THE INFLUENCE OF STATURE ON HUMAN VERTICAL JUMPING PERFORMANCE

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Humans become relatively weaker as they increase in size. Despite this, simulations have shown that increased size is of benefit in vertical jumping when isometric scaling is employed, due to beneficial effects on the shortening velocity of muscles. Human body mass scales allometrically with the square of stature and it is shown that, assuming constant body composition, strength scales as a function of stature and independently of width and depth. A four-segment planar torque-driven computer model was used to simulate squat jump performance. Body dimensions were scaled allometrically to stature ±3 standard deviations from the mean stature of a young European male (178.8 cm ± 7.22 cm). An increase in stature of 43.4 cm led to a 5.8 cm improvement in flight height, but a reduction in the relative peak power and average vertical acceleration of the mass centre. Increased stature may therefore be of benefit in developing high centre of mass velocities, but a disadvantage in acceleration.

KEY WORDS: simulation, scaling, strength, isometric, allometric

INTRODUCTION: Human strength, as determined from elite weightlifting and powerlifting performances across weight classes, has been shown to increase with body mass (m) to the power of two thirds ($m^{2/3}$), therefore people become relatively weaker as they get larger (Challis, 1999). Despite this, computer simulations have shown that large reductions in body size are a disadvantage in vertical jumping if the body is scaled isometrically (Bobbert, 2013). With decreased size, body segment lengths reduced and the angular velocities necessary to achieve a given linear centre of mass velocity were higher, increasing muscle contraction velocities and decreasing the force they could develop (Bobbert, 2013). This theoretical disadvantage is overcome to an extent by physiological and morphological changes which allow smaller animals to achieve similar jump heights to larger ones (Bobbert, 2013).
It is unknown whether humans exhibit similar adaptations across the much smaller ranges of body sizes they display. However, there is some evidence that joint torque-angular velocity relationships may be independent of body size (Folland et al., 2008). In this case taller people may have an advantage in bodyweight activities requiring high linear velocities of segment endpoints, or the whole-body centre of mass. Previous studies have not found an effect of stature on vertical jump performance (Davis et al., 2003; Aslan et al., 2011), but there is some evidence that increased stature is of benefit in other sports; the world's fastest male sprinters and swimmers have become taller and heavier, but also more slender, as world records have improved over the last 100 years (Charles and Bejan, 2009).
As stature (s) increases, muscle force increases with the body cross section which is proportional to s^2, but body mass (m) increases with s^3, hence strength scales with $m^{2/3}$. However, in humans m does not scale isometrically with s^3, rather it scales allometrically according to the Quetelet index with s^2, therefore taller people are typically more slender (Heymsfield et al., 2007).
The aim of this study was to develop a method of scaling strength allometrically as a function of stature and to use this to investigate the effects of altering stature on various squat jump performance metrics using a computer model. The vertical jump is an extremely common test of lower limb coordination, strength, and power (Petrigna et al., 2019) and therefore a suitable activity with which to assess the relationship between body size and athletic performance. With increasing stature, it is expected that the negative effects of lower relative strength leading to lower joint torques immediately after movemement initiation, and the beneficial effect of

lower angular velocities on joint torques later in the movement, will interact to influence jump height. It is hypothesised that increased stature will lead to: 1) higher jump heights; but 2) lower mean vertical accelerations.

