Effects of Neuromuscular Strength Training on Vertical Jumping Performance—A Computer Simulation Study

Akinori Nagano and Karin G.M. Gerritsen

The purpose of this study was twofold: (a) to systematically investigate the effect of altering specific neuromuscular parameters on maximum vertical jump height, and (b) to systematically investigate the effect of strengthening specific muscle groups on maximum vertical jump height. A two-dimensional musculoskeletal model which consisted of four rigid segments, three joints, and six Hill-type muscle models, representing the six major muscles and muscle groups in the lower extremity that contribute to jumping performance, was trained systematically. Maximum isometric muscle force, maximum muscle shortening velocity, and maximum muscle activation, which were manipulated to simulate the effects of strength training, all had substantial effects on jumping performance. Part of the increase in jumping performance could be explained solely by the interaction between the three neuromuscular parameters. It appeared that the most effective way to improve jumping performance was to train the knee extensors among all lower extremity muscles. For the model to fully benefit from any training effects of the neuromuscular system, it was necessary to continue to reoptimize the muscle coordination, in particular after the strength training sessions that focused on increasing maximum isometric muscle force.

Key Words: isometric force, contractile velocity, muscle coordination

Introduction

In several sports (e.g., volleyball), jumping ability is extremely important. Therefore, athletes make substantial efforts to improve their jumping performance. In principal there are two ways to accomplish this: (a) by altering the physical properties of the neuromuscular system, or (b) by optimizing the muscle coordination. Physical strength can be increased primarily by training specific neuromuscular strength characteristics, while muscle coordination can be improved primarily by practicing jumping movements (Bobbert & van Ingen Schenau, 1988).

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Many studies have investigated the effect of strength training on the physical properties of the neuromuscular system (e.g., McDonagh & Davies, 1984). Depending on the intensity and duration of the training program, joint torques can be increased by as much as 20 to 30% (Davies & Young, 1983; Komi, Viitasalo, Rauramaa, & Viikko, 1978). There is some evidence that the increase in muscle strength can be partly explained by an increase in the amount of muscle activation. Hakkinen and co-workers (Hakkinen, Newton, Gordon, et al., 1998; Hakkinen, Kallinen, Izquierdo, et al., 1998) reported that the amplitude of the integrated electromyographic activity (IEMG) of the mm. quadriceps femoris increased throughout a jumping training program.

Improvements in the physical properties of the neuromuscular system and in muscle coordination (i.e., activation amplitude and timing) will increase jumping performance. However, it is difficult to quantify how much each neuromuscular parameter (e.g., maximum isometric muscle force, maximum shortening velocity, and maximum muscle activation) contributes to increasing jumping performance. Typically, several neuromuscular parameters change simultaneously throughout a training program (Komi, 1986; Moritani & De Vries, 1979). Therefore, it is difficult if not impossible to isolate the effect of a single neuromuscular parameter on jumping performance in an experimental setting.

Human vertical jumping has also been studied intensively using forward dynamics simulation models (Anderson & Pandy, 1993; Bobbert, Gerritsen, Litjens, & van Soest, 1996; Bobbert & van Soest, 1994; Pandy & Zajac, 1991; Pandy, Zajac, Sim, & Levine, 1990; Selbie & Caldwell, 1996; Zajac, Wicke, & Levine, 1984). The advantage of this approach is that each parameter is under precise control and can be varied systematically. For example, Zajac et al. (1984) investigated the effect of selected muscle properties on jumping performance and found that the compliance of the musculo-tendon complex and the shape of the force-velocity curve of contractile elements had the largest effects.

This study offers important insights into the understanding of jumping mechanics. However, as the model had only one joint (the ankle), the mechanics of this system are likely to differ from a normal jumping movement. A multijoint, multi-muscle forward dynamics simulation model of vertical jumping (Bobbert & van Soest, 1994) was used to investigate the effect of strengthening lower extremity muscles on vertical jumping performance. As expected, increasing maximum isometric force of all lower extremity muscles increased vertical jumping performance, but only after the timing of the muscle activation patterns had been re-optimized. When the optimal muscle activation patterns for the original neuromuscular system (i.e., before strengthening) were used, the jumping movement became disrupted, resulting in jumping performance that was actually less than the optimally coordinated jump with the original (i.e., weaker) muscles. In this study the effect of strength training was represented solely by an increase in maximum isometric force production.

