CHANGES IN THE GRADIENT OF FORCE-VELOCITY PROFILES IN SIMULATIONS OF LOADED SQUAT JUMPS CAN BE INDUCED BY INCREASES IN MAXIMUM TORQUE AND RATE OF TORQUE DEVELOPMENT

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In multi-segment movements the relationship between the external applied force and the velocity of the whole body or limbs has often been shown to be quasi-linear. It has been proposed that there is an optimal force-velocity profile for an athlete and that deviations from this profile, termed either a ‘force-deficit’ or a ‘velocity-deficit’, can be corrected by training. The aim of this study was to test the hypothesis that alterations in the maximum torque and rate of activation of the torque generator in a two-segment computer model actuated solely by a knee torque generator can explain changes in the gradient of the force-velocity profile during simulations of loaded squat jumps. It was found that an increase in the rate of activation of the torque generator led to a reduction in the gradient of the force-velocity relationship, addressing a velocity-deficit, and an increase in the maximum torque resulted in an increase in the gradient of the force-velocity relationship, addressing a force-deficit. These results provide potential mechanisms by which force-velocity profiles obtained from loaded squat jumps can be altered by training.

KEY WORDS: computer, model, strength, power, training

INTRODUCTION: In multi-joint movements the relationship between the external applied force and the velocity of the whole body or limbs has often been shown to be quasi-linear (Jaric, 2015) this contrasts with the underlying relationship between force and contraction velocity in isolated muscle which is hyperbolic (Hill, 1938). It has been proposed that there is an optimal force-velocity (F-v) profile for an athlete (Samozino et al., 2012) and that deviation from this profile can be corrected by training which targets the deficit of the athlete (Jimenez-Reyes et al., 2017). Jimenez-Reyes et al. (2017) categorised athletes performing loaded squat jumps as having either a ‘force-deficit’ or a ‘velocity-deficit’ and allocated them to training groups accordingly; athletes with a force-deficit performed high load activities aimed at inducing high muscle forces, and athletes with a velocity-deficit performed low load activities aimed at inducing high velocities of muscle shortening. These training programmes were effective in improving vertical jump performance via alterations to the F-v profiles of the athletes, however, the mechanisms by which this training altered the F-v profiles are unknown.

It has been observed that the instructions given to athletes during maximal isometric contractions can influence both the maximum force they can exert and the rate at which they can exert it; in maximal voluntary isometric handgrip contractions, instructing participants to contract ‘fast’ versus ‘hard and fast’ resulted in a reduction in both the time to reach maximum force, and the maximum force exerted (Bemben et al., 1990). Balshaw et al., (2016) compared the effects of training protocols involving either explosive or sustained contractions, finding that maximum voluntary torque was increased more following sustained contractions, whereas rate of torque development showed larger improvements following explosive contractions. It is conceivable that athletes training to address a ‘force-deficit’ or ‘velocity-deficit’ as described by Jimenez-Reyes et al., (2017) influence these components; specifically, athletes with a ‘force-deficit’ train with high loads to improve the maximum absolute force they can produce with fewer time-constraints, and those with a ‘velocity-deficit’ train with low loads which lead to briefer movement times and a requirement to improve the rate at which they can produce force.

Therefore, the aim of this study was to test the hypothesis that changes in the gradient of the F-v profile obtained from a torque-driven computer model simulating loaded squat jumps can be induced by alterations in the maximum torque and rate of activation of the torque generator.

