DESIGN OF OPTIMAL STRATEGY FOR STRENGTHENING TRAINING IN VERTICAL JUMP: A SIMULATION STUDY

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Abstract: *The aim of this study was to investigate optimal muscle strengthening strategies in a vertical squat jump. In order to do that we used an optimization approach and a simulation technique. In the simulation, a neuro-musculo-skeletal model was used to generate a total number of 85 strengthening training trials. In each trial different muscle groups were strengthened gradually up to 20%. It was find here that strengthening of the monoarticular hip extensors jointly with either monorticular knee extensors, or with monoarticular ankle plantar flexors, was the most effective in increasing jump height. In addition it was also found that strengthening of monoarticular knee extensors together with hamstrings was also very advantageous, in comparison with other strengthening strategies. To conclude, optimization technique was successfully applied here to design optimal strategy for strengthening training in vertical jump. It seems that proposed in this study technique could be used further in sport to investigate optimal training strategies. Based on obtained here results, it is also conclude that strengthening of many groups of muscles is advantageous in jump training. This conclusion differs from the approach proposed in other literature, which states that the most effective way in jump training was by strengthening only one muscle group, this is monoarticular knee extensors solely.*

INTRODUCTION

One important topic in sport biomechanics is to increase a sport performance. In this study we investigate optimal muscle strengthening training in a vertical squat jump. We focus on the performance of vertical jump, as this movement is crucial in various sport disciplines like for an example: volleyball, basketball, soccer and others. For that reason it is important for trainers and for sportsmen to know how to effectively increase the jump performance.

One way to learn how to effectively train is by practicing (Zatsiorsky, 1995) and the other is to create a theoretical framework to first understand theoretical principles and then apply this knowledge in sport training (Bobbert and van Soest, 1994). This theoretical framework was used in this study.

Previous studies demonstrated that the most effective way to increase jump height is to increase muscle strength (Pandy et al., 1990). This can be done by a strength-training program,

