The Relationship Between Joint Strength and Standing Vertical Jump Performance

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The effect of joint strengthening on standing vertical jump height is investigated by computer simulation. The human model consists of five rigid segments representing the feet, shanks, thighs, HT (head and trunk), and arms. Segments are connected by frictionless revolute joints and model movement is driven by joint torque actuators. Each joint torque is the product of maximum isometric torque and three variable functions of instantaneous joint angle, angular velocity, and activation level, respectively. Jumping movements starting from a balanced initial posture and ending at takeoff are simulated. A matching simulation reproducing the actual jumping movement is generated by optimizing joint activation level. Simulations with the goal of maximizing jump height are repeated for varying maximum isometric torque of one joint by up to ±20% while keeping other joint strength values unchanged. Similar to previous studies, reoptimization of activation after joint strengthening is necessary for increasing jump height. The knee and ankle are the most effective joints in changing jump height (by as much as 2.4%, or 3 cm). For the same amount of percentage increase/decrease in strength, the shoulder is the least effective joint (which changes height by as much as 0.6%), but its influence should not be overlooked.

Keywords: strengthening, joint torque, muscular activation, optimization, simulation

Jumping for maximum height has been studied from various approaches. Strategies for maximizing jump height have been investigated by mathematical models of increasing complexity (Levine et al., 1983a, 1983b; Pandy et al., 1990; Van Soest et al., 1993; Selbie & Caldwell, 1996). Ground reaction forces (GRF), muscle electromyogram (EMG), and joint kinematics have been measured by numerous experimental studies (Bobbert & Van Ingen Schenau, 1988; Lees et al., 2004). Other researchers (Alexander, 1990; Seyfarth et al., 1999, 2000) used simple dynamic models to understand optimal running high- and long-jumping strategies.

The effects of arm swings on jump performance have been studied for a few decades. Researchers (Payne et al., 1968; Miller, 1976; Shetty & Etnyre, 1989; Harman et al., 1990) showed that arm swing can increase the GRF in the latter half of the propulsive phase, leading to enhanced net ground reaction impulse. Consequently, center of mass (CM) position and vertical velocity of at takeoff can be raised, which increases jump height. This kind of “transmission of force” theory proposed by Payne et al. (1968) and repeated by Dapena (1993), however, has been suggested as too simplistic a view by experimental (Harman et al., 1990) and simulation (Dapena, 1999) investigations. The “joint torque augmentation” theory (Feltner et al., 1999) suggests that upward acceleration of the arms causes the reaction force to act on the trunk, resulting in slower extension of the lower extremities and greater muscle force production (Dapena & Chung, 1988; Harman et al., 1990). There had been little direct evidence to support this theory until the study by Feltner et al. (1999).

Recently, Feltner et al. (2004) showed that arm swing decreases extensor joint torques early in the propulsive phase but augments these same extensor torques later in the propulsive phase. The increased jump height consists of increased CM height (54%) and vertical velocity (46%) at takeoff, while a different percentage distribution (28%
and 72%, respectively) was found by Lees et al. (2004). Hara et al. (2006) studied the effect of arm swing on lower extremities in vertical jumping. They concluded that increased jump height is mainly due to increased work done by the lower extremities, which is also a result from the additional load on the lower extremities because of arm swing.

Although various studies concerned different aspects of vertical jumping, only a few researchers investigated the effect of joint strength (resultant muscular strength) on jumping performance. Experiments by Tsiokanos et al. (2002) indicated a significant positive relationship between vertical jumping height and total work with hip and knee isokinetic extension moments, but low correlation coefficients between height and ankle plantar flexor moment. A simulation study (Nagano & Gerritsen, 2001) showed that the most effective way to improve jumping performance is to train the knee extensors among all lower extremity muscles. Similar to previous simulation results (Bobbert & Van Soest, 1994), reoptimizing muscle coordination to benefit fully from any training effects was shown to be necessary.

In strength-dependent exercises like jumping, athletes usually want to know the most effective way to train themselves. This is especially true when competitions are approaching. Thus, it is important to know which joints are crucial and should be focused on during training. However, previous researchers either concentrated mainly on the effect of shoulder joint (to study the role of arms) or disregarded countermovement and arm swing (which are usually observed in standing jumps) in simulations (Bobbert & Van Soest, 1994; Nagano & Gerritsen, 2001). Furthermore, the effect of muscle weakening on jump height was only investigated with very small decrement (4%) in maximum isometric force (Nagano & Gerritsen, 2001). The purpose of this study is to investigate the influence of changing strength at each joint on vertical jumping performance. In human experiments joint strength cannot be varied instantly, and it is impossible to strengthen/weaken muscles around a single joint without affecting other joints. Therefore, computer simulation with optimization serves as the best tool for the current study.