In addition to maximum isometric muscle force ($F_{max}$), parameters such as those describing the force-velocity relation, in particular maximum shortening velocity ($V_{max}$), can be modified as well during training and may also have an important effect on jumping performance (Zajac et al., 1984). In addition, based on Hakkinen et al. (Hakkinen, Kallinen, et al., 1998; Hakkinen, Newton, et al., 1998), the amplitude of the muscle activation patterns ($ACT_{max}$) may also have an important effect on jumping performance. The other question that arises is which muscle groups have the largest effect on jumping performance.

Therefore, the purpose of this study was to quantify the effect of strength training on maximum vertical jump height in a forward dynamics model by (a) altering specific neuromuscular parameters ($F_{max}$, $V_{max}$, and $ACT_{max}$), and (b) training specific muscle groups (hip extensors, knee extensors, and ankle plantarflexors).
Methods

The two-dimensional skeletal model used in this study consisted of four rigid segments: head/arms/trunk, thighs, lower legs, and feet (Figure 1). These segments were connected to each other by three revolute joints representing hips, knees, and ankles. The interaction between the feet segment and the floor was modeled using two viscoelastic elements (Gerritsen, van den Bogert, Hulliger, & Zernicke, 1995) (Appendix of present paper): one at the heels/floor contact point and one at the toes/floor contact point. Note that with such a ground reaction force model, the feet segment can leave the floor after pushing off.

The skeletal model was actuated by six Hill-type muscle models (Appendix) representing the six major muscles and muscle groups in the human lower extremity that contribute to jumping performance (Figure 1). Each muscle consisted of a contractile element (CE) representing all the muscle fibers, and a series elastic element (SEE) representing all the elastic components in series with the contractile element. CE activation dynamics, CE force-length, CE force-velocity, and SEE force-length relations were modeled with nonlinear functions (Cole, van den Bogert, Herzog, & Gerritsen, 1996; van Soest & Bobbert, 1993). An ODE was used to describe the delay between a muscle’s activation input and its active state (He, Levine, & Loeb, 1991).

![Musculoskeletal Model](image_url)

Figure 1 — The musculoskeletal model consisted of 4 segments: head/arms/trunk, thighs, lower legs, and feet; 3 joints: hips, knees, and ankles; and 6 lower extremity muscle groups: m. soleus, m. gastrocnemius, mm. vasti, m. rectus femoris, mm. glutei, and hamstrings. Parallel elasticity was represented by passive moments (M\text{pass}) about each joint as described in Gerritsen et al. (1998).
This forward dynamics model was implemented using DADS 9.01 (LMS CADSI, Coralville, IA) linked together with Fortran code describing the muscle activation and contraction dynamics, and the musculoskeletal interaction (Gerritsen et al., 1998; Nagano, Fukashiro, & Gerritsen, 2000). Anthropometric properties of the skeleton (derived from Clauser, McConville, & Young, 1969) and musculoskeletal parameters were also taken from Gerritsen et al. (1998) (Appendix). All simulations were started from a stationary squat position and were executed on an SGI workstation (Octane, Silicon Graphics Inc., Mountain View, CA). The only inputs to the entire model were activation patterns for each of the six muscles.

Optimizations were executed with a modified version (J.M. Winters, Catholic University of America, personal communication: new search directions are not purely random but partially dependent on previous successful ones) of the algorithm of Bremermann (1970) implemented in MatLab (The MathWorks Inc., Natick, MA) (Figure 2). The objective of the optimization was to find the muscle activation patterns that yield the highest jump possible, with jump height (JH) defined as the maximum height reached by the body’s center of mass (MCB) above the floor.

Each muscle activation pattern was specified by three parameters: onset time ($T_{on}$), offset time ($T_{off}$), and amplitude ($ACT$) (Figure 2). At the start of each simulation, the mono-articular muscles were activated such that the skeleton maintained the squat position. The resolution of $T_{on}$ and $T_{off}$ was set to 0.001 s, the resolution of $ACT$ was set to 0.001 (1.0 = maximum activation), and the resolution of JH was set to 0.0001 m. The optimization process was terminated when JH did not increase for 500

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**Figure 2 — Optimization of muscle activation patterns.** Parameters to specify the neuromuscular characteristics were modified to simulate training effects ($\Delta F_{max}$, $\Delta V_{max}$, and $\Delta ACT_{max}$). After each modification the muscle activation patterns were re-optimized to maximize the vertical height reached by the body’s center of mass. Onset time ($T_{on}$), offset time ($T_{off}$), and amplitude of activation ($ACT$, where $ACT \leq ACT_{max}$) were modified through optimization.
consecutive iterations (±3500 function evaluations). Initial guesses for $T_{\text{on}}$ and $T_{\text{off}}$ were derived from the EMG data presented in Jacobs, Bobbert, and van Ingen Schenau (1996). In order to help ascertain that the optimization process did result in a global optimum, after the optimization was finished, the solution was used as the initial guess for a subsequent optimization, which was terminated when JH did not increase for another 100 consecutive iterations (±700 function evaluations).

