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

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ABSTRACT

Generating high leg power outputs is important for executing rapid movements. Squats are commonly used to increase leg strength and power. Therefore, it is useful to understand factors affecting power output in squatting. We aimed to deconstruct the mechanisms behind why power is maximised at certain resistances in squatting. Ten male rowers (age = 20 ± 2.2 years; height = 1.82 ± 0.03 m; mass = 86 ± 11 kg) performed maximal power squats with resistances ranging from body weight to 80% of their one repetition maximum (1RM). Three-dimensional kinematics were combined with ground reaction force (GRF) data in an inverse dynamics analysis to calculate leg joint moments and powers. System centre of mass (COM) velocity and power were computed from GRF data. COM power was maximised across a range of resistances from 40-60% 1RM. This range was identified because a trade-off in hip and knee joint powers existed across this range, with maximal knee joint power occurring at 40% 1RM and maximal hip joint power at 60% 1RM. A quasi-linear system force-velocity relationship was observed that dictated large reductions in COM power below 20% 1RM and above 60% 1RM. These reductions were due to constraints on the control of the movement.

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 power output during ballistic leg extension. However, these velocities and forces only represent the overall net effect of all muscles that are acting in a coordinated fashion through multiple joints to effect the movement. Although total system power reflects the sum total of joint powers well for squats (Moir et al. 2012), maximal power for coordinated multi-joint dynamic tasks such as leg extension is likely constrained by coordination rather than simultaneously maximising power output of all contributing muscles and at all lower limb joints (Wakeling et al. 2010). Therefore, the resistance at which system power is maximised may not reflect the resistance at which each lower limb joint power output or individual muscle power output is maximised. It has been shown through experiments and simulations that for isometric and concentric leg pressing, magnitudes of individual joint torques are not always correlated with that of external limb force (Hahn 2011) and that external force-velocity relationships are not reflective of joint or muscle-level force-velocity relationships (Bobbert 2012; Hahn et al. 2014). Breaking down squatting mechanics to a joint level could reveal more about the mechanisms underpinning the optimal resistance for power production and elicit why a singular optimal resistance has not been clearly identified. Furthermore, understanding joint level power-resistance relationships may facilitate more tailored sport-specific power-based training programmes and improve our understanding of the efficacy of such programmes.

Flanagan and Salem (2008) quantified lower limb net joint moments and the work done by those moments during back squats with varied resistance, but without the aim of maximising power. These authors showed that the proportion of total work contributed at each joint varied with level of resistance. As added weight increased, a greater proportion of work was provided at the hip with a lesser contribution at the knee. The contribution of the ankle was never more than 10%. For jump squats, Moir et al. (2012) and Jandacka et al. (2014) have both shown that maximal system power is achieved at a different resistance from individual joint powers. This highlights that the relationship between total work or power output and external resistance is not necessarily constrained by the force-velocity properties of lower limb muscles, but is also influenced by a control strategy that changes with the external resistance. Therefore, it is important to investigate the contributions made at individual lower limb joints to power output during maximal power squatting to explain the relationship between resistance and system power output.

The aim of this study was to understand trends in mechanical power output during weighted back squats performed over a range of resistances by breaking it down to the level of individual lower limb joint mechanics in order to provide new insights into power-based resistance training methods. We hypothesised that total power output would be maximised over a broad range of intermediate resistances, surrounding 50% 1RM. Furthermore, we hypothesised that this broad range of optimal resistances would be a result of hip and knee joint powers being maximised at different resistances from one another - knee power at lower resistances and hip power at higher resistances.