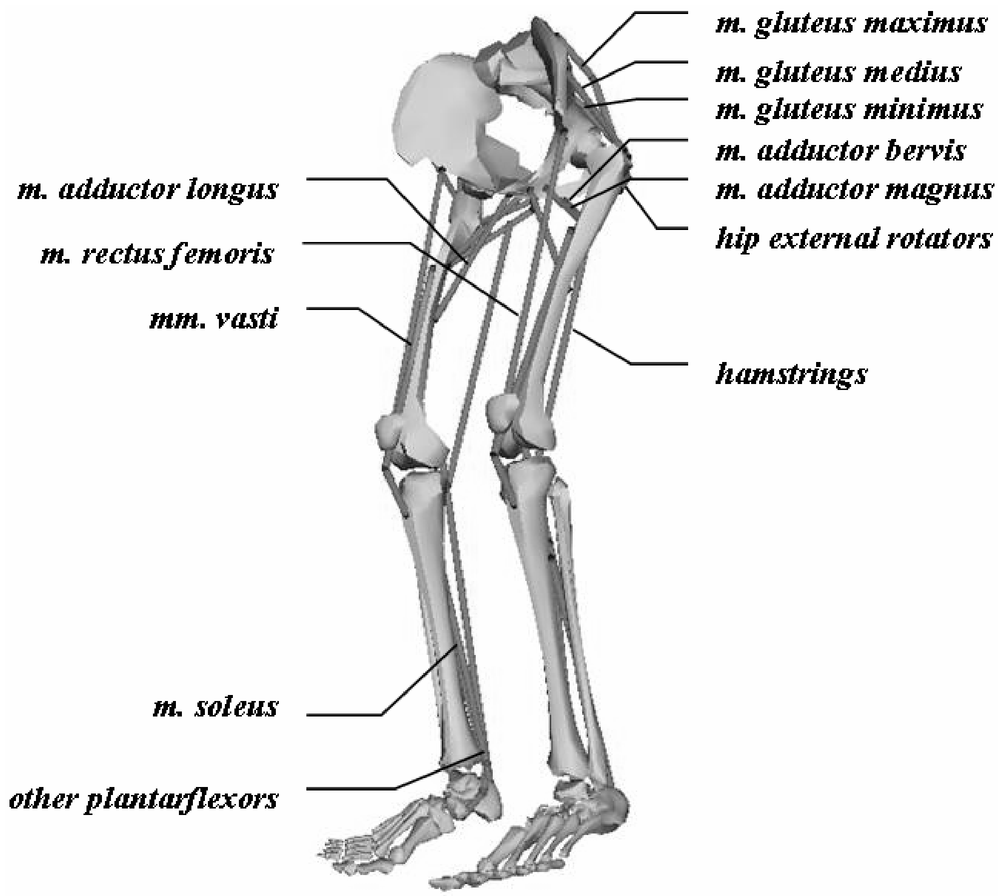

Figure 1: Neuro-musculo-skeletal model used in this study. Muscle paths were defined for 26 major muscle groups that are used in a squat jump. Since the model is bilaterally symmetric, the same muscle paths are used on the left and right sides of the body.

as a result of which, the physiological cross-sectional area of muscles increase. It was shown in preceding studies that the increase in jump performance depends to a large extent, on which group of muscles is strengthened (Prokopow, 2006). This is because different muscle groups play different roles in a performance of a motor task and therefore different is also the effect of strengthening of each group on jump performance. It was also previously demonstrated that the greatest effect on jump achievements was strengthening of knee extensors (Bobbert and van Soest, 1994).

The aim of this study was to investigate neuromuscular strengthening and which specific groups of muscles are the most effective in increasing jump performance after muscle strengthening. This knowledge is especially useful in design and carrying out jump training. Because it is difficult to precisely strengthen particular muscles in the human body we carried out experiments using a simulation technique in this study.

METHODS

In the present study a forward dynamics computer simulation and numerical optimization technique were used to simulate vertical squat jump (Nagano, 2001; Anderson, 1999). The model was three-dimensional and is presented on figure 1. It consisted of ten rigid body segments, this is: upper body, pelvis, right and left upper legs, right and left lower legs, right and left feet, and right and left toes. The model was free to make and break contact with the ground where the interaction between each contact point on a foot and the ground was modeled as a impulse equations reported in other literature (Anderson, 1999). At the initial time the body was assumed to be in a static squat position with the heels flat on the ground. Passive elastic joint moments were applied to each joint as a set of equation reported in other literature (Riener and Edrich, 1999). A total number of 26 Hill-type muscles drove the model (Hill, 1938). The parameters characterizing each modeled muscle were derived from other work (Delp et al., 1990). These were modeled as a contractile element and a series elastic element (Nagano, 2001). A set of first-order differential equations (Eqs. 1 & 2) described the delay between a muscle's activation and a muscle active state (Winters and Stark, 1988).

$$\dot{q} = \frac{u - q}{\tau(u, q)} \quad [1]$$

$$\tau(u, q) = \begin{cases} (\tau_{rise} - \tau_{decl}) \times u + \tau_{decl} & for\ u \geq q \\ \tau_{decl} & otherwise \end{cases} \quad [2]$$

In this equation above, $u \in [0, 1]$ is the neural excitation and the term $\tau(u, q)$ is a time constant. In this equation above, τ_{rise} and τ_{decl} are the activation and deactivation time constants respectively.

Each muscle activation pattern was specified by three variables: onset time, offset time, and magnitude of muscle activation. Optimal muscle activation pattern was found through semi-random numerical optimization wherein a maximum height reached by the body's center of gravity was used as an objective function. In the optimization process, onset and offset ranged between zero (simulation start time) and 0.5 s (simulation end time) and a magnitude of stimulation had a range zero (no excitation) to one (muscle fully excited), where virtually any value in that range could be chosen as a result of optimization process.

In order to examine the effect of muscle strengthening on increase in jump height, the maximal isometric forces of individual muscles were progressively increased by 5%, 10%, 15% and 20%. All individual muscles were strengthened one by one, then groups of muscles were strengthened and then all the muscles together were strengthened. After each strengthening trial, a new optimal muscle activation pattern was found by numerical re-optimization of the muscle activation pattern.

