vector's magnitude must increase, as must the hip joint extension moment. **C** - To increase the knee extensor moment by increasing the moment arm of the GRF vector at the knee, the hip extension moment must decrease and the GRF vector become more posteriorly oriented.
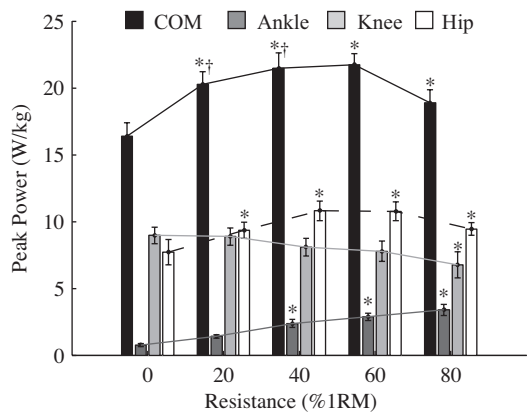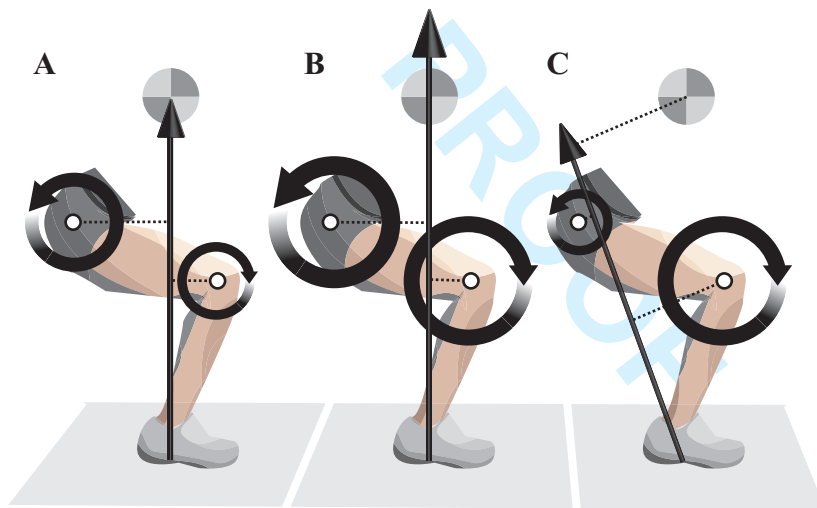
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A   **B**   **C**