EFFECT OF MUSCLE STRENGTH ON LONG JUMP PERFORMANCE

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Long jump performance is, among other factors, highly dependent on the athlete's ability to generate sufficient vertical velocity during take-off. For a certain time on the take-off board the impulse-momentum relationship states that vertical velocity is directly proportional to the vertical force applied to the body centre of mass and inversely proportional to the athlete's body mass. An increase in an athlete's strength is assumed to be followed by an increase in body mass. This study investigated how strength gains coupled with the corresponding body mass gains influenced jump length. The results showed that after an initial increase in jump length further increases in strength and body mass did not affect performance.

KEYWORDS: strength, long jump, computer simulation.

INTRODUCTION: Athletes engaged in power-based activities such as long jump often complement activity specific training with strength training. While the objective is increased strength, this will often be accompanied by increased body mass. There is general agreement in the literature that approach velocity is the single most important determinant for success in long jump (e.g. Hay, 1993). However, increasing the approach velocity decreases the time on the take-off board (t); for an athlete with a certain body mass (m), capable of exerting a certain vertical force (F) during take-off, the vertical take-off velocity (v) will be determined by the impulse-momentum relationship

$$F \cdot t = m \cdot v \qquad (1)$$

Thus, while increased approach velocity increases the horizontal take-off velocity, which is beneficial for performance, the effect of decreased take-off time will be decreased vertical take-off velocity and hence take-off angle, which is detrimental to performance, as demonstrated by Ssrensen et al. (1999a). Aside from the influence of increased strength on approach velocity, it might have a beneficial effect during the actual take-off. However, as increases in muscular strength, above what can be attained due to neural adaptation, must be assumed to require increased muscle mass, the application of (1) becomes complex. We speculate whether a jumper can get 'strong enough', i.e. if there is a limit above which further increases in strength followed by the inevitable corresponding body mass gains, performance will cease to improve. A deeper understanding of these relationships might assist in deciding where athletes should focus their training.
The purpose of this study was to utilise a computer simulation model to investigate the relationship between strength, body mass and jump length and specifically to test the hypothesised existence of an upper strength limit.

METHOD: We developed a two-dimensional, sagittal plane, musculo-skeletal model with six rigid segments: trunk, thighs, shanks and right foot. Frictionless hinge joints connected the segments. Eight major muscles/muscle groups were included in the model: tibialis anterior, soleus, gastrocnemius, vasti, rectus femoris, hamstrings, iliopsoas and glutei. Each muscle group was represented by a three-component Hill model from van Soest and Bobbert (1993), and mathematically formulated as an ordinary differential equation (ODE). Muscle activation dynamics was modelled as an additional ODE according to He et al. (1991). The model was bang-bang stimulation driven with turn-on and turn-off time for each muscle group as control parameters. Each simulation spanned the entire stance phase. The model was implemented on an Octane R10000 workstation (Silicon Graphics Inc.) using the DADS multi-body simulation software (version 8.5, CADSI, Coralville, IA), with modules added for muscle modelling.

Optimisation of the control parameters was conducted by iterative simulations according to an algorithm from Bremermann (1970), implemented in Matlab (MathWorks Inc., Natick, MA). Cost function for the optimisation was jump length calculated from kinematic take-off parameters. Initial kinematic data were obtained from high-speed film of an international level long jumper. Segment lengths and inertial parameters were obtained from Winter (1990) using height and body mass from this same long jumper. Vertical and horizontal ground reaction forces were implemented as a spring-damper element and dry frictional force, respectively. Development and validation of the model are extensively described in Sørensen et al. (1999b).

To investigate the relationship between muscle strength and jump length we took the model through a series of optimised jumps with strength for all 8 muscles systematically varied between baseline values (0% strength increase) and 60% strength increase. Assuming constant specific tension and cylindrical muscles a certain strength increase implies a physiological cross sectional area increase and hence volume and mass increase of similar relative magnitude. Thus, the relationship between body mass (m_{body}) and strength was calculated as

$$m_{body} = s * m_{muscle} + m_{n.m.} \qquad (2)$$

with s taking values of 1.00, 1.05, ... 1.60 and the constant non-muscle mass $m_{n.m.}$ being 50% of initial body mass.