METHODS: A four-segment rigid body planar computer model was constructed in Simscape Multibody (R2023a, Mathworks, MA, USA) to simulate a vertical squat jump (Figure 1). The four segments, representing the feet, shanks, thighs, and head-arms-and-trunk (HAT), were modelled as rigid rods, pin-linked at the ankle, knee, and hip joints. The model was actuated by torque generators representing the combined effect of the extensor muscles acting around the ankle, knee, and hip joints. Joint torque was the product of activation level, torque–angle, and torque-angular velocity functions (Allen et al., 2010). Strength and inertia 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). The foot-ground interface was modelled using contact spheres situated at the toe and heel. Simulations began static in a squat position and ended when the vertical ground reaction force (GRF) decayed to zero. The model was scaled to s, representing the mean stature of a young European male (178.8 cm ± 7.22 cm) (Jelenkovic, 2016) ±3 standard deviations. Body slenderness (S) was calculated according to the methods of Charles and Bejan, (2009) by modelling the body as a cylinder and calculating the ratio between its height and width, therefore a larger value indicates the body is more slender. It has been shown that proportions of human body tissues stay approximately constant across body sizes (Heymsfield et al., 2007). Based on this assumption, the relationship between m and strength can be shown to be independent of the scaling exponent (b) by which cross sectional area (c) increases with s. In this scenario, c and therefore muscle force (F), scales with s^b, m scales with $s \cdot s^b$, and acceleration should be proportional to the ratio of force and mass:

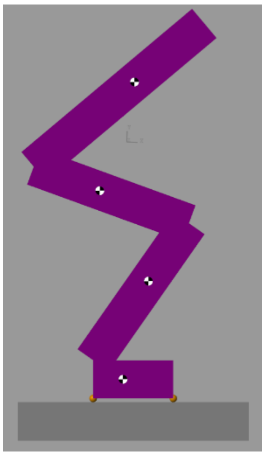

Figure 1: Four segment model.

$$\frac{F}{m} \propto \frac{s^b}{s \cdot s^b} \propto \frac{1}{s} \qquad (1)$$

Furthermore, it can be shown that the same principle applies for the relationship between joint torque (T) and moment of inertia (I). T is proportional to F multiplied by a muscle moment arm. Muscle moment arms would be expected to scale with s, therefore T is proportional to $s \cdot s^b$ or m. I is proportional to $m \cdot s^2$ or $s^3 \cdot s^b$, and and therefore angular acceleration should be proportional to the ratio of torque and moment of inertia:

$$\frac{T}{I} \propto \frac{s \cdot s^b}{s^3 \cdot s^b} \propto \frac{1}{s^2} \qquad (2)$$

Equations 1 and 2 demonstrate that relative strength decreases as a function of increasing stature, but independently of width and depth. Therefore, when altering s it was assumed that m scaled with s^2, lengths (l) and cross-sectional areas scaled with s, T with m and therefore also s^2, and I with $m \cdot s^2$ and therefore s^4. It was further assumed that, since all l scaled with s, a given angular displacement resulted in the same proportional linear displacement of the muscle-tendon units, and therefore torque-angle and torque-angular velocity relationships were unchanged by scaling. Initial torque generator activation levels were computed to ensure a static starting position. Torque generator activation parameters representing the ramp initiation and the time taken to move from the initial activation level to full activation were varied by a genetic algorithm to maximise the vertical displacement of the mass centre during flight (h_f). Other metrics reported are total height reached by the mass centre (h_{tot}), movement duration (t), mean vertical acceleration of the mass centre ($\bar{a}$), and peak external power relative to body mass (P_{max}). The latter was calculated by multiplying the vertical ground reaction force by the vertical mass centre velocity and dividing by body mass. Strictly, power cannot be resolved into directional components, however this scenario essentially represents a one-dimensional point mass model of the body and is often reported in studies of vertical jumping, since horizontal velocity is assumed to be negligible.

RESULTS: Table 1 shows the outcome of the scaling process and optimisations. With increased stature, body mass increased, but slenderness also increased. Jump performance improved with greater stature, with both flight height and total jump height increasing. Despite the improvement in jump performance, movement duration increased, and both average vertical acceleration and peak power decreased with increasing stature. Although absolute flight height and total jump height improved with increasing stature, they decreased as a proportion of stature.