The effects of strength training were simulated by systematically varying three neuromuscular parameters: (a) muscle strength, represented by varying the maximum isometric muscle force ($\Delta F_{\text{max}}$); (b) muscle speed, represented by varying the maximum shortening velocity ($\Delta V_{\text{max}}$); and (c) motor unit recruitment, represented by varying the maximum value of ACT ($\Delta \text{ACT}_{\text{max}}$). After each parameter modification, the muscle activation patterns were re-optimized as described previously.

Komi et al. (1978) reported a 20% increase in knee extension moments produced during maximum voluntary contraction (MVC) after 48 days of isometric strength training. Davies and Young (1983) also investigated the effect of isometric training and reported a 30% increase of mm. triceps surae MVC after 30 days of training. Narichi, Hoppeler, Kayser, et al. (1996) reported that 6 months of weight training of mm. quadriceps femoris resulted in a 21.1 to 29.6% increase of MVC. Muscle physiological cross-sectional areas can increase by as much as 33% as a result of training (Kawakami, Abe, Kuno, & Fukunaga, 1995). Similar numbers can be found in a review by McDonagh and Davies (1984). Based on these studies, a 20% increase in maximum isometric muscle force ($\Delta F_{\text{max}}$) was selected as the maximum effect of strength training to be considered. Intermediate increments (+4 to +16%) and a decrement (−4%) in $F_{\text{max}}$ were also simulated (Table 1).

Although there are discussions concerning the effect of strength training on muscle fiber type distribution (Lieber, 1992), it is well recognized that the shape of the force-velocity relationship can be modified during appropriate training sessions. Caiozzo, Perrine, and Edgerton (1981) showed that when isokinetic training was performed at relatively high speed (4.19 rad/s), the shape of the force-velocity curve was modified, demonstrating relatively higher force outputs at high velocities. Duchateau and Hainaut (1984) reported a 21% increase in maximum shortening velocity after 3 months of dynamic strength training. Toji, Suei, and Kaneko (1997) reported an increase in maximum shortening velocity of about 20% after 11 weeks of strength training.

Table 1 Parameters Before and After Training

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before</th>
<th>Intermediate</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{max}}$</td>
<td>96%</td>
<td>100%</td>
<td>104%</td>
</tr>
<tr>
<td>$V_{\text{max}}$</td>
<td>96%</td>
<td>100%</td>
<td>104%</td>
</tr>
<tr>
<td>$\text{ACT}_{\text{max}}$</td>
<td>88%</td>
<td>90%</td>
<td>92%</td>
</tr>
</tbody>
</table>

Note: $F_{\text{max}}$, $V_{\text{max}}$, and $\text{ACT}_{\text{max}}$ were modified to simulate the effects of training. The trainability of the individual parameters was derived from preceding studies.
Based on these studies, a 20% increase in maximum shortening velocity ($\Delta V_{\text{max}}$) was selected as the maximum effect of dynamic strength training. Intermediate increments (+4 to +16%) and a decrement (–4%) were also simulated (Table 1). Hill’s force-velocity relationship (Hill, 1938) can be stated mathematically as:

$$F = \frac{F_{\text{max}} b - aV}{V + b}$$

where $F$ is muscle force, $F_{\text{max}}$ is maximum isometric muscle force, $V$ is muscle shortening velocity, and $a$ and $b$ are system-dependent parameters governing this relationship. The maximum shortening velocity (when $F = 0$ N) is specified by parameters $a$ and $b$:

$$V_{\text{max}} = \frac{F_{\text{max}} b}{a}$$

Since parameter $b$ is relatively unaffected by training (Duchateau & Hainaut, 1984), the increase in $V_{\text{max}}$ was simulated by decreasing parameter $a$.

Hakkinen and co-workers (Hakkinen, Kallinen, et al., 1998a; Hakkinen, Newton, et al., 1998) reported significant increases in mm. quadriceps femoris IEMG while jumping after a period of strength training. This finding is in agreement with observations in dynamic knee extension/flexion training in which the IEMG increased by 10–19% (Hakkinen, Kallinen, Linnamo, et al., 1996). Similar results have been published by Hakkinen and Komi (1983) (about 10% increase), and by Higbie, Cureton, Warren, and Prior (1996) (7.1–20.0% increase). Similar numbers can also be found in a review by Enoka (1997). Based on these studies, it was assumed that the model can activate the muscles only up to 90% (i.e., $ACT_{\max} = 90\%$) before training. After training, $ACT_{\max}$ was set to 100% to simulate an increase in motor unit recruitment. Intermediate increments (92 to 98%) and a decrement (88%) were also simulated (Table 1).