MATERIALS & METHODS

Participants & Protocol - Ten male sub-elite rowers (mean age = 20 ± 2.2 years; height = 1.82 ± 0.03 m; mass = 86 ± 11 kg) experienced in performing weighted back-squats participated in the study. A strength and conditioning professional had assessed all participants' three-repetition maximum (3RM) no more than one month prior to their participation. Each participant gave written informed consent and an institutional ethics committee approved the study. Participants' 1RM was estimated as their 3RM multiplied by 1.08 (Baker et al. 2001) and they refrained from high intensity exercise for the 24-hours preceding data collection. Prior to commencing the protocol, participants performed a warm up on a bicycle ergometer and two warm up back squat sets at a weight of their choosing, all supervised by their coach. The participants then performed two sets of three back squats with 0, 20, 40, 60 and 80% of their 1RM using an Olympic barbell and additional weights as necessary. The 0% condition was body weight only and performed with the arms raised as if holding the barbell. All squats were performed with a depth that corresponded to a knee angle of 90° and five minutes rest was allowed between sets to avoid fatigue, although most sets were performed at resistances unlikely to cause neuromuscular fatigue responses (Brandon et al. in press). Participants lowered to the height of a horizontally oriented wooden pole that they could feel touch their buttocks but would not support any weight. The height of the pole was set prior to testing by having participants squat to an internal knee angle of 90 degrees (shank relative to thigh), measured with a manual goniometer. For the experimental squats, participants lowered at a steady controlled speed then were instructed to hold their position at the bottom of the squat for two seconds prior to maximising velocity (and therefore power) during the upward phase of the movement. However, participants were not permitted to lose contact with the ground at the end of extension so as to keep a comparable movement across all resistances.

Data Collection & Processing - An eight-camera motion capture system (Oqus, Qualisys, Sweden) sampling at 200 Hz was used to record three-dimensional positions of thirty-seven reflective markers attached to the lower limbs and pelvis of each participant. Marker positions were used to generate the kinematics for a seven-segment rigid body model of the lower limbs and pelvis (feet, shanks, thighs and pelvis). The lower limb model developed by Arnold et al. (2010) was used in OpenSim software v3.0 (Delp et al. 2007). The model was calibrated using static and dynamic calibration trials. In the static trial participants stood in a comfortable stance with hands on hips and the same pose was adopted for the dynamic trial where the participant performed several pelvic rotations that utilised the full range of circumduction at the hip joints. The dynamic trial was used to compute the location of functional hip joint centres in Visual 3D software (C-Motion Inc., USA) using an adaptation of the methods of Schwartz and Rozumalski (2005). Static trials were used to scale the generic skeletal model and generate an individually scaled model for each participant. This scaling was based on pairs of calibration markers on each segment. A scale factor for each segment was calculated as the distance between two calibration markers on that segment on the participant divided by the distance between the same markers on the generic model. The pelvis was scaled based on the distances between markers placed on the left and right anterior-superior iliac spines and the posterior superior iliac spines. An additional marker on the sacrum was used in addition to these markers to track the orientation of the pelvis during subsequent trials. The distances between the calculated hip joint centres and markers placed on the lateral and medial aspects of the knee joint line were used to scale the femurs. For the shank, the distance between the knee joint markers and markers on the medial and lateral malleoli were used. The feet were scaled by the distance between markers on the calcanei and distal phalanxes of the second toes. Segment masses were scaled to sum to the mass of the participant's lower body (61% total body mass) and keep the distribution of mass among segments the same as is in the generic model. To track segment motion during squatting trials, rigid clusters of four markers were taped securely to the lateral aspect of participants thighs and shanks, and additional markers at the first and fifth metatarsal-phalangeal joints were added to the foot to supplement the calibration markers. Participants wore tight-fitting spandex shorts to minimise cluster motion relative to the thigh segment.

The scaled model for each participant was used in an inverse kinematics analysis in OpenSim software v3.0 (Delp et al. 2007) using filtered three-dimensional marker positions recorded during squatting trials. The filter was a second order low-pass Butterworth digital filter with a cut-off of 10 Hz. Inverse kinematics analysis allows instantaneous joint angles for the ankle, knee and hip to be computed at each point in time. Half of the squat trials at each resistance were performed with only the right foot in contact with an in-ground force platform (OR6-5-2000, AMTI, USA). For these trials we combined the model kinematics with measured ground reaction force (GRF) data (sampled at 2000 Hz) in an inverse dynamics analysis to compute net muscle moments at the ankle, knee and hip joints of the right leg. These moments were multiplied by joint velocities (the first derivative of joint angles) to obtain instantaneous joint powers for the ankle, knee and hip. Positive joint moments and powers represent moments acting to extend the joint and work being done to extend the joint. For the other half of the squat trials, participants had both feet in contact with the force platform. These trials were used to calculate system centre of mass (COM) velocity and power via the following steps. First, system weight was subtracted from the vertical component of GRF to determine net GRF. The net GRF was divided by system mass to determine system acceleration. Acceleration was then integrated to calculate system COM velocity, and power was calculated as the dot product of COM velocity and GRF. Prior to any inverse dynamic analyses or COM power calculations, GRF data were filtered with a second order low-pass Butterworth digital filter with a cut-off of 25 Hz.