**Methods**

Although this study focuses on simulation, measurement of real jumping performance is necessary for model verification. Since the human model is intended to be subject-specific, only one subject (height 1.64 m, weight 55.0 kg) was tested. The mathematical model of Yeadon (1990) was used to calculate segmental inertia parameters (Appendix Table 1) with measured anthropometric data. After informed consent and approval by the University Human Subjects Research Review Committee was obtained, he performed five maximal-height standing vertical jumps. Enough time for warming up and for resting between jumps was given. Three high-speed cameras (240 Hz) and a motion analysis system (Motion Analysis, Eva 7.0, Santa Rosa, CA) recorded and determined positions of six reflective markers at the fifth metatarsal, ankle, knee, hip, shoulder, and wrist. The elbow motion was assumed motionless because in a preliminary experiment its range of motion was only within 7° during ground contact and was also neglected in a similar simulation model (Ashby & Delp, 2006).

A planar five-segment human body model is used to simulate standing vertical jumping from initiation to takeoff. Body segments are connected by frictionless hinge joints (Figure 1). The segments represent feet, shanks, thighs, HT (head-trunk), and the arms with fixed elbow joint. Torque actuators at the ankle, knee, hip, and shoulder joints are used to drive model movement, which starts from a balanced and nearly straight posture. The model can actively extend and flex these joints. Rather than modeling individual muscle function, these torque actuators represent total contributions of joint flexors and extensors. This is because joint torque produced by muscles is defined as the summation of the cross products of muscle forces and corresponding moment arms. Equations of motion are derived using AUTOLEV, a symbol manipulator for dynamic systems (http://www.autolev.com). Because motion in the current model is described by joint angles, the equations of motion relate joint torques to angular acceleration and segment moment of inertia. Thus the inertia effects are considered. Sources of model inputs/constraints and methods that obtained them are listed in the Appendix Table 2.

At each joint, the torque $T$ (effective torque on the sum of the left and right extremities) exerted is assumed...
to be the product of a maximum isometric torque $T_{\text{max}}$ and three variable factors:

$$T = T_{\text{max}} f(\theta) h(\omega) A(t)$$  \hfill (1)

This assumption preserves the characteristics of muscle force production, which depends on maximum isometric force, muscle length, and shortening velocity. Thus, functions $f(\theta)$ and $h(\omega)$ depend on joint angular position and angular velocity, respectively. A similar approach also constructed the surface for joint torque depending on both joint angle and angular velocity (Yeadon & King, 2002; King & Yeadon, 2005). The explicit function $A(t)$ corresponds to joint activation level, which models the effective activation of the muscles across the joint and characterizes the coordination strategy. This kind of approach has been verified for baseball pitching (Fujii & Hubbard, 2002) and gymnastics (King & Yeadon, 2004; King & Yeadon, 2005).

A cubic spline fit of five nodal values at equally spaced times throughout ground contact is used to represent $A(t)$. Five nodes suffice since the increase in jump height after doubling the number of nodes is less than 1%. The initial nodes are fixed to correspond to the torques needed for holding the initial posture. Positive and negative $A(t)$ represent actively extending and flexing, respectively, with full-effort joint extension/flexion corresponding to $A(t) = +1/−1$. Because muscular activation cannot change instantaneously, the rate of change in effective joint activation $dA/dt$ is constrained. An activation time constant of 80 ms near the geometric mean of muscle activation rise and decay time constants, typically taken to be 20 and 200 ms (Pandy et al., 1990), is assumed. Thus $|dA/dt|$ cannot exceed $1/0.08$ s$^{-1}$.

The joint angle factors $f(\theta)$ for the ankle, knee, and hip are taken from Pandy et al. (1990) in extension and Hoy et al. (1990) in flexion, respectively. For the shoulder joint $f(\theta)$ is taken from Otis et al. (1990). The angular velocity factor $h(\omega)$ is given by (Selbie & Caldwell, 1996):

$$\begin{align*}
h(\omega) &= \frac{(\omega_0 - \omega)}{(\omega_0 + \Gamma \omega)}, \quad \omega/\omega_0 < 1 \\
h(\omega) &= 0, \quad \omega/\omega_0 \geq 1
\end{align*}$$  \hfill (2)

where $\omega_0 = \pm 20$ rad/s is maximum joint extension (positive) or flexion (negative) angular velocity, $\omega$ is instantaneous joint angular velocity (positive in extension), and $\Gamma = 2.5$ is a constant shape factor. When $\omega(t)$ and $A(t)$ have different signs (eccentric muscle contraction), $h(\omega)$ is increased to a saturation value of 1.5 (Figure 2).