The three training effects ($\Delta F_{\text{max}}$, $\Delta V_{\text{max}}$, and $\Delta ACT_{\max}$) were simulated separately and in combination. When the training effects were simulated in combination, maximum changes in the three neuromuscular parameters $F_{\text{max}}$ (+20%), $V_{\text{max}}$ (+20%), and $ACT_{\max}$ (+10%) were applied: (a) for all muscles, (b) for m. soleus and m. gastrocnemius (primary ankle plantarflexors), (c) for mm. vasti and m. rectus femoris (primary knee extensors), and (d) for mm. glutei and hamstrings (primary hip extensors).

The effect of the simulated training sessions on jumping performance was evaluated by comparing the re-optimized JH between the standard (before training) model and the trained models ($\Delta JH$). The effect of the simulated training sessions on the optimal muscle activation patterns was evaluated by comparing $T_{\text{on}}$ and $T_{\text{off}}$ between the standard (before training) and the trained models ($\Delta T_{\text{on}}$ and $\Delta T_{\text{off}}$). As the neuromuscular model had six muscles, the averaged timing adjustment in muscle activation $\Delta T_{\text{ACT}}$ was quantified as follows:

$$\Delta T_{\text{on},i} = T_{\text{on},i} - T_{\text{on},i,\text{before}}$$

$$\Delta T_{\text{off},i} = T_{\text{off},i} - T_{\text{off},i,\text{before}}$$

$$\Delta T_{\text{ACT}} = \sqrt{\frac{\sum_{i=1}^{6} \Delta T_{\text{on},i}^2 + \sum_{i=1}^{6} \Delta T_{\text{off},i}^2}{6 \times 2}}$$
Results

The optimization of the muscle activation patterns always resulted in a well-coordinated jumping movement (Figure 3). Even though the general characteristics of the simulated vertical GRF profile were similar to experimental data (Fukashiro & Komi, 1987) (Figure 3), there was a tendency, observed in all simulations, for the simulated ground reaction force to increase earlier than the experimental data (Figure 3). The optimized JH (the maximum height reached by body’s center of mass above the floor) before training was 141.68 cm.

Figure 3 — (A) Simulated squat jumping movement ($\Delta t = 0.005$ s). Initial squat position (height of body’s center of mass = 62.52 cm above the floor) was kept for 0.05 s to ensure that there was no countermovement. Optimization of muscle activation patterns typically resulted in smooth, normal jumping movements. (B) Vertical ground reaction force (GRF$_z$) profiles during pushoff (takeoff = 0.0 s). Simulated GRF$_z$ profile (solid line) is similar to the GRF$_z$ profile (dashed line) reported by Fukashiro and Komi (1987).
As expected, JH increased when F_{max}, V_{max}, and ACT_{max} were increased for all muscles (Table 2). Increasing F_{max} parameters by 20% produced the largest increase in jumping performance (\Delta JH = +6.99 cm), whereas increasing V_{max} parameters by +20% produced the smallest effect (\Delta JH = +3.83 cm). Increasing V_{max}, F_{max}, and ACT_{max} simultaneously for all muscles resulted in a large increase in jumping performance (\Delta JH = +16.62 cm), which is greater than the sum of the \Delta JH for individual modifications of F_{max}, V_{max}, and ACT_{max} (\Sigma \Delta JH = +15.08 cm). When intermediate steps of training effects (96 to 120% for F_{max} and V_{max}; 88 to 100% for ACT_{max}) were simulated, linear relationships between JH and changes in F_{max}, V_{max}, and ACT_{max} were observed (Figure 4).

When F_{max} (+20%), V_{max} (+20%), and ACT_{max} (+10%) were manipulated simultaneously for ankle plantar flexors, knee extensors, and hip extensors, the optimized jump height increased by +3.15 cm, +9.61 cm, and +1.68 cm, respectively (Table 2). The sum of these \Delta JH (\Sigma \Delta JH = +14.44 cm) is smaller than the increase in jump height (\Delta JH = +16.62 cm) that was found when the manipulations were applied simultaneously to all the muscles.