Data Reduction & Statistics - All further analyses were conducted on data from the onset of upward motion (detected as onset of positive vertical velocity of the sacral marker) to the end of the upward motion (detected as the end of positive vertical velocity of the sacral marker) and this will be referred to as upward motion from hereafter. During upward motion we calculated the average velocity ($\bar{v}$), moment ($\bar{M}$) and power ($\bar{P}$) at the ankle knee and hip joints as the integral of the respective instantaneous signals, divided by the time taken [similar to the methods of Farris and Sawicki (2012; 2012)]. Peak positive joint velocity (v_{pk}) moment (M_{pk}) and power (P_{pk}) were also calculated during upward motion. For trials where COM power was computed, average and peak velocities, GRF and powers were computed similarly. Normalised values for most metrics were computed by division by body mass and are reported in units per kilogram. All metrics were averaged within each resistance to provide group means and standard deviations. To test for statistical differences in COM metrics between resistances, a one-way repeated measures ANOVA and a Bonferroni adjustment was employed with the alpha level set to $P \leq 0.05$. For joint metrics a two-way (joint x resistance) repeated measures ANOVA with a Bonferroni adjustment was used. Where a significant main effect was detected for a variable, Tukey's post-hoc test was used to elicit between which pairs of resistances and joints significant differences existed. All hypothesis testing was performed in Prism software v6.0 (GraphPad Software Inc.).

RESULTS

COM mechanics - There was a significant ($F = 20.9$, $P < 0.0001$) main effect of resistance on average COM power ($\bar{P}_{COM}$). $\bar{P}_{COM}$ was significantly ($P < 0.05$) greater at resistances of 20, 40 and 60% 1RM than for 0% and 80% 1RM resistances (Figure 1A). However, the 20, 40 and 60% conditions were not significantly different from one another ($P > 0.05$), indicating a broad range of resistances (20-60% 1RM) over which $\bar{P}_{COM}$ was maximised. When $\bar{P}_{COM}$ was plotted against average COM velocity ($\bar{v}_{COM}$) for each resistance (Figure 1B), $\bar{P}_{COM}$ was greatest at resistances that produced intermediate velocities (20-40% 1RM). Notably, when moving from 20% to 0% 1RM and from 60% to 80% 1RM, there were large reductions in $\bar{P}_{COM}$ (Figure 1B). Average vertical GRF ($\bar{F}_{GRFz}$) decreased with increasing $\bar{v}_{COM}$ in non-linear fashion especially at the extremes of resistance values, where the relationship deviated most from the linear fit provided for comparison (Figure 1B).

Average Joint powers - The two-way ANOVA results indicated a significant effect of resistance ($F = 8.3$, $P < 0.0001$), joint ($F = 97.3$, $P < 0.0001$) and their interaction ($F = 21.9$, $P < 0.0001$) on $\bar{P}$. Average ankle power output ($\bar{P}_A$) was the smallest contributor to total $\bar{P}$ at all resistances, never providing more than 16% (Figure 2A). The magnitude of $\bar{P}_A$ was significantly greater ($P < 0.05$) at 40, 60 and 80% 1RM resistances than at 0%. The magnitude of knee joint average power output ($\bar{P}_K$) exhibited a significant ($P < 0.05$) decline as resistance increased above 20% 1RM (Figure 2A). Furthermore, the knee joint contributed 50% of the total power output at the 20% 1RM resistance but only 34% at a resistance of 80% 1RM. Conversely, hip joint average power output ($\bar{P}_H$) significantly increased as resistance increased from 20% to 40% 1RM and reached a maximum at 60% 1RM before falling again at 80% 1RM (Figure 2A). This meant that $\bar{P}_H$ contributed a greater proportion of total power at high resistances.

