OPTIMISING MECHANICAL POWER OUTPUT IN WEIGHTED BACK SQUATS - A JOINT LEVEL ANALYSIS

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When performing resistance training to improve muscular power output it is desirable to train with a resistance that maximises mechanical power. Previous studies investigating what resistance maximises power output show varied results and generally lack mechanistic conclusions. To address this we studied the whole-body and lower-limb joint mechanics of weighted back squatting. Ten male rowers performed maximal power squats with an Olympic bar and weights equivalent to 0, 10, 20, 40, 60 & 80% of their 1 RM. Whole-body power did not peak at a single resistance but over the range of 20-60%. This was owing to a trade-off in knee and hip powers that were maximised at 20% and 60%, respectively. When determining training resistances, practitioners should consider what joint powers should be emphasised in relation to the mechanics of the target sport.

KEY WORDS: resistance training, inverse dynamics, joint moment, joint velocity

INTRODUCTION: Developing greater muscular power output is a key goal of athletic training programmes for many athletes. Typically, a part of this programme will include resistance training in the form of weight lifting exercises. It has been shown that to achieve the greatest improvements in muscular power output, the training task should be performed against the resistance that maximises power output (Kaneko, Fuchimoto, Toji & Suei, 1983). Therefore it is desirable to know what level of resistance will result in maximal power production. As a result this topic has received considerable attention in the literature but these studies have produced greatly varied results reporting maximal power production to occur anywhere between 0 and 60% dependent on the exercise (Baker, Nance & Moore, 2001; Cormie, McCaulley, Triplett & McBride, 2007). In terms of lower limb exercises the two most prevalent are the squat and jump squat with maximal power being developed at low resistances for the jump squat and typically near 50-60% of 1 repetition maximum (RM) for the squat (Cormie et al. 2007, Bevan et al. 2010). However, peak power for the optimal resistance in these studies was not significantly different from peak power for a large range of resistances surrounding the optimal resistance. It has been shown that this optimal range of resistances for power production is dictated by a trade-off in movement velocity and net external forces (Cormie et al. 2007). However, these velocities and forces only represent the overall net effect of all muscles that are acting in a coordinated fashion through joints to effect the movement. Breaking down squatting mechanics to a joint level could reveal more about the mechanisms dictating the optimal resistance for power production in squatting and elicit why a singular optimal value has not been observed.

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. They 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 ankle's contribution was never more than 10%. This highlights that the total work output is not solely dependent upon the force-velocity properties of lower limb muscles but also is influenced by a control strategy that changes with the external resistance. It is therefore important to investigate the contributions made at individual lower limb joints to power output during maximal power squatting to understand the relationship between resistance and total power output.

The aim of this study was to break down mechanical power output during weighted back squats performed over a range of resistances from the whole-body level to that of individual lower limb joints. We hypothesised that total power output would be maximised over an intermediate range of added weights surrounding 50% 1RM. Furthermore, we hypothesised that this broad range of optimal resistance would be a result of individual joint powers being maximised at different resistances from one another (knee power at lower resistances and hip power at higher resistances).

METHODS: Participants - Ten male sub-elite rowers (mean age 20 ± 2.2 yrs height 1.82 ± 0.03 m mass 86 ± 11 kg), experienced with squatting and who's 3 RM had been assessed by a strength and conditioning professional in the last month participated in the study. Each participant gave written informed consent and the study was approved by the institutional ethics committee. **Protocol** - Each participant's 1 RM was estimated as their 3 RM multiplied by 1.08 (Baker et al. 2001). The participants then performed two sets of three weighted back squats with 0, 20, 40, 60 and 80% of their 1 RM 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 participants were instructed to make the extension phase as fast as possible without allowing their feet to leave the ground (i.e. maximising power without jumping). **Data Collection & Analysis** - One of the two sets at each weight was completed with both feet on a single force platform (AMTI, USA) and the other set with only the right foot in contact with the force platform. The first set was for the purpose of calculating centre of mass (COM) mechanics from the ground reaction forces (GRF) that were sampled at 2000 Hz. COM velocity was calculated from the GRF. Briefly, the total system weight (body plus added weight) was subtracted from the vertical component of GRF and the result was divided by the combined mass of the body and additional mass to give acceleration. Acceleration was then integrated to calculate system COM velocity. The dot product of COM velocity and GRF gave instantaneous COM power. GRF data were sampled synchronously with motion capture data. The motion capture system (Qualisys, Sweden) recorded the positions of thirty-two reflective markers (at 200 Hz) placed on both lower-limbs and the pelvis to reconstruct a seven-segment scaled rigid-body model for each participant incorporating feet, shanks, thighs and pelvis. This model was generated using Visual 3D software (C-Motion Inc., USA) and the same software was employed to perform three-dimensional inverse kinematic and inverse dynamic analyses to obtain instantaneous angles, angular velocities, moments and powers for the ankle, knee and hip joints of the right leg. The left leg was assumed to behave symmetrically and thus, joint moments and powers from the right leg were doubled to represent both legs. **Data Reduction & Statistics** - All data were computed for the extension phase of the squat when positive power is generated and positive work is done. Average positive power for the COM and each joint was calculated by integrating instantaneous power over the extension phase to obtain work and dividing work by the time taken for extension. Similarly, average joint moments were computed as the integral of the joint moment, divided by extension time and average joint velocity as the integral of velocity divided by extension time. Peak powers, velocities and moments were calculated as the maximum of their respective instantaneous signals during the extension phase. All outcome metrics were calculated for each individual squat and averaged across the three squats at each level of added mass. A two-way repeated measures ANOVA was used to test for significant main effects of added weight and joint on joint mechanics metrics. A one-way repeated measures ANOVA was used to test for an effect of added weight on COM mechanics metrics. Tukey's Post-hoc test was employed to test for pairwise significant differences between levels of added weight and between joints.