Investigated were 16 muscles: m. gluteus maximus, m. adductor magnus, hamstrings, m. rectus femoris, mm. vasti, m. gastrocnemius, m. soleus, and other plantarflexors. Remaining muscles, modeled in the muscluloskelatal system, were not investigated because they were found to be inactive in the simulation of squat jump.

RESULTS

In all simulation experiments the numerical optimization procedure generated a natural-looking and smooth squat jumping motion. Figure 2 presents a jump motion of the model with original muscle strength (this is before strengthening trials), in which jump height was 34.57 cm. It was observed in all strengthening trials that the muscles, which were strengthened, generated more force during push-off phase. In addition, the amount of knee extension, ankle plantarflexion, hip flexion and joint moments all changed.

The effect of strengthening of each muscle group (modeled in the neuro-musculo-skeletal system) is presented on figure 3. Jump height increased the most after strengthening of ankle monoarticular plantar flexors and knee monoarticuar extensors (1.63 cm and 1.45 cm respectively when muscles strength was increased by 20%). The sum of the jump height increased due to strengthening of individual muscles, which was virtually the same as an effect of strengthening of all muscles simultaneously (difference ≤2 mm). However this was not true when the whole group of muscles were strengthened. The sum increase in jump height resulting from a strengthening of individual muscles differed from the increase in jump height resulting from when a group of muscles were strengthened simultaneously. In the case of some muscles, jump height increased much more when the muscles were strengthened as a group. This was the case for strengthening of m. soleus and m. rectus femoris as well as mm. vasti and hamstrings when they were strengthened as a group. On the other hand, strengthening of some muscles (e.g. m. adductor magnus and hamstrings) as a group increased jump height less then the sum increase in jump height when muscles were strengthened individually.