Average Joint moments - The two-way ANOVA results indicated a significant effect of resistance ($F = 220.8$, $P < 0.0001$), joint ($F = 29.7$, $P < 0.0001$) and the interaction ($F = 23.4$, $P < 0.0001$) on $\bar{M}$. Average ankle moment ($\bar{M}_A$) and average hip moment ($\bar{M}_H$) increased significantly ($P < 0.01$) with each increment in resistance, excepting the final increment (60-80% 1RM) for $\bar{M}_A$ (Figure 2B). The average knee moment ($\bar{M}_K$) significantly increased from 0-20% 1RM but did not significantly increase for subsequent increments in resistance (Figure 2B).

Average Joint velocities - The two-way ANOVA results indicated a significant effect of resistance ($F = 28.7$, $P < 0.0001$) and joint ($F = 176.4$, $P < 0.0001$) but no interaction ($F = 1.5$, $P = 0.18$) on $\bar{v}$. Average ankle, knee and hip joint velocities ($\bar{v}_A$, v_K, $\bar{v}_H$) all significantly ($P < 0.0001$) declined with each increment in resistance (Figure 2C).

Peak powers - COM P_{pk} was significantly affected by resistance ($F = 23.0$, $P < 0.0001$), increasing with each increment in resistance up to 40% 1RM, after which it did not significantly change despite trending to a reduction at 80% 1RM (Figure 3). For joint P_{pk} there was a significant effect of resistance ($F = 11.7$, $P < 0.0001$), joint ($F = 61.1$, $P < 0.0001$) and their interaction ($F = 9.6$, $P < 0.0001$). Ankle P_{pk} increased from 0-40% 1RM ($P < 0.05$)

but did not significantly increase for any further increments in resistance (Figure 3). There was a significant ($P < 0.05$) reduction observed in knee P_{pk} between the 0% 1RM and 80% 1RM resistances (Figure 3). Hip P_{pk} increased significantly ($P < 0.05$) from 0% 1RM resistance to 20% 1RM but did not increase with further resistance increments (Figure 3).

DISCUSSION

This study sought to explain trends in system power output with varied resistance during weighted back squats by analysing joint level mechanics. Our first hypothesis was that a broad range of resistances surrounding 50% 1RM would provide equivocal maximal powers. This was supported as $\bar{P}_{COM}$ was maximised for resistances from 20-60% 1RM. We also hypothesised that this broad range would be observed because knee and hip joint powers would be maximised at different resistances from one another. This was supported by our observation of an apparent trade-off between $\bar{P}_H$ and $\bar{P}_K$ across the range of resistances from 20-60% 1RM.

Joint powers - The trade-off between contributions at the hip and knee to overall power was evidenced by distinctly different trends in $\bar{P}_K$ and $\bar{P}_H$ with varying resistance. $\bar{P}_H$ was greatest at 60% 1RM with a significant decrease in power occurring if the resistance was increased or decreased from 60% (Figure 2A). However, $\bar{P}_K$ was greatest at 20% 1RM and was less at greater resistances. The respective maximum values of $\bar{P}_K$ and $\bar{P}_H$ were similar in magnitude and from Figure 2A it can be seen that the trends of $\bar{P}_K$ and $\bar{P}_H$ across different resistances are almost a mirror image of one another. This explains the broad range of resistances over which $\bar{P}_{COM}$ was maximised. At the lower end of this maximal range (20% 1RM) $\bar{P}_K$ was maximised, but $\bar{P}_H$ was significantly below its maximum. The exact opposite was true for the upper end of the range (60% 1RM) and at the intermediate resistance (40%) where both $\bar{P}_K$ and $\bar{P}_H$ were less than maximal but summed to a similar total power as at 20% and 60%

1RM. Thus, the broad range of resistances over which $\bar{P}_{COM}$ was maximised was dictated by a trade-off between $\bar{P}_K$ and $\bar{P}_H$. $\bar{P}_A$ made such a minimal contribution to total power that we considered it insignificant in this part of the discussion.