RESULTS: With baseline values (0% strength, increase, 0% body mass increase) the model jumped approximately 6.66 m (Figure 1). When strength was increased by up to 20% accompanied by a corresponding body mass increase up to 10%, jump length increased almost linearly to approximately 6.73 m. This was accomplished by an increased take-off angle, as resultant velocity remained nearly constant. The components of the increased take-off angle were increased vertical and decreased horizontal velocity.

Further increases in strength and body mass above 20% and 10%, respectively, did not result in improved jump length. The ratio between horizontal velocity increase and vertical velocity decrease resulted in decreased take-off angle, which counteracted the otherwise beneficial increase in resultant velocity.

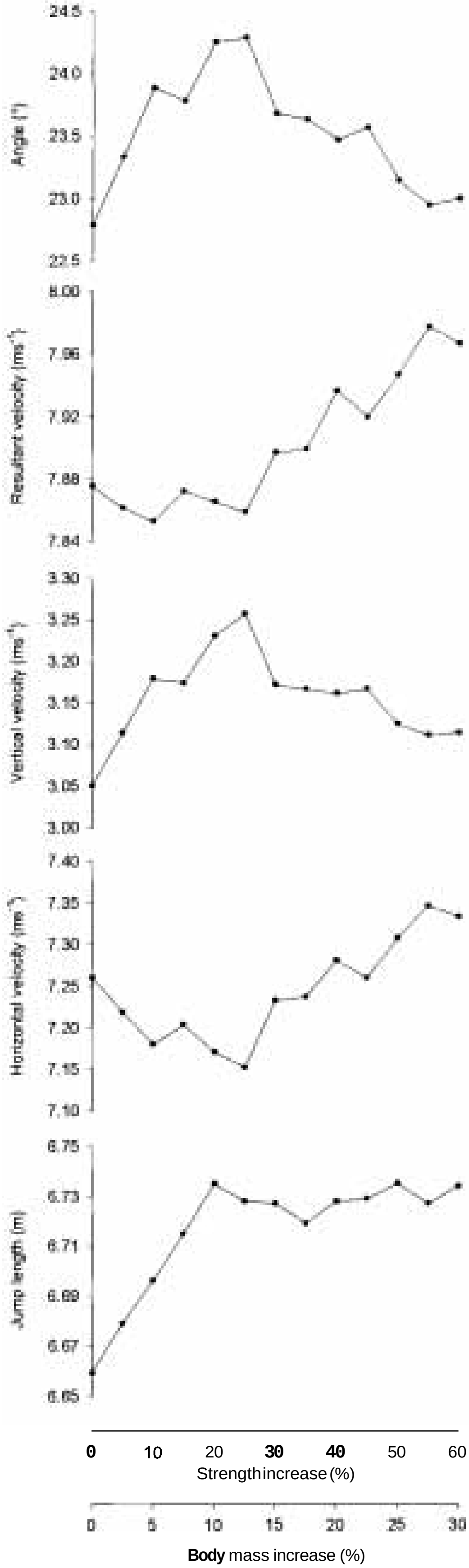

Figure 1 - Jump length and kinematic take-off parameters vs. relative strength and body mass increase.

DISCUSSION: The results showed that a strength increase up to 20% above baseline values allowed the model to generate more vertical velocity during take-off. Despite a simultaneous decrease in horizontal take-off velocity, resulting in nearly constant resultant velocity, the take-off angle increased sufficiently to increase jump length from approximately 6.66 m to 6.73 m. Strength increases above 20% was apparently counteracted by the concurrent body mass increase; vertical velocity started to decrease again, so despite increases in horizontal and resultant velocities, take-off angle decreased and jump length remained nearly constant at approximately 6.73 m. This renders our hypothesis about the existence of an upper strength limit probable. For our model the optimum strength-body mass relationship was obtained when the baseline muscle mass (=50% body mass) was increased 20%, i.e. when muscle mass made up approximately 55% body mass. We will discuss the relevance of this value later.

The major advantage of using computer simulation for this type of study is its exploratory nature – the ability to answer 'what-if question like 'what happens if the athlete increases his strength?' (Vaughan, 1984). While such questions can be addressed via longitudinal intervention studies, the total control over input parameters as offered by a computer simulation model can never be obtained. This said, however, the limitations of computer models should be kept in mind, most importantly that simulation experiments only tell the truth about the model that was used (van den Bogert and Nigg, 1999). Confidence in a model is acquired through proper validation, but the basic dilemma, as pointed out by Panjabi (1979), is that a model can only be validated in a number of 'known situations', yet its purpose is to predict behaviour in 'unknown situations'. The model used in this study, with baseline values for strength and body mass, was validated by its ability to reproduce muscle stimulation patterns, ground reaction force profiles and kinematics from the literature and from the athlete providing data for the model (Sørensen et al., 1999b). When we changed the model's strength and body mass in this study, we essentially used it in unvalidated and unknown situations. However, the above mentioned validation parameters stayed within literature values, so we still had confidence in the model's ability to perform realistic long jumps.