METHODS: A two-segment rigid body planar computer model was constructed in Simscape Multibody (R2021a, Mathworks, MA, USA) to simulate a weighted squat jump. The two segments represented the shanks, and the thighs, with the mass of the combined head, arms, and trunk (HAT) plus additional mass representing a weighted barbell added as a point mass at the hip. The hip joint was constrained to move vertically, directly above a fixed ankle joint, resulting in only one degree of freedom in the model, the knee joint angle. The model was actuated by a torque generator at the knee joint, this represented the knee joint musculature and had three elements: a torque-angular velocity component; a torque-angle component; and an activation timing component. Model parameters were taken from Allen et al., (2010) and were representative of a male triple jump athlete (age: 22 years; mass: 72.6 kg; height: 1.82 m). Simulations began with an initial knee angle of 90° and ended when the vertical ground reaction force (GRF) decayed to zero. Initial activation levels were chosen to ensure a static starting position (i.e. the vertical GRF was equal and opposite to the bodyweight) and the time taken to move from this initial activation level to full activation was reduced pro rata from the activation time required for the torque generator to move from zero to full activation. Simulations were run with additional masses ranging from 0 kg to 160 kg (the maximum mass at which all models were able to complete the movement) at 20 kg intervals.
Least squares regression lines were fit to the time-averaged vertical velocity of the system centre of mass (CoM) ($\bar{v}$) and the vertical GRF ($\bar{F}$) over the simulation to obtain linear F-v relationships defined by the points at which the line intersected the force ($\bar{F}_0$) and velocity ($\bar{v}_0$) axes (Samozino, 2012). In addition to the F-v relationships, the product of $\bar{F}$ and $\bar{v}$ was used to calculate mean power $\bar{P}$ from which power-velocity (P-v) relationships (Samozino, 2008) and maximum power ($\bar{P}_{max}$) were obtained. To test the effects of theoretical training programmes aimed at correcting either a 'force-deficit' or a 'velocity-deficit' in the F-v profile, the activation dynamics of the torque generator were manipulated: to simulate the outcome of a programme aimed at correcting a 'velocity-deficit' (velocity-trained), the activation time taken for the torque generator to move from zero to fully activated was reduced to 100 ms from the baseline value of 150 ms; to simulate the outcome of a programme aimed at correcting a 'force-deficit' (force-trained), the maximum torque the torque generator could produce was increased by 10%.

RESULTS: The observed F-V relationships were all approximately linear ($R^2 \geq 0.99$) (Figure 1). An increase in the rate of activation of the torque generator led to a reduction in the gradient of the F-v relationship (Figure 1), resulting in an increase in $\bar{v}_0$, a decrease in $\bar{F}_0$, and an increase in $\bar{P}_{max}$, which was achieved at a higher velocity (Table 1). An increase in the maximum torque of the torque generator resulted in an increase in the gradient of the F-v relationship (Figure 1), causing an increase in $\bar{F}_0$, a decrease in $\bar{v}_0$, and an increase in $\bar{P}_{max}$ which was achieved at a similar velocity to the baseline model (Table 1).

Table 1
Model parameters

	Baseline	Velocity-trained	Force-trained
$\bar{v}_0$ (m/s)	1.52	1.69	1.48
$\bar{F}_0$ (N)	2890	2805	3266
$\bar{P}_{max}$ (W)	1101	1186	1207
$\bar{F}_0$ (N/kg)	39.8	38.6	45.0
$\bar{P}_{max}$ (W/kg)	15.2	16.3	16.6