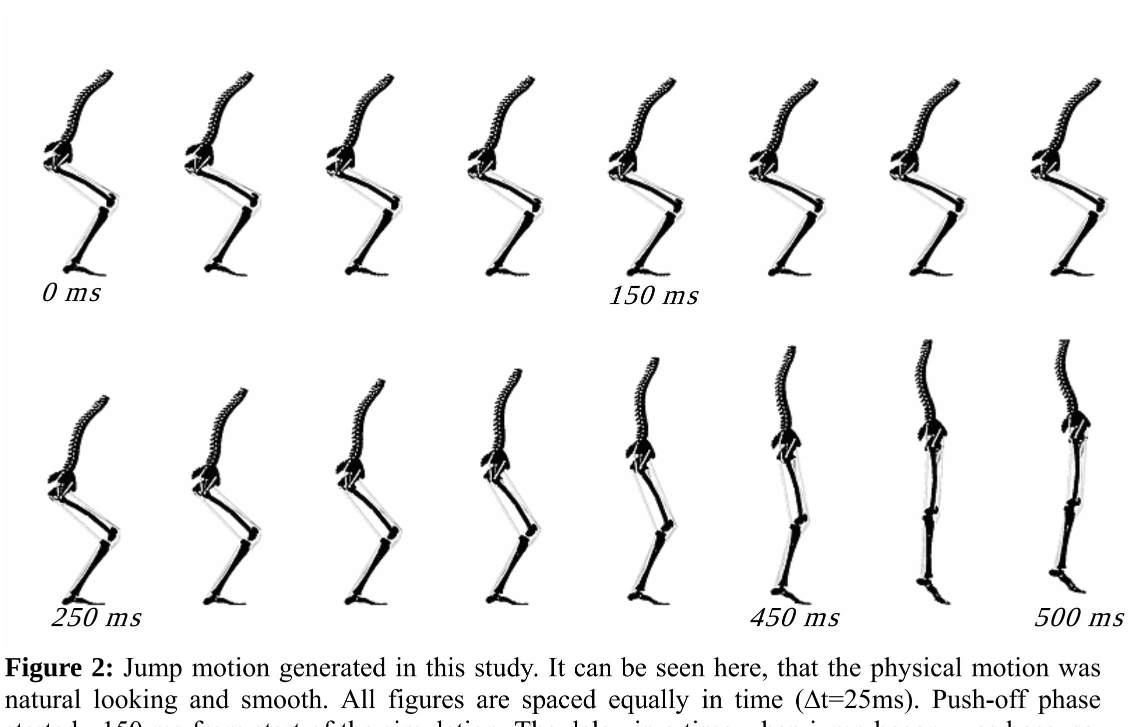

Figure 2: Jump motion generated in this study. It can be seen here, that the physical motion was natural looking and smooth. All figures are spaced equally in time (Δt=25ms). Push-off phase started ~150 ms from start of the simulation. The delay in a time when jump began, was because, muscles needed to develop initial forces. Therefore initial movement presented in the first figures only minimal changes in captured body movement were observed.

Jump height increased by the greatest amount after strengthening of monoarticular hip extensors jointly with monorticular knee extensors (increase by 2.93 cm when strengthened 20%), or ankle plantar flexors (increase by 2.6 cm). The increase in strength of monoarticular knee extensors jointly with hamstrings was also very effective in increasing jump performance (2.44 cm).

In some trials muscle strengthening was ineffective since strengthened muscle groups did not generate higher jump. In these cases the additional force produced by muscles did not contribute significantly to the increase in jump height because there was no mechanical solution in which the higher force produced by strengthened muscles could be effectively used to increase the vertical acceleration of the body's center of gravity (figure 4). This was observed when hip extensors with hamstrings were strengthened as group, or when m. rectus femoris and m. gastrocnemius were strengthened as a group. In these cases, the increase in jump height was small.

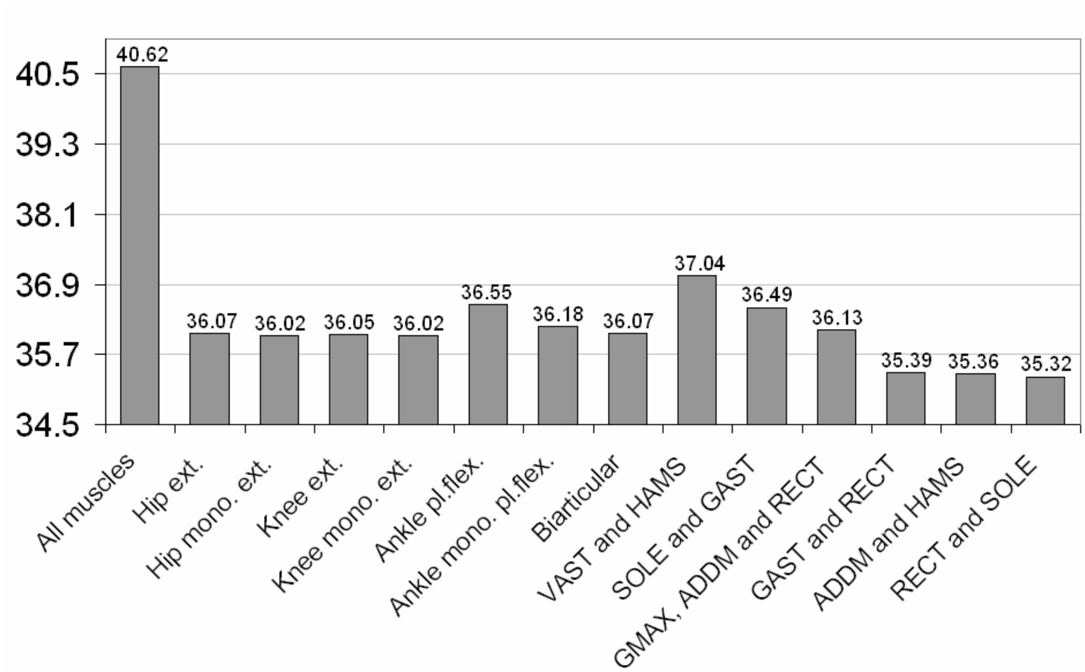

Figure 3: The effect of strengthening groups of muscles on jump height. Jump height before muscle strengthening was 34.57 cm. After strengthening of all muscles by 20% jump height was 40.62 cm. Jump height increased the most notable after strengthening of knee monoarticular extensors (mm. vasti) and ankle plantarflexors. Only 15 out of 85 trials are presented for the reason that those trials yield the most significant results (see the text). Abbreviations of muscle names used in the figure: VAST (mm. vasti), HAMS (hamstrings), SOLE (m. soleus), OPFL (other plantarflexors), GAST (m. gastrocnemius), ADDM (m. adductor magnus), GMAX (m. gluteus maximus), and RECT (m. rectus femoris).