Due to model simplicity and the fact that dependences of joint torque on angle and angular velocity are averaged values from other studies, exact measurement of joint $T_{\text{max}}$ for the subject is considered unnecessary. Rather, values of $T_{\text{max}}$ at different joints are estimated by the following two-stage optimization procedure, in which nodal values of $A(t)$ and the four $T_{\text{max}}$ for joint extension are control variables. $T_{\text{max}}$ for joint flexion are assumed to be 0.25, 0.5, 0.5, and 1.5 times the maximum extension torque for the ankle, knee, hip, and shoulder, respectively (Hoy et al., 1990; Otis et al., 1990). The optimization in the first stage finds the control variables such that the simulated joint (ankle, knee, hip, shoulder, and wrist) positions match those in the highest real jumping trial. That is, the sum of the squared differences in joint positions at all instants is minimized. In searching for the optimum, an averaged difference within 5 mm is deemed acceptable and the accepted solution sets are used for the second stage.

During the second stage, another optimization is performed to avoid joints being “too strong” or “too weak.” Because the highest jumping trial should be nearly optimal, it is plausible to assume that by varying

![Figure 2](image)

**Figure 2** — Angular velocity factor $h(\omega)$ for joint extension activation ($A(t) > 0$). The function is decreased to zero if $\omega \geq \omega_0$ (maximum angular velocity). When $\omega < 0$ and $A(t) > 0$ (or $\omega > 0$ and $A(t) < 0$), $h(\omega)$ increases to a saturation value 1.5, that effectively models eccentric muscle contraction.
from penetrating the ground, a passive torque modeled be active. Instead of using a constraint to prevent the heel hyperextension. Only the GRF constraint was found to at takeoff and joint angle constraints to prevent joint force (GRF, calculated using simulated CM acceleration) takeoff condition that requires zero ground reaction when it lies outside \([-1, 1]\). Other constraints are the activations), from different joint torque patterns (actually nodal torque maximization procedure.

These best estimated joint \(T_{\text{max}}\) (maximum isometric torque) are used as nominal joint strength values. To examine how joint strength affects performance, the strength for a single joint is then varied (while keeping other \(T_{\text{max}}\) values unchanged) and joint activation patterns are optimized for giving maximal simulated jump heights. It has been shown that joint torque can be increased by approximately 20–30% (Cannon et al., 2007; Davies & Young, 1983; Komi et al., 1978). In the current study, each \(T_{\text{max}}\) is varied within ±20% or ±100 N·m to include more general cases. Although in reality changing strength implies changing muscle mass, it is assumed that change of mass is negligible.

The control goal is to maximize the objective function (jump height) \(J_0\):

\[
J_0 = (y_f^2 - v_f^2/2g)
\]

where \(y_f\) and \(v_f\) are the jumper CM takeoff vertical position and velocity. Since different takeoff times \(t_f\) result from different joint torque patterns (actually nodal torque activations), \(t_f\) is also a control variable (Bryson, 1999). Maximizing \(J_0\) is subject to state and control constraints. In optimal torque activation calculations, nodal activation is not constrained formally. Rather \(A(t)\) is truncated when it lies outside \([-1, 1]\). Other constraints are the takeoff condition that requires zero ground reaction force (GRF, calculated using simulated CM acceleration) at takeoff and joint angle constraints to prevent joint hyperextension. Only the GRF constraint was found to be active. Instead of using a constraint to prevent the heel from penetrating the ground, a passive torque modeled by a rotational spring-damper system is applied at the toe joint when angle \(\theta\) is below its initial value to simulate heel–ground interaction (Pandy et al., 1990).

Whenever constraints are violated, a penalty function is subtracted from the objective function \(J\) to give the new objective function \(J_1\) (Reklaitis et al., 1983):

\[
J_1 = J - \sum_i c_i \pi_i
\]

where \(\pi_i\) is the square of the constraint violation and \(c_i\) is a weighting coefficient chosen to be \(10^5\). Thus the problem becomes an unconstrained maximization, where possible violations of the constraints decrease the value of the objective function. The choice of weighting coefficient is made by trial and error. This is because GRF at takeoff is assumed to be less than 0.1 N in both vertical and horizontal directions, which cannot be achieved if the weighting coefficients are smaller than \(10^5\).

