THE EFFECT OF COORDINATION ON VERTICAL JUMPING PERFORMANCE

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The purpose of this study was to gain a better understanding of why coordination, or the timing of muscle actions, affects performance in vertical jumping. A forward dynamic simulation model was used, which calculated the motion corresponding to stimulation-time input to the muscles. A maximum-height jump was found by optimizing the stimulation-time input. Jump height amounted to 41 cm. Subsequently, the solution space was constrained by demanding that soleus was switched on 100 ms before any of the other muscles, and the stimulation-time input was again optimized. Jump height in the constrained jump was 9 cm less than that in the maximum-height jump, primarily because glutei and hamstrings produced less work. In the constrained jump, the glutei dissipated energy early in the push-off, and during shortening they produced less energy because their shortening velocity increased too quickly. These undesired effects could be explained by the effects of premature rotation of the foot on the motion in the hip joint. The analysis presented in this paper shows by which mechanisms the timing of muscle actions affects performance in vertical jumping.

KEY WORDS: human, model, explosive movements, control, simulation, optimization.

INTRODUCTION: It is generally acknowledged that athletic performance depends on both the properties of the musculoskeletal system and the control of this system. The control of the musculoskeletal system, popularly referred to as coordination, timing, or technique, essentially involves the specification of the amount of stimulation of each muscle as a function of time. From a theoretical point of view, the properties of the system determine the maximum performance that can be achieved. However, given the properties of the musculoskeletal system and the external forces, a specific muscle stimulation pattern leads to a specific pattern of segmental rotations, and therewith to the actual performance achieved, which may be less than the maximum performance. Kinematic and electromyographic patterns observed during various movements can be found abundantly in the literature. It has often been reported that different subjects display similar, stereotyped, kinematic patterns. This is the case, for example, in vertical jumping.

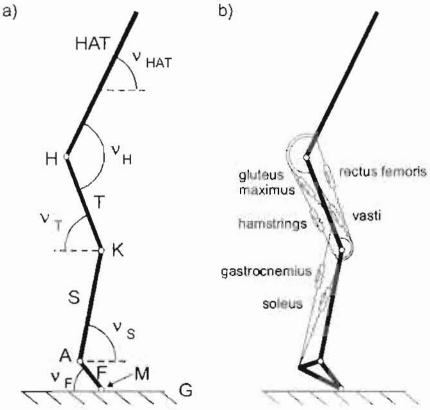


Figure 1. a) Definition of segment angles φ of the feet (F), shanks (S), thighs (T) and head-arms-trunk (HAT). In experiments these segments were defined by markers placed on fifth metatarso-phalangeal joint (M), ankle (A), knee (K), hip (H) and neck. The definition of hip joint angle is also shown. **b)** Model of the musculoskeletal system used for forward dynamic simulations, comprising six muscles represented by Hill-type muscle models. The mass of the model was 82 kg.

In a previous study (Bobbert & van Zandwijk, 1999), markers were placed on the body to define the angles of upper body (head, arms and trunk), thighs, shanks and feet (Fig. 1a). The angle-time histories displayed by different subjects performing vertical squat jumps converged to a common pattern, in which a proximo-distal sequence could be discerned (Fig. 2, Fig. 3): first rotation of the upper body, subsequently rotation of the upper legs and lower legs, and finally rotation of the feet. In the literature, several ideas have been presented as to why this sequence occurs (Hudson, 1986).

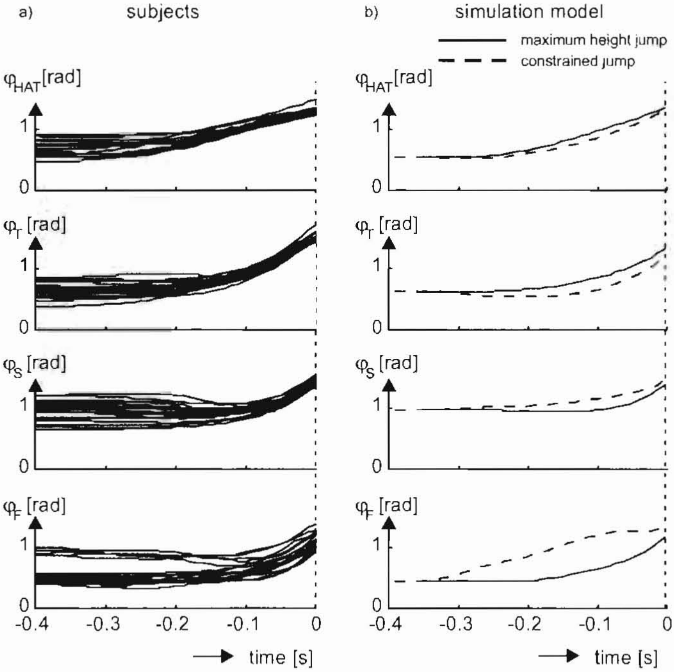
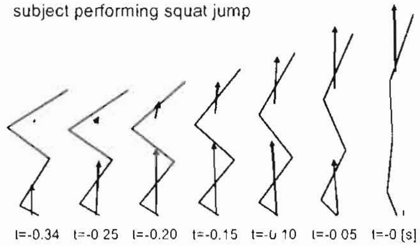