<table>
<thead>
<tr>
<th>Individual Parameters: All Muscles</th>
<th>Before training</th>
<th>( \Delta F_{\text{max}} ) (+20%)</th>
<th>( \Delta V_{\text{max}} ) (+20%)</th>
<th>( \Delta ACT_{\text{max}} ) (+10%)</th>
<th>( \Delta F_{\text{max}} + \Delta V_{\text{max}} + \Delta ACT_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump height (cm)</td>
<td>141.68</td>
<td>148.67</td>
<td>145.51</td>
<td>145.94</td>
<td>158.30</td>
</tr>
<tr>
<td>( \Delta \text{Jump height} ) (cm)</td>
<td>–</td>
<td>+6.99</td>
<td>+3.83</td>
<td>+4.26</td>
<td>+16.62</td>
</tr>
<tr>
<td>( T_{\text{takeoff}} ) (s)</td>
<td>0.340</td>
<td>0.315</td>
<td>0.330</td>
<td>0.325</td>
<td>0.300</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Individual Muscle Groups: ( \Delta F_{\text{max}} ) (+20%) + ( \Delta V_{\text{max}} ) (+20%) + ( \Delta ACT_{\text{max}} ) (+10%)</th>
<th>Before training</th>
<th>Ankle p. flexors</th>
<th>Knee extensors</th>
<th>Hip extensors</th>
<th>All muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump height (cm)</td>
<td>141.68</td>
<td>144.83</td>
<td>151.29</td>
<td>143.36</td>
<td>158.30</td>
</tr>
<tr>
<td>( \Delta \text{Jump height} ) (cm)</td>
<td>–</td>
<td>+3.15</td>
<td>+9.61</td>
<td>+1.68</td>
<td>+16.62</td>
</tr>
<tr>
<td>( T_{\text{takeoff}} ) (s)</td>
<td>0.340</td>
<td>0.335</td>
<td>0.310</td>
<td>0.335</td>
<td>0.300</td>
</tr>
</tbody>
</table>

*Note:* Jump height, the increase in jump height (\( \Delta JH \)) with respect to the before-training model, and duration of the pushoff (\( T_{\text{takeoff}} \)) were quantified. \( F_{\text{max}} \) (+20%), \( V_{\text{max}} \) (+20%), and \( ACT_{\text{max}} \) (+10%) were manipulated individually and in combination (top), and for individual functional muscle groups (ankle plantar flexors, knee extensors, hip extensors), as well as for all muscles (bottom).
Figure 4 — Change in jump height associated with changes in neuromuscular parameters. Linear relationships ($r^2 = 1.0$) were observed between $\Delta F_{\text{max}}$, $\Delta V_{\text{max}}$, and $\Delta ACT_{\text{max}}$ and jump height. Slope of the linear polynomial was largest for $ACT_{\text{max}}$; however, as the trainability of this parameter (+10%) was lower than for the other two (+20%), a smaller gross increase in jump height can be expected by training $ACT_{\text{max}}$ compared to training $F_{\text{max}}$. 
Figure 5 — Changes in timing of muscle activation patterns ($\Delta T_{ACT}$) associated with changes in neuromuscular parameters. As the modification of parameters (i.e., training effects) increased, greater adjustments were needed in the timing of muscle activation. Note that as $\Delta T_{ACT}$ was measured as the deviation of the timing of muscle activation patterns from those of the standard model, $\Delta T_{ACT}$ was equal to 0.0 for $F_{max} = 100\%$, $V_{max} = 100\%$, and $ACT_{max} = 90\%$. 
There were adaptations in T<sub>on</sub> and T<sub>off</sub> associated with the alterations in neuromuscular parameters. As a result, ΔT<sub>ACT</sub> generally increased as the values for ΔF<sub>max</sub>, ΔV<sub>max</sub>, and ΔACT<sub>max</sub> increased (Figure 5). This was particularly true for ΔF<sub>max</sub>, but was not so evident for ΔV<sub>max</sub>. On the other hand, although muscles could be activated submaximally, the optimization process always resulted in maximum muscle activation (i.e., ACT = ACT<sub>max</sub>).

**Discussion**

Although there are many training regimens, it is difficult to suggest which type of training is the most effective and which muscle groups should be targeted primarily. The goal of this study was to investigate the effects of altering specific neuromuscular parameters (F<sub>max</sub>, V<sub>max</sub>, and ACT<sub>max</sub>) on vertical jump performance. We also investigated the effect of altering neuromuscular parameter values of specific muscle groups (hip extensors, knee extensors, and ankle plantarflexors) on vertical jumping performance.