Force and velocity - While joint powers provide descriptive insight into the observed trends in $\bar{P}_{COM}$, to gain insight into the underlying mechanisms we also reported forces, joint moments and velocities. The force-velocity relations that exist for isolated skeletal muscle were documented some time ago (Fenn & Marsh 1935; Hill 1938). An exponential decay in force with increasing velocity was described by Hill's (1938) hyperbolic equation and this relation results in a maximal power output at approximately one-third of maximal shortening velocity. However, experiments that have characterised the external or joint force-velocity relationships in multi-joint tasks such as leg extension generally report a quasi-linear force-velocity relationship at the system or joint level (Perrine & Edgerton 1978; Rahmani et al. 2001; Macaluso & De Vito 2003; Pearson et al. 2004; Bobbert 2012) although Hahn et al. (2014) showed that a linear fit underestimated maximum joint velocity. In our data, we observed a system-level force-velocity relation for squatting that deviated from a linear fit and was not hyperbolic (Figure 1B). The most notable deviations of this trend from linear and hyperbolic relationships were at the extremes of the resistances tested. This indicates that leg extension powers were limited at these resistances by factors other than the maximal force-velocity properties at the level of muscle or the system.

For the change in $\bar{F}_{GRFz}$ that occurs between 60 and 80% 1RM, $\bar{v}_{COM}$ was decreasing to its lowest value. If the only constraint on force production was that dictated by the force-velocity relation of muscle we would expect $\bar{F}_{GRFz}$ to increase exponentially with decreasing velocity. However, this was not the case as an increase in $\bar{F}_{GRFz}$ that was even slightly less than linear, (as might be expected at the whole-limb level) was observed between 60 and 80% 1RM

(Figure 1B). At this time, $\overline{M}_H$ was significantly increasing with each increment in resistance (Figure 2B) and so did not appear to indicate any constraints on muscle force or joint torque production. However, $\overline{M}_K$ did not significantly increase for any increments in resistance above 20% 1RM. Potentially this suggests an inability to produce a greater knee extensor moment at high resistances and this could have been constraining force production at those resistances. However, the intrinsic force-velocity relationship of knee extensor muscles or the joint torque-velocity relationship would not dictate this, as both would predict that greater forces could be generated at slow velocities. Alternatively, we propose that the inherent mechanical constraints of the task would have prevented any further increases in knee extensor moments at high resistances. Here we refer to the need to control the direction of the GRF as described by van Ingen Schenau and colleagues (1992). To consider this we will neglect inertial factors and consider the problem as a quasi-static scenario where the direction of the reaction force is dictated by the magnitudes of the joint moments only. Figure 4A schematically illustrates the current data, where the ground reaction force (black arrow) is acting vertically through the COM and the hip and knee joint moments are balanced accordingly. For the knee extensor joint moment to be larger, either the magnitude of the GRF must be increased (Figure 4B) or the moment arm of the force about the knee joint must be increased (Figure 4C). The former would involve a concomitant increase in the hip joint moment, which may not be possible if the hip joint extensors are already maximally active. The latter would involve reorienting the force vector away from the vertical in a posterior direction (Figure 4C), with several negative consequences. First, the hip joint moment would need to be reduced as the force vector passed closer to the hip joint centre. Second, the force would generate a de-stabilising moment about the COM. Third, a large component of the force would now be acting to accelerate the COM posteriorly not vertically, which is not useful for the task. Therefore, we propose that at high forces the knee moment cannot be increased to the limits dictated by muscle or joint-level force-velocity properties because of a constraint imposed on knee joint extension moments by the need to control the direction of the GRF vector. This, combined with a reduction in COM velocity, is why we observed a large drop-off in $\bar{P}_{COM}$ when resistance increased to 80% 1RM. We did not measure muscle activation but one would expect pre-activation of muscles before leg extension to have been greater at higher resistances. However, if this were to have impacted the force-velocity relationship, the forces and moments at high resistances should trend to be greater than linear rather than less than linear as we observed.