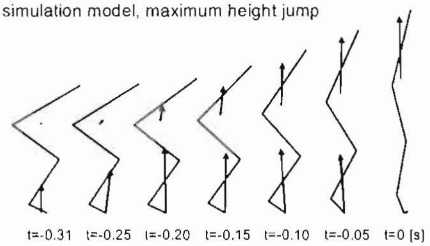
Figure 2. a) Segment angle-time histories (see definition in Fig. 1a) measured in a study of 21 subjects performing vertical squat jumps (Bobbert & van Zandwijk, 1999). **b)** Same variables as in (a) for the optimal solutions for the simulation model, obtained in unconstrained and constrained optimization of muscle stimulation onset times using height reached by the center of mass as criterion. In the constrained optimization, it was demanded that soleus was stimulated first and that the onset times of the other muscles were delayed by at least 100 ms.

It has been proposed, for example, that subjects are actually trying to rotate all segments simultaneously, but that the acceleration of the upper body initially forces the knee and ankle into additional flexion, so that a proximo-distal sequence ensues (Hopper, 1973). However, if subjects wanted to rotate their segments simultaneously, they would surely have been able to learn the stimulation pattern required to realize this. It seems more logical to hypothesize that for vertical jumping the pattern of segment rotations presented in Fig. 2 is itself the optimal pattern for jumping, given the properties of the musculoskeletal system. In vertical jumping, achievement may be defined as the height to which the center of mass is projected into the air. After take-off, the height of the center of mass increases only because kinetic energy is converted to potential energy. Consequently, jump height depends on the effective energy of the center of mass at take-off, i.e. the sum of potential energy and kinetic energy due to the vertical velocity of the center of mass. This effective energy, in turn, is the product of the amount of work produced by the muscles during the push-off and the efficacy ratio, denoting which fraction of this work converted into effective energy (Bobbert & van Soest, 2001). Thus, if coordination affects performance, it must affect either the work output of the muscles, the efficacy ratio, or both.

a) subject performing squat jump



b) simulation model, maximum height jump



c) simulation model, constrained jump

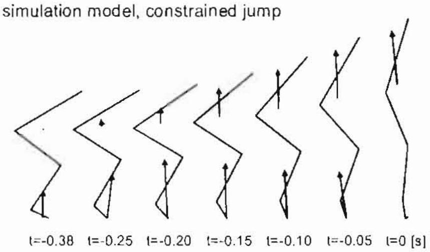


Figure 3. Stick diagrams of the push-off in maximum height squat jumping for a typical subject **(a)** and for the maximum height jump and the constrained jump of the simulation model (**b-c**). In each panel the leftmost stick diagram depicts the position at the start of upward motion of the center of mass, the rightmost one the configuration at the last frame before take-off, and the intermediate diagrams are spaced 50 ms in time, starting at the instant of take-off (t=0) and counting backwards in time. In each stick diagram, the ground reaction force vector is represented with its origin at the center of pressure, and the velocity vector of the center of mass is shown with its origin at the location of the center of mass.

To investigate the effects of coordination, one needs to manipulate the muscle stimulation pattern and observe the ensuing movement pattern and performance. Unfortunately, human subjects are unable to change their control and still produce a maximum-effort jump. The required manipulations can be performed, however, in an optimal control model of vertical jumping. In a recent study (Bobbert & van Soest, 2001), such a simulation model was used to analyze the effect of a premature rotation of the foot, caused by an early activation of the soleus. It was found that jump height decreased primarily because muscle work was reduced, and to a lesser extent because the efficacy ratio was reduced. The present study follows up on this finding, with the purpose of gaining a better understanding of how coordination affects the work output of muscles in vertical jumping.