When F<sub>max</sub>, V<sub>max</sub>, and ACT<sub>max</sub> were increased separately by 20%, 20%, and 10% for all muscles, jump height increased by +6.99, +3.83, and +4.26 cm, respectively (Table 2). The increase in jumping performance as a result of increasing F<sub>max</sub> by 20% is similar to the increase of +7.8 cm reported by Bobbert and van Soest (1994). The results suggest that the largest increase in jumping performance can be expected by focusing strength training on increasing the muscle physiological cross-sectional area (i.e., F<sub>max</sub>). However, it should be noted that the effects of V<sub>max</sub> and ACT<sub>max</sub> on jump height are also substantial. In fact, when F<sub>max</sub>, V<sub>max</sub>, and ACT<sub>max</sub> were increased simultaneously by 20%, 20%, and 10% for all muscles, jump height increased by +16.62 cm (Table 2), which is 1.54 cm higher than the increase in jump height obtained by summing individual factors (+15.08 cm). Mechanically this result suggests that the model could make use of strengthened individual neuromuscular factors even more by coordinating the interaction among the three factors: F<sub>max</sub>, V<sub>max</sub>, and ACT<sub>max</sub>.

When intermediate increments (Table 1) in individual parameters were simulated, clear linear relationships were found between all individual neuromuscular parameters and vertical jumping performance (Figure 4). Bobbert and van Soest (1994) also observed a linear characteristic for jump height as a function of F<sub>max</sub>. From current results this appears to be the case not only for F<sub>max</sub> but also for the other two neuromuscular parameters that were examined: V<sub>max</sub> and ACT<sub>max</sub>.

This implies that although several discrete increases were simulated in this study, it is possible to interpolate or extrapolate the data points and provide suggestions for more general situations. This is important, because as the trainability of individual factors was derived from the studies cited, the trainability for individual subjects could easily be over- or underestimated. In practical situations, the variations in F<sub>max</sub> and V<sub>max</sub> are not independent from each other (Eq. 2). Therefore, it is important to recognize that there might be nonlinear training effects caused by altering F<sub>max</sub> and/or V<sub>max</sub>.

When the optimal muscle activation pattern from the standard (i.e., before-training) model was applied to the strengthened model (ΔF<sub>max</sub> = +20%, ΔV<sub>max</sub> = +20%, ΔACT<sub>max</sub> = +10% for all muscles), the increase in jumping performance was only +14.15 cm, which is noticeably smaller than the +16.62 cm that was obtained after re-optimization of the muscle activation patterns. This result suggests that although jumping performance can be expected to improve simply by strengthening the neuromuscular system, a re-optimization of the muscle activation patterns is needed in order to achieve a further (+14.9%) improvement in jumping performance. Even though the jumping
movement was not disrupted without re-optimization as reported in Bobbert and van Soest (1994), it is evident that only after the muscle activation patterns have been re-optimized can the model make full use of its newly strengthened muscles.

When $F_{\text{max}}$ (+20%), $V_{\text{max}}$ (+20%), and $ACT_{\text{max}}$ (+10%) were manipulated simultaneously for individual functional muscle groups (ankle plantar flexors, knee extensors, and hip extensors), the optimal jump height increased by +3.15 cm, +9.61 cm, and +1.68 cm, respectively (Table 2). The sum of these numbers (+14.44 cm) is smaller than the increase in jump height that was found when these manipulations were performed for all muscles simultaneously (+16.62 cm). This result suggests that the model could make use of the strengthened neuromuscular system even more by coordinating the interaction among all muscle groups.

It is obvious that the most effective way to improve jumping performance is to simply train all muscles ($\Delta JH = +16.62$ cm); however, a large part (57.8%) of the improvement can be attributed to strengthening the knee extensors ($\Delta JH = +9.61$ cm) only. Bobbert and van Soest (1994) also investigated strengthening the knee extensors only, and found a noticeably smaller increase in jump height (+3.0 cm; $\Delta F_{\text{max}} = +20\%$). The increase in jump height was larger in this study (+9.61 cm) because, in addition to parameter $F_{\text{max}}$, parameters $V_{\text{max}}$ and $ACT_{\text{max}}$ were also manipulated, illustrating once again that factors other than $F_{\text{max}}$ are also important contributors to jumping performance.

Although three parameters ($T_{\text{on}}$, $T_{\text{off}}$, and $ACT$) were modified for individual muscles through optimization, it was found that in all the cases the optimum value of $ACT$ was equal to the maximum possible value, $ACT_{\text{max}}$. This result was not self-evident, as there was a possibility it might be beneficial to activate muscles submaximally for the sake of body coordination and balance. Instead, it appears that the best strategy is to fully activate all muscles. The timing of muscle activation ($T_{\text{on}}$ and $T_{\text{off}}$) was adjusted in response to the simulated training effects in the neuromuscular parameters (Figure 5). This was particularly noticeable for $\Delta F_{\text{max}}$. The adjustments, $\Delta T_{ACT}$, increased as the modifications in the neuromuscular parameters increased. This suggests that adjustments in the timing of muscle activation are still required after further neuromuscular training. Although the relationship between $\Delta T_{ACT}$ and $\Delta F_{\text{max}}$ appears to be linear, the relationships between $\Delta T_{ACT}$ and $\Delta V_{\text{max}}$, and $\Delta T_{ACT}$ and $\Delta ACT_{\text{max}}$, clearly are not linear.