The downhill simplex method (Nelder & Mead, 1965; Press, 1997) is used as the optimization algorithm. To find the global rather than a local optimum, varying initial guesses and restarting the optimization from a newly found optimum is employed.

**Results**

As was mentioned above, the two-stage optimization is used for determining joint \(T_{\text{max}}\) and for model verification. Maximum torque (in newton meters) determined for the ankles, knees, hips, and shoulders are 500.21, 481.10, 511.02, and 179.87, respectively. The matching simulation and measured actual jumping motion are almost identical (Figure 3). Simulated and actual jump heights are 1.2941 m and 1.2978 m, respectively. Kine- matic variables at takeoff are compared in Table 1. Joint torque and activation of the matching simulation show the pattern of relaxation and minor flexion followed by maximal extension (Figure 4).

Maximum jump height achieved after changing a single joint \(T_{\text{max}}\) is shown in Figure 5. This comparison is done by increasing/decreasing 100 N·m (with an interval of 10 N·m) for a joint \(T_{\text{max}}\) while keeping other joint strength unchanged. The strength–height curve of each joint shows somewhat linear relation. The level

<table>
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<tr>
<th>Table 1</th>
<th>Comparison of Kinematic Variables at Takeoff for the Matching Simulation and Measured Motion</th>
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<tbody>
<tr>
<td></td>
<td>(x) (meters)</td>
</tr>
<tr>
<td>Simulation</td>
<td>0.0524</td>
</tr>
<tr>
<td>Measured</td>
<td>0.0583</td>
</tr>
</tbody>
</table>

*Note.* The symbols \(x\), \(y\), \(v_x\), \(v_y\), and \(H\) stand for takeoff CM horizontal position, vertical position, horizontal velocity, vertical velocity, and jump height, respectively. The origin is at the ball of feet.
Figure 3 — Matching simulation ( - - ) and measured jumping motion ( — ) in stick figures from static standing posture to take-off.

Figure 4 — Simulated joint torque ( — ) and activation ( · · · ) at each joint with normalized time ( 0 at initiation and 1 at takeoff). Each torque is normalized by dividing by its maximum isometric value. The general activation pattern involves relaxation and minor flexion (negative value) followed by full extension. The abrupt change in torque values at about 63% of ground contact is due to the passive torque for preventing the heel from penetrating the ground.

of effectiveness in height increase due to joint strength increase (at 100 N·m) is in the order of knee, ankle, shoulder, and hip. On the other hand, losing 100 N·m in joint strength causes height decrease in the order of ankle, shoulder, knee, and hip. Decreasing ankle and shoulder strength has stronger impact in jump height than increasing strength, and this is especially true for the shoulder. On the contrary, gaining strength for the knee and hip has stronger influence on jump height than losing strength.
The effect of percentage change in joint $T_{\text{max}}$ on jumping height is also compared (Figure 6). In general, the ankle and knee are the most effective joints in changing jump height, whereas the shoulder is the least effective joint. Changing ankle and knee strength within 10% seems to have comparable effects on jump height. But for a 20% strength increase, the knee is more effective in jump height increase, whereas the ankle is more effective for a 20% strength decrease. For the hip and shoulder, increasing strength within 2% and decreasing strength...
within 10% seems to have comparable effects on jump height. However, the shoulder becomes less effective in changing height for larger strength gain/loss.

**Discussion**

It will be beneficial for coaches and athletes to know which joints should be focused on during their workout exercise to have the most effective training results. Since experimental measurements may be biased by various uncontrollable factors, computer simulation is used in this study. The present human model neglects muscle biarticularity and tendon elasticity. The former has been shown to have very little effect on jump height in simulations replacing gastrocnemius with a uniarticular ankle plantar flexor (Pandy & Zajac, 1991; Van Soest et al., 1993). The inclusion of series elastic element at the ankle joint improved the agreement between actual and simulated movement by less than 2% (Yeaton & King, 2002). Although torque production according to Equation 1 may not be a perfect global parameterization, its shape (a three-dimensional surface) is similar to those measured experimentally (Yeaton & King, 2002; King & Yeaton, 2005). In addition, the current model has other limitations because it assumes full body symmetry on both sides and is actuated by a single torque generator at each joint. Thus, the model is unable to deal with body asymmetry, coactivation, and synergy effects. However, since the model reasonably reproduced actual jumping motion and similar models have been validated (Fujii & Hubbard, 2002; King & Yeaton, 2004; King & Yeaton, 2005), these simplified assumptions are deemed reasonable.