DISCUSSION AND CONCLUSIONS

The present study was designed to investigate optimal strategies of muscle strengthening in a vertical jump. The results obtained demonstrated the greatest increase in jump performance could be obtained in two ways: (i) through a great increase in one muscle group (ii) through a moderate increase in groups of muscles.

In the case of strengthening only one group of muscles, then strengthening of ankle monoarticular plantar flexors or monoarticular knee extensors was the most effective.

On the other hand, moderate strengthening of many groups of muscles is more practical and is used in training [1]. While strengthening of these groups of muscles was not very effective in increasing jump performance when strengthened individually, it turned out, that the most effective way to increase jump performance is to strengthen more than one group of muscles at once. The most effective groups to strengthen were: i) the monoarticular hip extensors jointly with monorticular knee extensors, or ii) monoarticular hip extensors jointly with ankle plantar flexors, or iii) monoarticular knee extensors jointly with hamstrings.

Therefore, when each muscle group was strengthened individually the effect on jump height was small but when two or more muscle groups were strengthened jointly, the effect on jump height was significant. For example strengthening of biarticular muscles increased jump height significantly when they were jointly strengthened with the monoarticular muscle group.

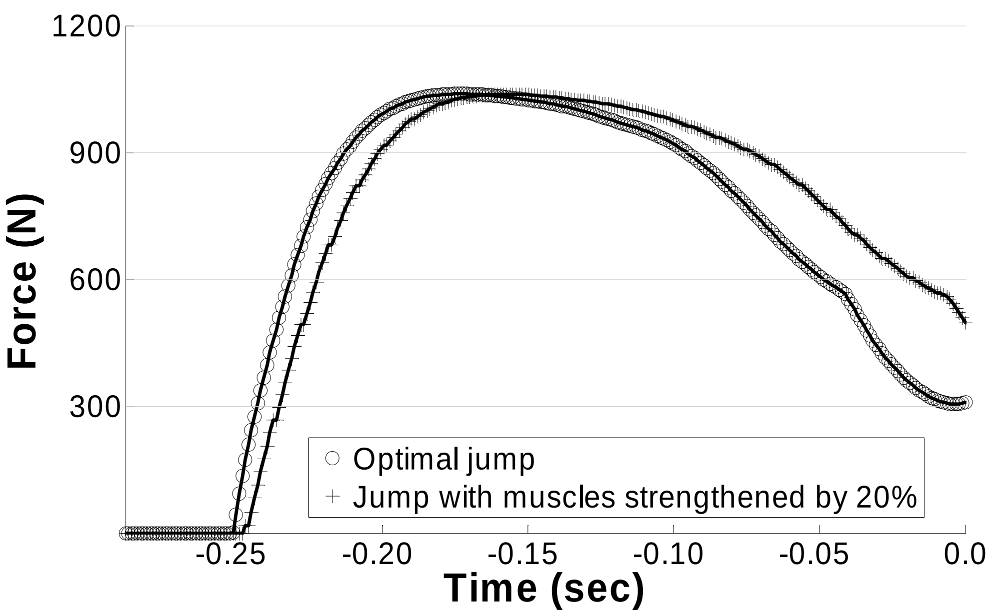

Figure 4: Force generated by m. adductor magnus in the jump where m. gastrocnemius was strengthening jointly with m. rectus femoris. Time is expressed relatively to take-off. Jump height increased slightly after strengthening of these two biarticular muscles jointly. Even force generated by strengthened muscles increased, force generated by m. adductor magnus and other monoarticular muscles declined in order to generate optimal jump. Consequently, strengthening jointly of these two biarticular muscles had a small effect on jump performance.