RESULTS: Average power (P_{avg}) of the COM was maximised across the midrange of added weights from 20-60% 1RM (Fig. 1A). P_{avg} for these weights was greater than for 20% and 80% 1RM but not different from one another. Hip P_{avg} increased almost linearly with added weight up to 60% 1RM where it peaked and then decreased significantly from 60-80% 1RM (Fig.1B). Knee P_{avg} showed an opposite trend to that of the hip, being maximised at 0-20% 1RM and then significantly decreasing from 20-40% 1RM and continuing to decrease through to 80% 1RM. The magnitudes of hip and knee average powers at their respective maxima were similar (Fig. 1B). Ankle P_{avg} was significantly less than knee and hip P_{avg} across all weights contributing only ~10% of the total power output at all three joints (Fig. 1B).

Average joint moments (M_{avg}) at the hip increased with every increment in weight (Fig. 1C). However, M_{avg} at the knee increased from 0-20% 1RM but then did not significantly increase from the value at 20% 1RM at any subsequent added weight (Fig. 1C). Ankle joint M_{avg} increased with each added weight increment up to 60% 1RM where it plateaued (Fig. 1C). Average joint angular velocity (V_{avg}) at the hip significantly decreased with increases in added weight (Fig. 1D) and the same trend was observed for knee and ankle V_{avg} (Fig. 1D).

Peak COM power increased with added weight up to 40% 1RM and plateaued (Fig. 2). Hip peak power increased from 0-20% 1RM with no further increases (Fig. 2). The only difference in peak knee power was from 0-80% 1RM (Fig. 2). Peak ankle power increased from 0-40% 1RM only (Fig. 2).