Based on the results, the following three points may be suggested in terms of training to enhance jumping performance: training programs should emphasize (a) exercises to increase maximum muscle forces (i.e., cross-sectional area) by going through heavily loaded weight training using free weights and/or weight training machines; (b) exercises that focus mostly on the muscles around the knee joints; and (c) exercises that also incorporate jumping movements so that the athletes can learn how to use the strengthened muscles.

This study was conducted using a two-dimensional model with six lower extremity muscle groups. This is a simplification of actual human jumping which happens in 3-D space and involves many more muscle groups. Since each muscle group was regarded as a single unit, and a muscle coordination pattern was specified by three variables (onset, offset, amplitude), finite control of muscles was not possible with this model. However, this simplified model captures important aspects of actual human jumping, as the nature of the movement is basically two-dimensional and includes the mechanically important muscle groups. The fact that this simplified musculoskeletal model could reproduce the characteristics of actual human jumping movements (see kinematics and kinetics in Figure 3) supports the validity of the model.
To conclude, all three neuromuscular parameters ($F_{\text{max}}$, $V_{\text{max}}$, and $\text{ACT}_{\text{max}}$), which were manipulated to simulate the effects of strength training, had substantial effects on jumping performance. Part of the increase in jumping performance could be explained solely by the interaction between the three neuromuscular parameters. It appears that the best way to improve jumping performance is to focus the training on the knee extensors among all the lower extremity muscles. To fully benefit from any training effects of the neuromuscular system, it is necessary to continue to re-optimize muscle coordination, in particular after strength training sessions that focus primarily on increasing maximum isometric muscle force.

References


**Appendix**

**Ground reaction force model**

The ground reaction force model was adopted from Gerritsen et al. (1995). When there is a contact between heels/toes and the ground (i.e., \( z \leq 0.0 \) m),

\[
\text{GRF}_z = a|z|^\beta (1 - \beta \cdot z) \tag{A1}
\]

where \( \text{GRF}_z \): the vertical component of the ground reaction force, \( z \): the vertical position (floor = 0.0 m) of heels/toes, \( \alpha = 0.25 \times 10^9 \text{ Nm}^{-3} \) and \( \beta = 1.0 \text{ sm}^{-1} \) (when there is no contact between heels/toes and the floor (i.e., \( z > 0.0 \) m), \( \text{GRF}_z = 0.0 \text{ N} \)). With this ground reaction force model, the feet segment can leave the floor after the push-off phase.

**Muscle activation/contraction dynamics**

The variables \( \text{ACT} \) and the active state of the muscle (\( q \)) are related (activation dynamics) to each other through the following formula (He et al., 1991):

\[
\dot{q}(t) = (\text{ACT}(t) - q(t)) \cdot (t_i \cdot \text{ACT}(t) + t_e) \tag{A2}
\]

where

\[
t_2 = \left(1/t_4\right), \quad t_4 = \text{time constant for de-activation (65 ms)} \tag{A3}
\]

\[
t_1 = \left(1/t_4 - t_2\right), \quad t_4 = \text{time constant for activation (55 ms)} \tag{A4}
\]

Formulae to describe the muscle contraction dynamics were adopted from van Soest and Bobbert (1993) and Cole et al. (1996). \( F_{\text{ISOM}} \) is the force relative to \( F_{\text{max}} \) that would be produced isometrically:

\[
F_{\text{ISOM}} = c \cdot \left(\frac{L_{CE}}{L_{CEopt}}\right)^2 - 2c \cdot \left(\frac{L_{CE}}{L_{CEopt}}\right) + c + 1 \tag{A5}
\]

where

\[
c = \frac{-1}{\text{width}^2} \tag{A6}
\]

\( L_{CEopt} \): optimum muscle fiber length, \( L_{CE} \): muscle fiber length, width: maximum length range of force production relative to \( L_{CEopt} \).

For the concentric phase,

\[
V_{CE} = -\text{FACTOR} \cdot L_{CEopt} \cdot \left(\frac{F_{\text{ISOM}} + A_{REL}}{F} \cdot B_{REL} - B_{REL} \right) \tag{A7}
\]

where

\[
\text{FACTOR} = \text{Min} \left(1, 3.33 \cdot q\right) \tag{A8}
\]
\( A_{\text{REL}} = 0.41 \) and \( B_{\text{REL}} = 5.2 \) for the original (before training) model, respectively.