At the other extreme, we examined the system force-velocity behaviour changes between 20% and 0% 1RM resistances. Here we observed that $\bar{P}_{COM}$ was considerably less at 0% 1RM than at 20% 1RM (Figure 1A & B). This was owing to a reduction in $\bar{F}_{GRFz}$ that was accompanied by a relatively small increase in $\bar{V}_{COM}$. The small increase in $\bar{v}_{COM}$ was less than a linear force-velocity relation would have predicted (Figure 1B) and therefore also less than what would be expected based on the force-velocity relationship of isolated muscle or joints at high velocities. An explanation for this may again rest within the apparent constraints of the task. Because a squat exercise was used, participants were instructed not to leave the ground for any of the resistances. However, to maximise power at low resistances one would typically jump. Bobbert and van Ingen Schenau (1988) observed that an important contributor to maximal power in vertical jumping was high velocity ankle extension late before take-off. Magnitudes of ankle extension velocity in that study were similar to, or even greater than, knee and hip extension velocities. However, in our data $\bar{v}_A$ and peak ankle velocity were significantly ($P < 0.0001$) less than for the knee and hip at all resistances. This is likely because of the imposed restriction to stay grounded that would have required our participants to decelerate the upward motion of the COM at the end of the movement. Given the apparent importance of ankle joint velocity in contributing to COM velocity, our restricting it likely constrained the participants' capacity to generate large power outputs at low resistances. At low resistance power will be more determined by COM velocity than GRF. In order to make fair comparisons of a squat across resistances it was necessary to restrict participants from jumping. Other studies investigating the power-resistance relationship in squat jumping have revealed that $\bar{P}_{COM}$ was actually maximised when jumping with no additional resistance above body mass (Cormie et al. 2007; Moir et al. 2012; Jandacka et al. 2014). Therefore, the constraint to not jump likely limited velocity and power production potential at low resistances.

Average vs. Peak Power - In the present study we have primarily focussed on average powers as a metric of power output. This is because the average power produced during leg extension reflects both the amount of mechanical work done and the rate at which it was done. However, some similar existing studies report peak powers (Cormie et al. 2007; Bevan et al. 2010). Our intention here is not to conclude which is more appropriate but to note that findings may differ depending on the authors' choice of metric. A close inspection of Figures 1 and 3 reveals that although $\bar{P}_{COM}$ did not increase significantly from 20% 1RM to 40% 1RM, COM P_{pk} did. Also, the significant changes in $\bar{P}_H$ and $\bar{P}_k$ that occurred with increments between 20% 1RM and 80% 1RM were not always evident in the P_{pk} values for these joints. One explanation for the discrepancies between trends in average and peak powers is the potential influence of interdependent torque-angle-angular velocity relationships that have been documented in multi-joint tasks (Hahn et al. 2014). Because joint velocities were different at different resistances, the optimum joint angle for producing torque or power would likely be different too. Thus it was possible that for the different resistances, the angle at which peak power was reached was less optimal for that velocity than was the case at other resistances. However, this joint position effect should not have influenced average powers, as setting the starting position controlled the range of motion. Therefore, we recommend exercising caution when comparing results based on peak powers with those from average powers and that careful thought should be given to which metric is most appropriate for a given purpose.

PERSPECTIVES

Conventional paradigms for training the development of muscular power incorporate high resistance exercises followed by a progression that includes lighter, more sport-specific exercises (Cormie et al. 2011). Our data suggest that this progression can be achieved in squatting without compromising on power production because heavier weights and somewhat lighter resistances resulted in similar power output. Furthermore, joint level power profiling such as we have shown might facilitate better matching of lighter weights to the sporting task of an athlete. For example, choosing a resistance that has a similar breakdown of joint contributions to total power as the task. In this study to make fair comparisons across resistances we restricted our participants to remaining grounded and not performing a jump squat. A more likely progression at lighter weights would be to jump and this might provide a better match to many sporting tasks in terms of coordination and with fewer constraints, result in greater power outputs than observed for squats (Bevan et al. 2010; Bobbert 2014). However, our purpose was to illustrate the fundamental mechanical principles using squatting as an example, not a comprehensive resource of power-resistance data which remains an important future direction for the field.

CONCLUSIONS

In this study we sought to deconstruct the power-resistance relationship in a back-squat exercise by examining system force-velocity relationships and joint-level mechanics. We found a broad range of intermediate weights could maximise COM power. This range was determined by trading-off knee and hip joint powers that were individually maximised at different resistances. 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. At low resistances power was less because participants were not permitted to jump and this limited the capacity of the ankle joint to contribute to increasing the COM velocity late in the movement. Our findings provide new perspectives and support for power-based training programmes that employ a progression through a range of resistances and incorporate sport-specific exercises.