METHOD: For the simulations we used a two-dimensional forward dynamic model of the human musculoskeletal system (Fig. 1b). The model has been described in detail elsewhere (van Soest, Schwab, Bobbert, & van Ingen Schenau, 1993). It had muscle stimulation as a function of time as independent input and calculated internal states and forces of muscles, as well as the motion of body segments. Specifically, the model consisted of four rigid segments representing upper body, thighs, shanks and feet. The segments were interconnected by hinge joints representing hip, knee and ankle joints. Six major muscle-tendon complexes actuated this skeletal sub-model: hamstrings, gluteus maximus, rectus femoris, vasti, gastrocnemius and soleus. Each of them was represented using a Hill-type muscle model. This model consisted of a contractile element (CE), a series elastic element (SEE) and a parallel elastic element (PEE), and has also been described in full detail elsewhere (van Soest & Bobbert, 1993). Briefly, behavior of SEE and PEE was determined by a quadratic force-length relationship. Behavior of CE was more complex: CE contraction velocity depended on active state, CE length and force. The relationship between active state (essentially representing the relative amount of Ca^{++} ions bound to troponin) and muscle stimulation STIM, was modeled as a first order process (Hatze, 1981). STIM, ranging between 0 and 1, was a one-dimensional representation of the effects of recruitment and firing frequency of α-motor neurons. To find the maximum-height jump, the model was first put in a starting position corresponding to the semi-squatted position selected by subjects, with the heels touching the ground. The initial STIM levels of the mono-articular glutei, vasti and soleus were set in such a way that static equilibrium was achieved in this position. Subsequently, STIM was allowed to switch once from this initial value to the maximal value of 1.0 and thereafter had to remain maximal until take-off. Under this restriction, the motion of the body segments, and therewith performance of the model, depended on six parameters: the instants at which the STIM of each of the muscles switched from the initial value to the maximal value. Thus, an optimization problem could be formulated: finding the combination of six switching times that produced the maximum value of the height achieved by the center of mass. This problem was solved with the help of a genetic algorithm (van Soest & Casius, 2002). The optimization ran for 500 generations of a population of 100 chromosomes, each of which was a bit-string coding one combination of the six stimulation onset times. Control was manipulated as follows. We constrained the stimulation onset space by demanding that the soleus was switched on 100 ms before any of the other muscles, and re-optimized the stimulation onset times of the other muscles. This re-optimization ensured that in spite of the manipulation, the system was still performing a vertical jump. This jump will henceforth be referred to as the "constrained jump".

RESULTS AND DISCUSSION: To evaluate the model, the maximum height jump of the model was compared with maximum height jumps of the subjects. The movement of the model corresponding to the optimal combination of switching times closely resembled that of the subjects, as illustrated in Fig. 2 and Fig. 3. Just as in the subjects, the kinematic pattern of the maximum height jump of the model involved a proximo-distal sequence in joint rotations, although the foot started to rotate relatively early in the simulation. We take this correspondence between experimental and simulation results as an indication that the model satisfactorily represented the salient characteristics of the real system and that the optimization criterion was properly chosen. In the optimal solution, the hamstrings were switched on first, immediately followed by the glutei and gastrocnemius (Table 1).

Table 1. Stimulation onset times of the muscles in the simulated maximum height jump and in the constrained jump. Times were expressed relative to take-off (t=0).

	SOL	GAS	VAS	REC	GLU	HAM
maximum-height jump	-0.267	-0.282	-0.253	-0.139	-0.283	-0.306
constrained jump	-0.386	-0.090	-0.236	-0.088	-0.286	-0.286

SOL: soleus; GAS: gastrocnemius; VAS: vasti; REC: rectus femoris; GLU: glutei; HAM: hamstrings.

In the solution for the constrained optimization problem, hamstrings and glutei were activated precisely 100 ms after the soleus, i.e. as soon as the imposed delay was over, and gastrocnemius was not activated until just before take-off. Jump height was reduced by 9 cm. This was primarily due to a decrease in kinetic energy of the center of mass at take-off, which in turn was primarily due to a decrease in the total work output of the muscles (Table 2).

Table 2. Values for selected variables related to jumping performance in the simulated maximum height jump and in the constrained jump.