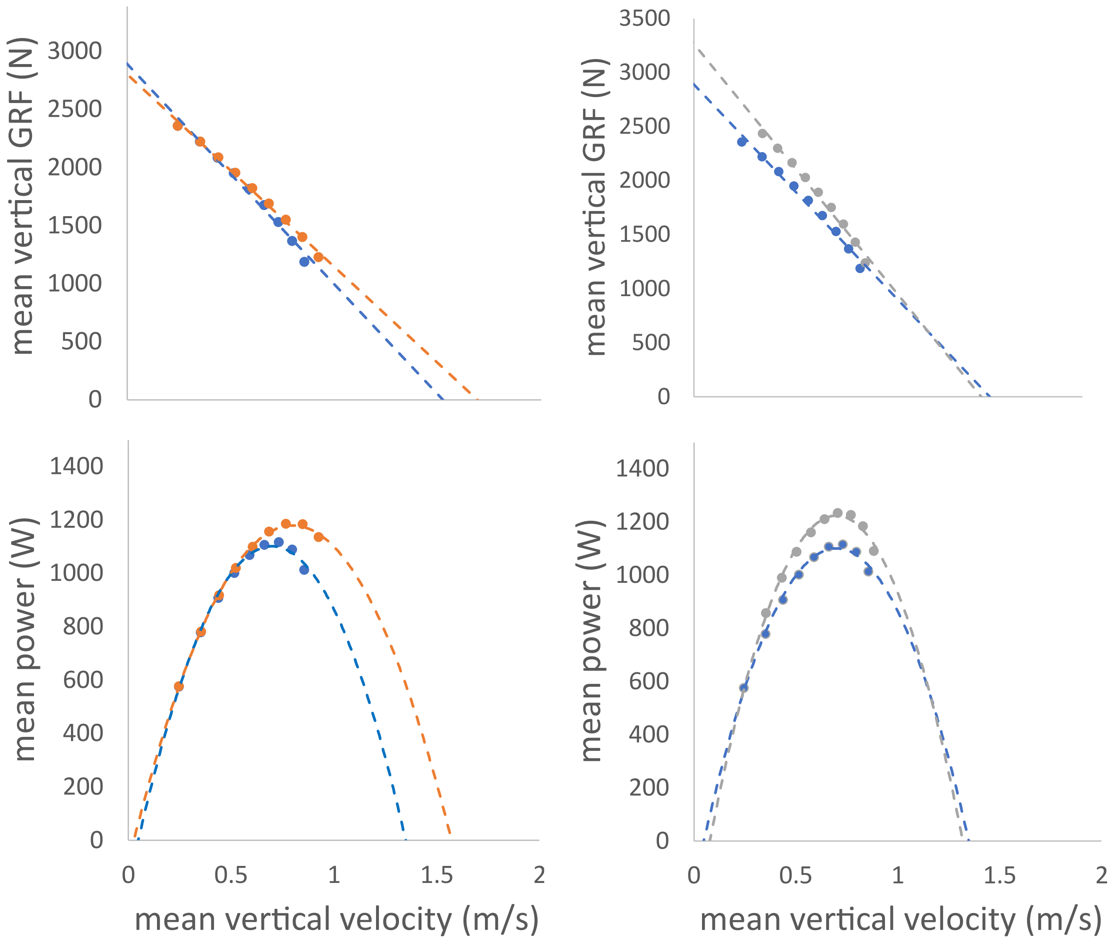

Figure 1: F-v **(top) and** P-v **(bottom) relationship for velocity-trained (orange) and force-trained (grey) models versus the baseline model in blue.**

DISCUSSION: The hypotheses that changes in maximum torque and rate of torque development can alter the gradient of the F-v profile were borne out by the results. Increasing the maximum torque the model was able to produce increased the gradient of the F-v relationship, which would act to reduce a 'force-deficit', and increasing the rate of torque development decreased the gradient of the F-v relationship which would act to reduce a 'velocity-deficit'. These results provide a potential mechanism by which F-v profiles can be altered due to training in loaded squat jumps (Jimenez-Reyes et al., 2017).
The linear F-v models were defined by two parameters - $\bar{F}_0$ and $\bar{v}_0$ - it is tempting to view these as having mechanical meaning, for instance $\bar{F}_0$ represents the maximum isometric force, and $\bar{v}_0$ represents the velocity at which GRF decays to zero. This is complicated in this case by the fact that the values are time-averaged over the push off phase, therefore it is difficult to practically define these parameters. For instance, it is unclear at what joint angle $\bar{F}_0$ should be measured, and to calculate $\bar{v}_0$, the average GRF should be zero, but it is not immediately obvious how to obtain an average GRF of zero, since GRF cannot be negative in this scenario. In any case, the results of this investigation indicate that these numbers are not necessarily indicative of the underlying model parameters. For example, an increase in the activation rate of the torque generator resulted in a reduction in $\bar{F}_0$ (Table 1), but the isometric strength of the model remained the same as the baseline model. The reduction in $\bar{F}_0$ was a consequence of the increase in the average force and velocity at the lower loads, reducing the gradient of the F-v line and resulting in a reduction in the value at which the line intercepts the force axis (Figure 1). Similarly, an increase in the maximum torque resulted in a decrease in $\bar{v}_0$ (Table 1),

but the maximum angular velocity of shortening of the torque generator remained the same; the reduction in $\bar{v}_0$ was simply a consequence of increases in the average force and velocity at the higher loads (Figure 1). For this reason, it is perhaps more sensible not to think of $\bar{F}_0$ and $\bar{v}_0$ as having mechanical meaning, but simply as parameters of a model which represents the time-averaged F-v relationship over a range of practically measurable loads.