One important observation that can be made when analyzing the results in this study is that muscle strengthening is effective only if strengthening has two features that must both be present: (i) strengthened muscles must generate extra forces and (ii) these extra forces must be used effectively by musculoskeletal system to increase jump height.

It is evident in presented results that in some cases the greater force developed by strengthened muscles cannot be used effectively to increase jump performance. The reason for this is the mechanical limitation of the neuro-musculo-skeletal system. The greater force of strengthened muscle groups changes i) forces of other muscles and ii) jump mechanics, but there is no mechanical way, for this greater force to be used effectively through out all musculoskeletal system in order to significantly increase jump performance. Therefore strengthening some combinations of muscle groups is ineffective in increasing jump performance. That result was observed for example in the case of strengthening of monoarticular hip extensors and hamstrings.

To conclude, even jump performance can be increased by strengthening one monoarticular muscle group. Our results suggest that strengthening of two and more groups of muscles is more effective. Our results indicated that especially effective was the strengthening of i) the monoarticular hip extensors jointly with monorticular knee extensors, or ii) monoarticular hip extensors jointly with ankle plantar flexors, or iii) monoarticular knee extensors jointly with hamstrings.

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REFERENCES

Anderson, F.C., Pandy, M.G., 1999. A dynamic optimization solution for vertical jumping in three dimensions. Computer Methods in Biomechanics and Biomedical Engineering 2, 201 231.

Bobbert, M.F., van Soest, A.J., 1994. Effects of muscle strengthening on vertical jumps: a simulation study. Medical Science Sports Exercise 27, 1012-1020.

Bobbert, M.F., van Zandwijk J.P., 1999. Dynamics of force and muscle stimulation in human vertical jumping. Medical Science Sports Exercise 31(2), 303-310.

Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F.E., Topp, E.T., Rosen, J.M., 1990. An interactive graphicsbased model of the lower extremity to study orthopaedic surgical procedures. IEEE Transactions in Biomedical Engineering, 37, 757-767.

Fukashiro, S., Komi, P. V., 1987. Joint moment and mechanical power flow of the lower limb during vertical jump. International Journal of Sports Medicine 8 (Suppl. 1), 15-21.

Hill, A., V., 1938. he heat of shortening and the dynamic constants of muscle. Proceedings of the Royal Society of London Series B 126, 136-195.
Nagano, A., 2001. A computer simulation study on the potential locomotor patterns of Australopithecus afarensis (A.L. 288-1). Dissertation, Arizona State University, AZ, USA.
Nagano, A., Gerritsen, K.,G.,M., 2001. Effects of neuro-muscular strength training on vertical jumping performance - a computer simulation study. Journal of Applied Biomechanics 17, 27-42.
Pandy, M.G., Zajac, F.E., Sim, E., Levine, W.S., 1990. An optimal control model for maximum-height human jumping. Journal of Biomechanics 23, 1185-1198.
Prokopow, P., 2005a. A simulation study of optimal neuromuscular strengthening in vertical jump. In proceedings of the 2nd Second Asian Pacific Conference on Biomechanics, Taipei, Taiwan.
Prokopow, P., 2005b. The effects of muscle strengthening on neural control, muscle forces and motion mechanics in a squat jump In proceedings of the 3rd IASTED International Conference on Biomechanics. Benidorm, Spain.
Prokopow, P., 2006. The effects of muscle strengthening on neuro-musculo-skeletal dynamics in a squat jump: a simulation study. Journal of Biomechanics (in print).
Prokopow, P., Hay, D., Fukashiro, S., Himeno R., 2005. Quantitative evaluation of the importance of coordination on jump achivements and kinematics in human vertical squat jump. Japanese Journal of Biomechanics in Sports and Exercise 9 (2), 1-14.
Riener, R., Edrich, T., 1999. Identification of passive elastic joint moments in the lower extremities. Journal of Biomechanics 32, 539-544.
Winters, J.M., Stark. L., 1988. Estimated mechanical properties of synergistic muscles involved in movements of a variety of human joints. Journal of Biomechanics 21(12),1027-1041.
Zatsiorsky, V. M., 1995. Science and practice of strength training. Human Kinetics, Champaign, IL.