The downhill simplex algorithm is known to be a local rather than a global optimization method (Nelder & Mead, 1965; Press, 1997). Starting the optimization near a local optimum will inevitably end up being trapped at this point. To avoid this problem, a great number of varying initial guesses randomly distributed in the design space are used. Optimal solutions presented here are the best ones chosen from those local optimum points. In addition, to ensure that the current solutions are truly optimal, the genetic algorithm (Belegundu & Chandrupatla, 1999) is employed first. Followed by the downhill simplex method, identical solutions are obtained. These solutions, i.e., optimizers for the objective function, are joint activation nodal values (plotted with cubic spline interpolation in Figure 4) that result in maximum jump height.

The present model reasonably reproduces joint kinematics in actual jumping motion (Figure 3 and Table 1). Maximum isometric joint torque values calculated by the optimization procedure are comparable with those (550, 500, and 600 N·m for the ankle, knee, and hip, respectively) in a previous study that used a heavier (85 kg) model (Selbie & Caldwell, 1996). Joint torque values produced during jumping motion (Figure 4) are also comparable with those measured experimentally (Feltner et al., 2004; Lees et al., 2004). The considerable negative value in hip activation reveals the importance of countermovement before extending for maximum jump height.

Although muscle EMG was not recorded in the present experiment, optimal simulated joint torque activation patterns somewhat resemble actual muscle activities. Joint activation reaches its maximum in the order of shoulder, knee, hip, and ankle. This partial agreement between the current results and the proximal-to-distal strategy (Bobbert & Van Ingen Schenau, 1988) is probably due to the inclusion of arm motion. Lees et al. (2004) reported a substantial (19%) decrease in biceps femoris activity when the arms were added to the jumping motion. This would cause hip torque reduction while allow an increase in the knee torque (Lees et al., 2004), which also supports the current results in which the knee is maximally activated shortly before the hip.

Same as previous studies (Bobbert & Van Soest, 1994; Nagano & Gerritsen, 2001), reoptimization of activation after joint strengthening is necessary. If identical activation pattern is applied to strengthened joints, jump height is decreased by about 2 cm rather than increased. This indicates that strength training solely may not be an effective way to enhance performance unless it is combined with practicing the actual movement.

Although there is infinite number of possibilities for producing the same joint torque, the experimental studies (Cannon et al., 2007; Davies & Young, 1983; Kon et al., 1978) have assured us that there must be at least one feasible muscle force combination for producing the increased torque after training. Except for the shoulder, maximum isometric joint torque values are around 500 N·m. Thus 20% of change is approximately equivalent to changing the torque values by 100 N·m for the ankle, knee, and hip. Although changing shoulder $T_{max}$ by the 100 N·m is probably unfeasible, the results may be valuable information since they show theoretically what happens when actual experiments cannot be performed.

The knee and ankle are the most important joints for jump height (Figure 6). The 3-cm height increase for 20% increase in knee extensors in the results of Bobbert and Van Soest (1994) is very close to the current simulation. Although jump height increase due the combined effect of enhanced muscle strength, maximum contraction velocity, and activation amplitude is larger (Nagano & Gerritsen, 2001), the influence is in the same order (knee, ankle, and hip) as the current results.

The present study investigates in more detail the influence of strength decrease on jump height. Surprisingly, height decreases the most due to losing strength in the ankle rather than the knee. One possible explanation might come from the coordination strategy adopted by the human subject and consequently the simulation model (that initially matches the measured motion). That is, the heel is lifted and strikes the ground before upward thrust (Figure 3). With weakened joints, the model probably relies on this strategy more, and decreasing ankle strength may deteriorate more severely the ability to employ this strategy than decreasing knee strength.
Whether this assumption is true or the ankle is indeed the most important joint when strength is decreased will require further studies.

Although the shoulder is the least effective joint for changing jump height (Figure 6), its influence should not be overlooked. A 100 N·m increase in shoulder strength (over 50% increase) results in larger jump height than that achieved after the same amount of strength increase (about 20% increase) in the hip. Losing shoulder strength influences jump height more than gaining strength. A simulation with no shoulder strength is also performed and the height is decreased by nearly 9 cm. This is very close to the height difference of 8.6 cm and 10.1 cm between jumps with and without arms in experiments performed by Lees et al. (2004) and Hara et al. (2006), respectively.