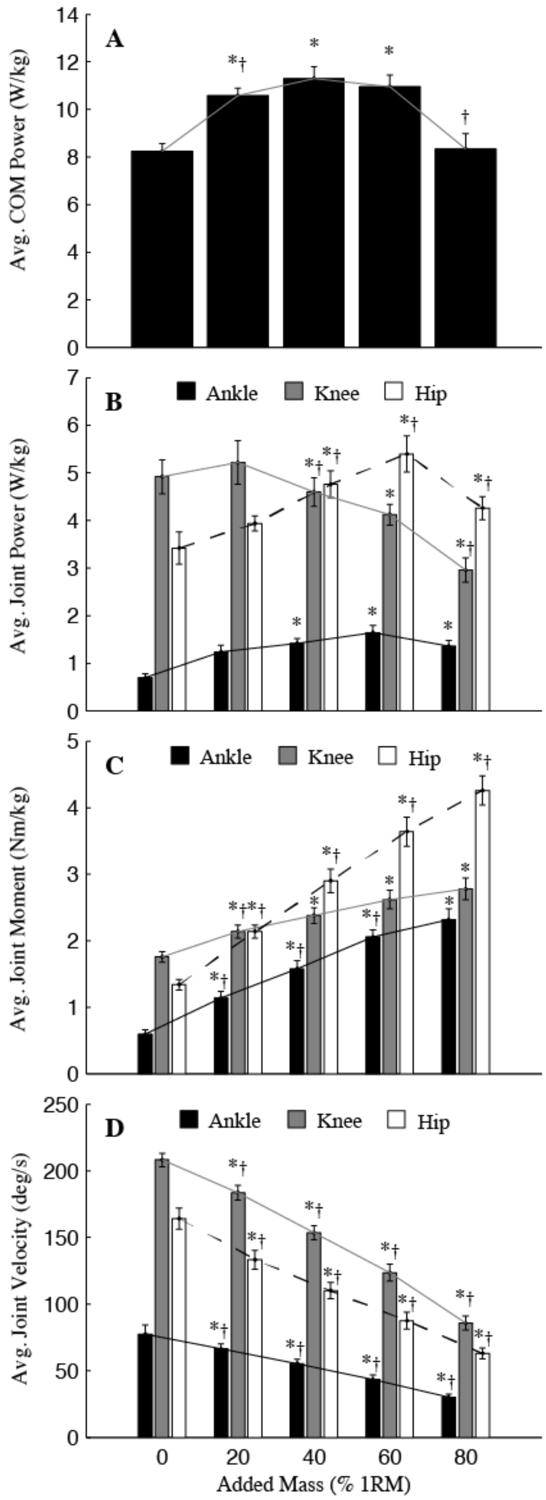

Figure 1. Group mean (± s.e.m.) average COM power (A), average joint powers (B), average joint moments (C) and average joint velocities (D). *significant difference (P<0.05) from the 0% 1RM condition and † significant difference from the next lightest weight (e.g. 40% 1RM vs 20% 1RM)

DISCUSSION: In this study we aimed to break down mechanical power output to the level of joints during weighted back squats. This was with the intention of explaining the variation in total mechanical power output with varied resistance. Our first hypothesis was that total power output would be maximised across a range of intermediate resistances. This was confirmed by our data that showed weights from 20-60% 1RM resulted in greater P_{avg} than for other resistances (Fig. 1A). Similarly, peak power was greatest for added loads of 40-60% 1RM and this finding is in reasonable agreement with previous work (Cormie et al. 2007).

Our second hypothesis predicted that lower limb joint powers would be maximised at different resistances. This was also supported by our data that highlighted distinctly different trends in knee and hip P_{avg}. Hip P_{avg} was greatest at 60% 1RM with a significant decrease in power occurring if the added weight was increased or decreased from 60% (Fig. 1B). However, knee P_{avg} peaked at 20% 1RM and decreased at resistances greater than 20%. The respective maximum values of knee and hip P_{avg} were similar in magnitude and from Figure 1B it can be seen that the trends of hip and knee P_{avg} across different resistances are almost a mirror image of one another. This explains the broad range of resistances over which COM power is maximised. At the lower end of this range (20% 1RM) knee joint P_{avg} is maximised but hip joint power is significantly below its maximum. The exact opposite is true for the upper end of the range (60% 1RM) and at the intermediate weight (40%) both are less than maximal but sum to a similar total power as at 20% and 60% 1RM. Thus, the broad range of weights over which COM P_{avg} was maximised was dictated by a trade-off between hip and knee P_{avg}. Ankle P_{avg} made such a minimal contribution to total power we considered it insignificant in this discussion.

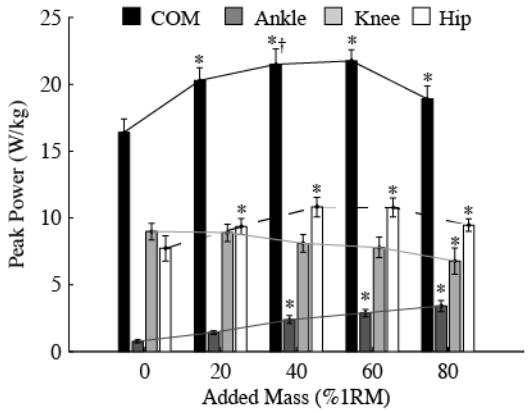

Figure 2. Group mean (± s.e.m.) peak power for the COM, ankle, knee and hip joints. *significant difference (P<0.05) from the 0% 1RM condition and † significant difference from the next lightest weight

The trend in hip P_{avg} can be explained when looking at the M_{avg} and V_{avg} data for that joint (Fig. 1C-D). Hip M_{avg} increased continually with increasing resistance, but hip velocity decreased concomitantly and the trade-off between the two resulted in maximum hip P_{avg} occurring at 60% 1RM. However, knee M_{avg} did not increase significantly beyond 20% 1RM. Thus, knee P_{avg} was largely dictated by knee V_{avg} and therefore peaked at 20% 1RM. Our contention was that the lack of increase in knee M_{avg} beyond 20% 1RM is a control strategy to maintain a vertically oriented GRF vector and prevent overbalancing. This need for control limited knee power production.

CONCLUSION: The constraint of having to control squatting motion enforced a trade-off between knee and hip power outputs as the resistive weight was increased. This caused the total power output to be maximised across a broad range of resistances. Practitioners prescribing training exercises for power development should consider what joint power outputs they want to emphasise, not just whole body power output.

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