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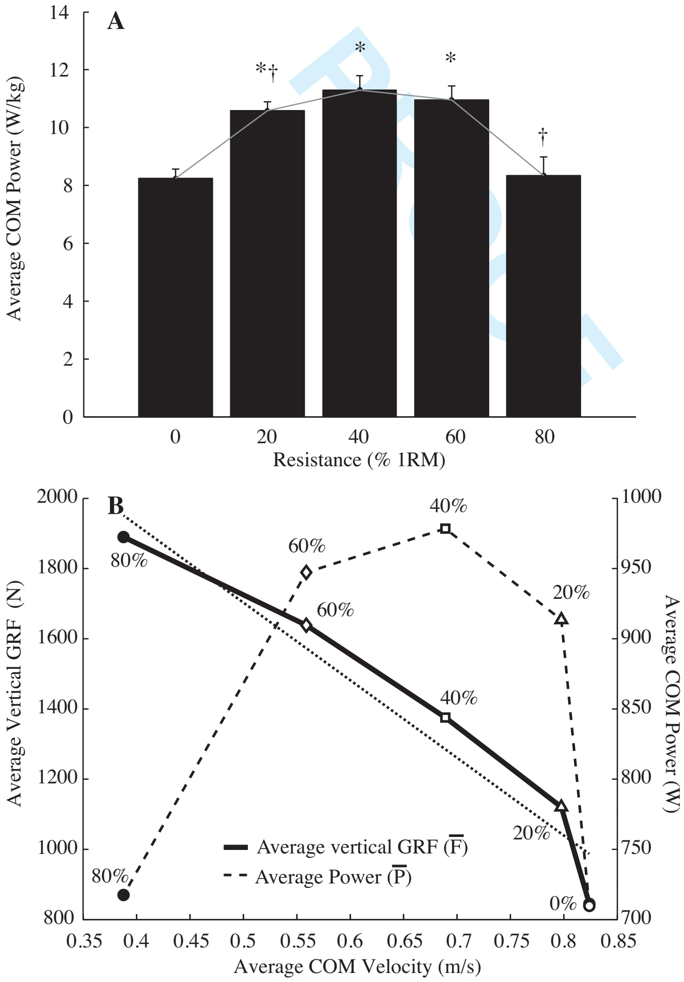
FIGURE LEGENDS

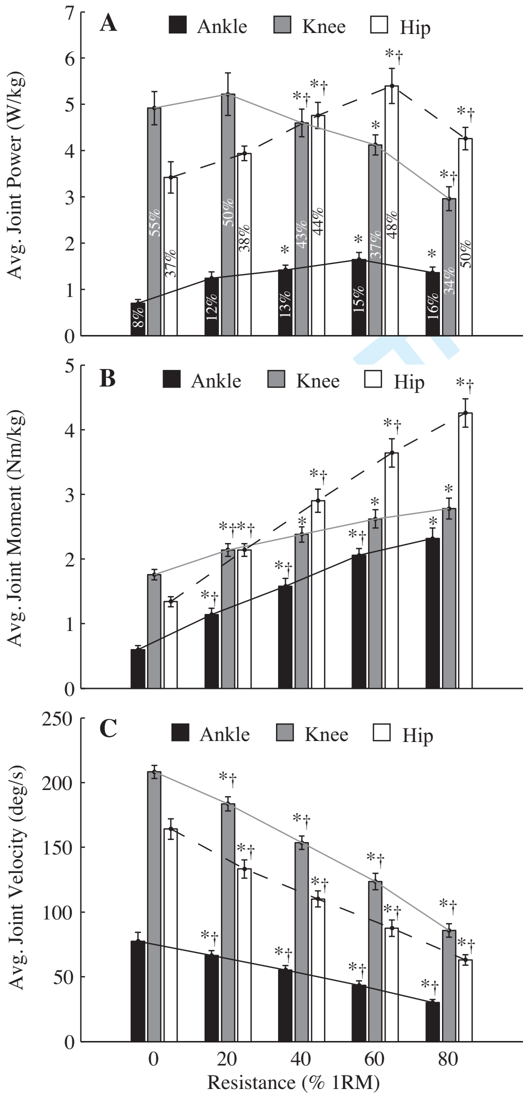
Figure 1. A - Group mean (± s.e.m.) COM average power at each resistance. *Denotes a significant difference from 0% 1RM and † denotes a significant difference from the next lightest resistance. **B** - Group mean system force-velocity (solid line, left vertical axis) and power-velocity (dashed line,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