The somewhat linear strength–height relation is similar to that in Nagano and Gerritsen (2001) in which the total effect of strengthening/weakening all three joint extensors (ankle plantar flexor, knee, and hip extensors) is considered. The more complex rather than linear strength–height relation should be the consequence of countermovement and arm motion, which were not considered previously (Bobbert & Van Soest, 1994; Nagano & Gerritsen, 2001).

In addition to solely joint strength, possible effects from the coordination among joints are also investigated. Nagano and Gerritsen (2001) reported that the sum of height increase, caused by changing neuromuscular parameters in ankle plantar flexors, knee extensors, and hip extensors separately, is smaller than the increase due to simultaneous modification of parameters in all these muscles. However, this effect is not found with the present model. That is, height increase from simultaneous increase in strength for all four joints is about the same as the sum of increase due to individual change in joint strength. This discrepancy may be the result of manipulating altogether muscle strength, shortening velocity and maximum activation amplitude in Nagano and Gerritsen’s study (2001). Muscle biarticularity, though aids only slightly in jump height, may also be a reason for the enhanced coordination among joints and the additional height increase.

In conclusion, the knee and ankle are the most effective joints in changing jump height. Although the shoulder is the least effective joint for the same amount of percentage increase/decrease in strength, its influence should not be overlooked. Joint activation patterns should be reoptimized after joint strengthening to increase jump height. With the present model assumptions, additional height increase due to the coordination among joints is not observed. Since the model is two-dimensional and joint torque only represents effective muscle function, effects of body asymmetry or individual muscle action will be investigated by a three-dimensional musculoskeletal model in future studies.

References


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**Appendix**

**Appendix Table 1** Model Anthropometric Parameters

<table>
<thead>
<tr>
<th></th>
<th>Mass (kilograms)</th>
<th>Length (meters)</th>
<th>Distal end to CM (meters)</th>
<th>Moment of inertia (kg·m²)</th>
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</thead>
<tbody>
<tr>
<td>Feet</td>
<td>1.63</td>
<td>0.125</td>
<td>0.105</td>
<td>0.005</td>
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<tr>
<td>Shanks</td>
<td>6.01</td>
<td>0.385</td>
<td>0.219</td>
<td>0.075</td>
</tr>
<tr>
<td>Thighs</td>
<td>15.01</td>
<td>0.420</td>
<td>0.256</td>
<td>0.227</td>
</tr>
<tr>
<td>HT</td>
<td>26.36</td>
<td>0.501</td>
<td>0.316</td>
<td>1.832</td>
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<tr>
<td>Arms</td>
<td>5.99</td>
<td>0.562</td>
<td>0.301</td>
<td>0.190</td>
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<tr>
<td></td>
<td>Sources</td>
<td>Obtaining methods</td>
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<tr>
<td>Model initial joint</td>
<td>Initial joint angles are from measured data. Initial activations are</td>
<td>Simplex algorithm (with varying initial guesses and restarting optimization from newly found optima)</td>
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<td>angles and</td>
<td>calculated for holding that posture.</td>
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<td>activation.</td>
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<tr>
<td>Joint activation</td>
<td>Variables that can be optimized in this study.</td>
<td>Downhill simplex algorithm (with varying initial guesses and restarting optimization from newly found optima)</td>
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<td>nodal values (actual</td>
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<td>model motion).</td>
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<tr>
<td>Angle–torque relation</td>
<td>Pandy et al., 1990 (ankle, knee, and hip extension). Hoy et al., 1990</td>
<td>Simulation with experimental validation</td>
<td></td>
<td></td>
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<tr>
<td>$f(\theta)$</td>
<td>(ankle, knee, and hip flexion). Otis et al., 1990 (shoulder).</td>
<td>Simulation with experimental validation</td>
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<tr>
<td></td>
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<td>Experimental measurements</td>
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<td>Angular velocity–torque</td>
<td>Selbie &amp; Caldwell, 1996.</td>
<td>Based on Alexander (1990) and previous experiments.</td>
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<td>relation $h(\omega)$</td>
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<td>and constants $\omega_0, \Gamma$.</td>
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<td>Passive torque</td>
<td>Pandy et al., 1990.</td>
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<td>simulating heel–ground contact.</td>
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<td>dA/dt</td>
<td>$ constraint.</td>
<td>According to muscle activation rise and decay time constants (Pandy et al., 1990).</td>
<td>Based on previous experiments.</td>
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