For the eccentric phase,

\[
V_{CE} = -L_{\text{CEopt}} \left( \frac{c_1}{F_{\text{asympt}}} - c_2 \right) \\
F_{\text{asympt}} = F_{\max} \cdot \frac{c_1}{c_2} \\
c_2 = -F_{\text{isom}} \cdot F_{\text{asympt}} \\
c_1 = \frac{\text{FACTOR} \cdot B_{\text{REL}} \cdot (F_{\text{isom}} + c_2)^2}{(F_{\text{isom}} + A_{\text{REL}}) \cdot \text{Slopefactor}} \\
c_3 = \frac{c_1}{(F_{\text{isom}} + c_2)} \\
\]

where \( c_1, c_2, c_3 \) were parameters to specify the shape of the eccentric force-velocity relationship:

\( F_{\text{asympt}} \) is the asymptotic maximum force value in the eccentric phase (relative to \( F_{\max} \)), and \( \text{Slopefactor} \) is the ratio between eccentric and concentric derivatives \( dF/dV_{CE} \) at \( V_{CE} = 0.0 \). \( F_{\text{asympt}} = 1.5 \), \( \text{Slopefactor} = 2.0 \) were used (van Soest & Bobbert, 1993). Again, these formulae (Eq. A5–A12) were adopted from van Soest and Bobbert (1993) and Cole et al. (1996).

**Musculoskeletal interaction**

Parameter values to specify muscle properties and the musculo-skeletal interaction were adopted from Gerritsen et al. (1998) (Table 3). Muscle properties: maximum isometric muscle force (\( F_{\max} \)), optimum muscle fiber length (\( L_{\text{CEopt}} \)), maximum length range of force production relative to \( L_{\text{CEopt}} \) (width), and tendon slack length (\( L_{\text{slack}} \)). Musculoskeletal interaction: origin-insertion length was calculated as a function of joint angles:

\[
L_{OI} = A_0 + d_{\text{hip}} \theta_{\text{hip}} + d_{\text{knee}} \theta_{\text{knee}} + d_{\text{ankle}} \theta_{\text{ankle}} \\
\]

where \( L_{OI} \): musculotendon origin-insertion length, \( \theta_{\text{hip}} \): hip flexion angle in radians (full extension = 0.0), \( \theta_{\text{knee}} \): knee flexion angle in radians (full extension = 0.0), and \( \theta_{\text{ankle}} \): ankle dorsiflexion angle in radians (full plantar flexion = 0.0).

**Table 3 Parameter Values to Specify Muscle Properties and Musculoskeletal Interaction**

<table>
<thead>
<tr>
<th>Muscles</th>
<th>( F_{\max} )</th>
<th>( L_{\text{CEopt}} )</th>
<th>Width</th>
<th>( L_{\text{slack}} )</th>
<th>( A_0 )</th>
<th>( d_{\text{ankle}} )</th>
<th>( d_{\text{knee}} )</th>
<th>( d_{\text{hip}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm.glutei</td>
<td>3409.6</td>
<td>0.200</td>
<td>0.625</td>
<td>0.157</td>
<td>0.271</td>
<td>0</td>
<td>0</td>
<td>0.062</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>3538.0</td>
<td>0.104</td>
<td>1.197</td>
<td>0.334</td>
<td>0.383</td>
<td>0</td>
<td>0</td>
<td>0.072</td>
</tr>
<tr>
<td>m.rectus femoris</td>
<td>1325.8</td>
<td>0.081</td>
<td>1.443</td>
<td>0.398</td>
<td>0.474</td>
<td>0</td>
<td>0</td>
<td>0.050</td>
</tr>
<tr>
<td>mm.vasti</td>
<td>14806.0</td>
<td>0.093</td>
<td>0.627</td>
<td>0.223</td>
<td>0.271</td>
<td>0</td>
<td>0</td>
<td>0.042</td>
</tr>
<tr>
<td>m.gastrocnemius</td>
<td>3277.4</td>
<td>0.055</td>
<td>0.888</td>
<td>0.420</td>
<td>0.404</td>
<td>0.053</td>
<td>0</td>
<td>0.020</td>
</tr>
<tr>
<td>m.soleus</td>
<td>7766.4</td>
<td>0.055</td>
<td>1.039</td>
<td>0.245</td>
<td>0.201</td>
<td>0.053</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note*: Values were adopted from Gerritsen et al. (1998).