It has been proposed that F-v relationships can be used as a simple routine test of function (Jaric, 2015). The results of this investigation shed light onto the mechanisms which may underpin this function, an athlete who exhibits a force-deficit could train to increase their maximum force using high-load, isometric and low-velocity contractions, and an athlete who exhibits a velocity-deficit could train using explosive contractions aimed at maximum rates of force development (Balshaw et al., 2016). With reference to the previous paragraph, any changes to the F-v relationship should be interpreted carefully, since increases in either $\bar{F}_0$ or $\bar{v}_0$ could be accompanied by decreases in the other parameter, which may not be representative of the underpinning mechanics. The results of the individual trials at each load should be compared in this case to establish whether the performance of the athlete has really decreased at a particular load.

The study had several limitations; a very simple model was used, comprising two-segments constrained to have one degree of freedom at the knee joint, which was actuated by a single torque generator, whereas a human performing a squat jump has many body segments, joints, and muscles which require complicated activation sequences to achieve an optimal performance. However, this simple model did reproduce the important features of F-v relationships which have been observed in humans performing loaded squat jumps 'in vivo' and its simplicity allowed the effects of individual parameters to be observed in isolation. The parameters investigated were altered by arbitrary amounts to induce plausible changes to the F-v relationship, the changes in the parameters may not necessarily be practically achievable, but the direction of the effects should be maintained for changes of different magnitudes. It is also possible that changes to other aspects of the model such as the maximum velocity of shortening of the torque generator could bring about similar changes to the F-v relationship, however strength training interventions have been shown to result in slowing of the contractile properties of the muscle-tendon unit, with strength increases attributed predominantly to improvements in neural drive, alongside increases in muscle volume (Balshaw et al., 2016).

CONCLUSION: The results of this study provide potential mechanisms by which the gradient of F-v relationships can be altered to address perceived strength imbalances; athletes aiming to address a force-deficit could train to increase maximum isometric force, and athletes aiming to address a velocity-deficit could train to increase rate of force development.

REFERENCES:

Allen, S.J., King, M.A., Yeadon, M.R. (2010). Is a single or double arm technique more advantageous in triple jumping? *J. Biomech.,* 43, 3156-3161.

Balshaw, T.G., Massey, G.J., Maden-Wilkinson, T.M., Tillin, N.A., & Folland, J.P. (2016) Training-specific functional, neural, and hypertrophic adaptations to explosive- vs. sustained-contraction strength training. *J. Appl. Physiol.*, 120, 1364-1373.

Bemben, M.G., Clasey, J.L.,& Massey B.H. (1990). The effect of the rate of muscle contraction on the force–time curve parameters of male and female subjects. *Res. Quart. Exercise Sport*, 61, 96-99.

Hill, A.V. (1938) The Heat of Shortening and the Dynamic Constants of Muscle. *Proc. Royal Soc. B.*, 126, 136-195.

Jaric, S. (2015). Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks. *Int. J. Sports Med.*, 36(9), 699-704.

Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J-B. (2017) Effectiveness of an Individualized Training Based on Force-Velocity Profiling during Jumping. *Front. Physiol.*, 7, 677.

Samozino, P., Morin, J.-B., Hintzy, F., & Belli, A. (2008). A simple method for measuring force, velocity and power output during squat jump. *J. Biomech.*, 41, 2940-2945.

Samozino, P., Rejc, E., Di Prampero, P.E., Belli, A., & Morin, JB. (2012) Optimal force velocity profile in ballistic movements – altius: citius or fortius? *Med. Sci. Sports Exerc.,* 44, 313-322.