Table 1
Jump performance metrics as a function of stature

	-3SDs	0	+3SDs
s (cm)	157.1	178.8	200.5
m (kg)	54.1	70.1	88.1
S (−)	7.50	8.00	8.48
h_f (cm)	55.0	57.7	60.8
h_{tot} (cm)	150.0	165.2	180.2
t (s)	0.277	0.299	0.343
$\bar{a}$ (m.s^{-2})	11.86	11.25	10.07
P_{max} (W/kg)	79.8	77.7	75.4

DISCUSSION: The aim of this study was to develop a method of scaling strength allometrically as a function of stature and to use this to investigate the influence of stature on squat jump performance. It was shown in Equations 1 and 2 that, assuming constant proportions of body tissues, strength relative to body mass and inertia would be expected to scale as a function of stature, and independently of width or depth. In this study, where body mass scaled with the square of stature according to the Quetelet index, strength would be expected to increase with $m^{1/2}$ rather than $m^{2/3}$ as has been observed in elite weightlifters and powerlifters (Challis, 1999). However, it is likely that body mass does not scale with the square of stature in these populations, since taller and more slender athletes would be at a disadvantage. It is unknown how strength scales with body size across the general population.

As hypothesised, an increase in stature of 43.4 cm led to a 5.8 cm improvement in flight height, but a reduction in the relative peak power and average vertical acceleration of the mass centre. These results highlight the potentially substantial effect of stature on human jumping performance across a range representative of the vast majority (±3SDs ≈ 99.73%) of the European young adult male population. Although previous studies have found no effect of stature on vertical jump height, this may have been masked by larger inter-individual variation in other factors which govern performance such as body fat percentage and muscle size (Davis et al., 2003). For instance, Aslan et al., (2011) compared the mean jump performance of two groups split by stature, the stature difference between groups was 9 cm and the taller group jumped ~2 cm higher. This is more than the expected difference observed in the current study for this range in stature, however, large group variances in jump height meant that this difference did not reach the requisite alpha level in statistical tests.

The mechanisms underpinning improvements in jump performance with increased stature - that longer body segments offer an advantage when developing high centre of mass or segment endpoint velocities due to the associated reduction in muscle contraction velocities - have implications for many sporting activities. For instance, they are consistent with observations that the world's fastest sprinters and swimmers have become taller, heavier, and more slender over time, alongside improvements in world records (Charles and Bejan, 2009). The shorter movement duration and increased average vertical acceleration and peak power

with smaller stature are also consistent with observations that sprint runners competing over shorter distances requiring high initial accelerations are shorter than those competing over longer sprints where acceleration is less influential (Weyand and Davis, 2005). It should be noted that average vertical acceleration and peak power were not included in the objective function, so it is conceivable that the magnitude of these differences could alter if they were explicitly optimised for, but it seems likely that the direction would be maintained.
Due to the allometric scaling of body proportions in this study, slenderness increased with increased stature (Table 1), but it was shown that relative strength was independent of width or depth, so there was no performance benefit to being more or less slender. Hence, it is possible that the observed increase in slenderness seen in elite sprinters and swimmers is just a byproduct of the beneficial increase in stature. However, the model used in this study was very simple and lacks potentially influential components such as fluid dynamics (Charles and Bejan, 2009). The possibility of slenderness altering independently of stature due to changes in relative body composition was also not considered, which would have other implications for performance outside the scope of this investigation. The model was not formally evaluated, but the parameters which governed the size and strength of the model were used in a successfully evaluated model of triple jumping (Allen et al., 2010) and the jump heights achieved by the model were similar to those observed in the literature (Davis et al., 2003). Any modelling assumptions were common to all models, so should have similar effects in each condition and should not affect the conclusions.

CONCLUSION: The results of this study represent the first quantitative information on the potential implications of stature for human vertical jump performance. Assuming a constant body composition it was shown that relative strength changed as a function of stature, and not width or depth. Increased stature resulted in an increase in jump height but a decrease in average acceleration and relative peak power. The beneficial effect of increased stature on the development of centre of mass velocity may partly explain why elite sprinters and swimmers have become taller as world records have improved over time. Future work should investigate the effect of altering stature directly in simulations of sprinting and swimming.

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