Another limitation of this study was the disregard of the influence of strength on approach velocity. It can be argued that sprinters mainly benefit from extreme strength during the start, while the influence on maximal running speed is less obvious. As long jumpers are free to choose their approach so maximal speed is reached at take-off, the strength-approach velocity relationship might be of less importance in long jump. Nevertheless, conclusions drawn from this study only apply to the influence of strength on the jumper's actions on the take-off board.

The model's baseline value for relative muscle mass was somewhat arbitrarily set to 50%. Values from the literature range between approximately 40% for normal, untrained individuals and 60% for individuals with extreme muscularity (e.g. Schibye and Klausen, 1992). Long jumpers are generally considerably more muscular than untrained individuals, however, not to the extreme of, say, competitive bodybuilders, so an in-between value of 50% was considered realistic. This arbitrarily chosen baseline value had a direct influence on the 55% relative muscle mass value, which we found optimal for our model. Hence, in addition to the other limitations of computer models, this requires the upper strength limit demonstrated in this study to be considered only phenomenological. Still, our finding rejects the perhaps naïve assumption that because strength gains are accompanied by relatively smaller body mass gains, performance gains from increased strength are essentially limitless. While our inability to make generalisations with respect to the relative muscle mass value from model to humans detracts from the immediate usefulness for coaches/athletes, we still consider the demonstrated influence of strength and body mass on take-off kinematics and subsequent jump length valuable knowledge. If, for instance, an athlete after a period of strength training resulting in increased strength and body mass, is not able to increase vertical take-off velocity and angle above pre-training values (Figure 1), is must be considered a possibility that he has reached (or passed) the optimum strength-body mass ratio.

CONCLUSION: This study investigated the relationship between strength, body mass and jump length with specific emphasis on the existence of an upper strength limit with respect to performance. The results showed that the model increased its performance until a relative muscle mass of approximately 55% body mass was obtained. Further increases in strength and body mass did not affect performance. Thus, we postulate the existence of an upper strength limit. Practical implications for coaches/athletes include better possibility to determine whether strength training will benefit a particular athlete.

REFERENCES:

Bremermann, H. (1970). A method of unconstrained global optimization. MathematicalBiosciences, 9, 1-15.

Hay, J.G. (1993). Citius, altius, longius (faster, higher, longer): the biomechanics of jumping for distance. Journal of Biomechanics, 26(Suppl. 1), 7-21.

He, J., Levine, W.S. & Loeb, G.E. (1991). Feedback Gains for Correcting Small Perturbations to Standing Posture. *IEEE* Transactions on automatic control, 36, 322-332.

Panjabi, M. (1979). Validation of mathematical models. Journal of Biomechanics, 12, 238.

van den Bogert, A.J. & Nigg, B.M. (1999). Biomechanics of the musculo-skeletal system. Chichester: John Wiley & Sons Ltd.

van Soest, A.J. & Bobbert, M.F. (1993). The contribution of muscle properties in the control of explosive movements. Biological Cybernetics, 69, 195-204.

Schibye, B. & Klausen, K. (1992). Menneskets *fysiologi* (pp. 104-105) [in Danish]. Copenhagen, FADL.

Ssrensen, H., Simonsen, E.B. & van den Bogert, A.J. (1999a). Influence of approach velocity on long jump performance. International Society of Biomechanics XVIIth Congress, August 8-13, Calgary, Canada (submitted).

Ssrensen, H., Simonsen, E.B. & van den Bogert, A.J. (1999b). A simulation model of the long jump take-off. VIIth International Symposium on Computer Simulation in Biomechanics, August 6-7, University of Calgary, Canada (submitted).

Winter, D.A. (1990). Biomechanics and motor control of human movement (pp. 52, 56-57). New York: John Wiley & Sons, Inc.

Vaughan, C.L. (1984). Computer simulation of human motion in sports biomechanics. Exercise and Sport Sciences Reviews, 12, 373-416.

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