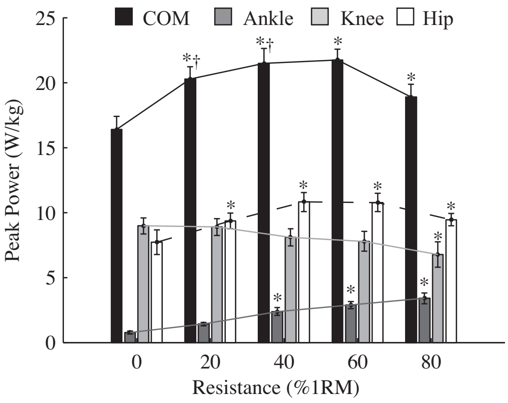
Figure 2. Group mean (± s.e.m.) average joint power (**A**), average joint moment (**B**) and average joint velocity (**C**) for the ankle (black), knee (grey) and hip (white). For joint powers, the percentage of total average power (sum of the three joint powers) provided by each joint at each resistance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

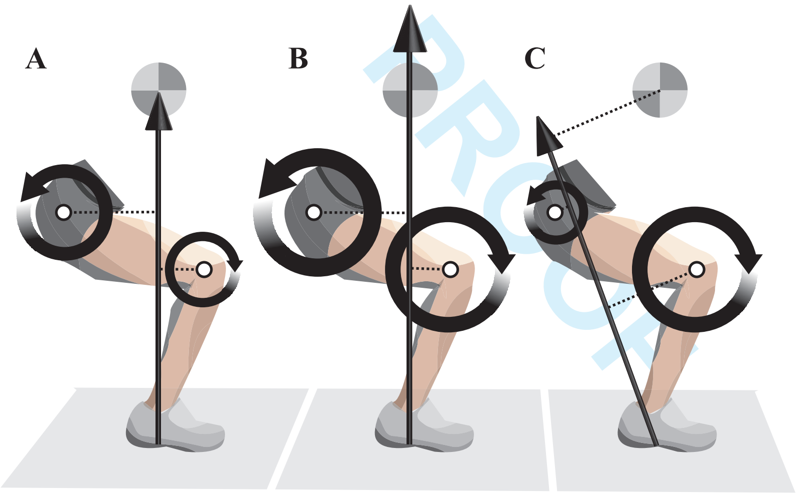
Figure 3. Group mean (± s.e.m.) peak COM (black), ankle (dark grey), knee (light grey) and hip (white) powers. *Denotes a significant difference from 0% 1RM and † denotes a significant difference from the next lightest resistance.

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.


A
Average COM Power (W/kg)
0
2
4
6
8
10
12
14
*†
*
*
†
0
20
40
60
80
Resistance (% 1RM)
B
Average Vertical GRF (N)
800
1000
1200
1400
1600
1800
2000
Average COM Power (W)
700
750
800
850
900
950
1000
80%
60%
40%
20%
0%
80%
60%
40%
20%
Average vertical GRF ($\overline{F}$)
Average Power ($\overline{P}$)
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
Average COM Velocity (m/s)


A
Ankle
Knee
Hip
Avg. Joint Power (W/kg)
0
1
2
3
4
5
6
7
8%
55%
37%
12%
50%
38%
13%
43%
44%
15%
37%
48%
16%
34%
50%
*
*†
*†
*
*
*†
*
*†
*†
B
Ankle
Knee
Hip
Avg. Joint Moment (Nm/kg)
0
1
2
3
4
5
*†
††
*†
*
*†
*†
*
*†
*
*
*†
C
Ankle
Knee
Hip
Avg. Joint Velocity (deg/s)
0
50
100
150
200
250
*†
*†
*†
*†
*†
*†
*†
*†
*†
*†
*†
*†
0
20
40
60
80
Resistance (% 1RM)


COM
Ankle
Knee
Hip
Peak Power (W/kg)
25
20
15
10
5
0
*†
*†
*
*
*
*
*
*
*
*
*
*
*
0
20
40
60
80
Resistance (%1RM)


A
B
C