	$\Delta y_{CM,\,max}$	$\Delta E_{pot,\,to}$	$E_{kin,\,to}$	W_{tot}	R_{eff}
maximum-height jump	0.41	308	287	686	0.87
constrained jump	0.32	304	220	632	0.83

$\Delta y_{CM,\,max}$: jump height, i.e. maximum height of CM relative to height in upright standing;
$\Delta E_{pot,\,to}$: potential energy at take-off relative to potential energy in starting position;
$E_{kin,\,to}$: kinetic energy of center of mass at take-off dur to vertical velocity of center of mass;
W_{tot}: total work done by the muscles during the push-off phase;
R_{eff}: efficacy ratio.

Only about 3 cm of the drop in jump height was explained by a reduction in the efficacy ratio. When we look at the work contributions of the individual muscles, we note that in the constrained jump soleus produced more work, but the total total work output of the muscles was less (Table 3). This was due to a reduction in the work of gastrocnemius, glutei and hamstrings (Table 3).

Table 3. Work produced by the muscles during the push-off in the simulated maximum height jump and in the constrained jump.

	SOL	**GAS**	**VAS**	**REC**	**GLU**	**HAM**
maximum-height jump	87	50	171	10	244	125
constrained jump	142	5	173	5	207	100

SOL: soleus; GAS: gastrocnemius; VAS: vasti; REC: rectus femoris; GLU: glutei; HAM: hamstrings.

The reduced work output of gastrocnemius may be explained as follows. The activation of soleus caused plantarflexion and a shortening of the gastrocnemius. Since gastrocnemius was not activated until shortly before take-off, it traveled the major part of its shortening range at submaximal force, and produced less work than in the maximum-height jump. The late activation of gastrocnemius, and the concomitant reduction in work output of this muscle, may be interpreted as an attempt by the optimization algorithm to counterbalance the impending adverse effects of premature activation of soleus. The reduction in the work output of glutei and hamstrings, however, was an inevitable consequence of the early rotation of the foot caused by premature activation of soleus, as will be explained below. Fig. 4 presents force and shortening velocity of the glutei as a function of contractile element length. The work produced is equal to the surface under this curve. It can be seen that in the maximum-height jump, the contractile elements were only shortening and producing work. In the constrained jump, however, they initially lengthened while exerting force, meaning that they were dissipating part of the extra work produced by soleus. Specifically, glutei dissipated 10 J in the constrained jump. During the concentric phase in the constrained jump, the force of glutei dropped faster with distance shortened than in the maximum height jump (Fig. 4), which was caused by the fact that shortening velocity increased faster with distance shortened.

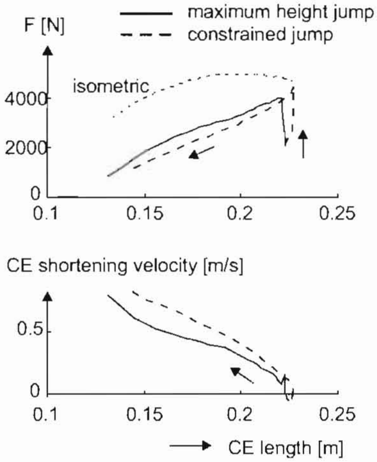


Figure 4. Force and shortening velocity of contractile elements (CE) of glutei plotted as function of length of CE, for the maximum-height jump and the constrained jump of the simulation model. The parabola labeled "isometric" represents the force that can be produced at maximum active state and zero shortening velocity. Arrows indicate the direction of time.

Moreover, at take-off, the contractile elements were shortened less in the constrained jump than in the maximum-height jump. The same was true for hamstrings. Why did the glutei dissipate energy early in the push-off in the constrained jump? Because the premature activation of soleus initially accelerated the hip joint into flexion (note the negative angular velocity of the hip joint in Fig. 5)! This was due to the dynamic coupling of the segments (Zajac & Gordon, 1989). In less abstract terms, the activation of the soleus caused an upward acceleration of the knee joint (Fig. 5). Because the knee and hip joint moments were not adapted, the heavy segments proximal of the knee could not match this acceleration, and the hip joint was pushed into flexion. Why did the shortening velocity of contractile elements of glutei and hamstrings increase faster with distance shortened in the constrained jump than in the unconstrained jump? Essentially, this was because the upward acceleration of the knee was missing in remainder of the push-off phase (except for the last 30 ms, Fig. 5). During the push-off, the upward acceleration of the knee joint is needed to counteract the effect of the muscles that accelerate the hip joint into extension, and thereby prevent a rapid increase in hip joint angular velocity. In the unconstrained jump, the foot had already rotated and could no longer contribute to vertical acceleration of the knee. As a result, the hip joint angular velocity increased faster in the constrained jump than in the maximum height jump (Fig. 5). Finally, why were the hip extensor muscles shortened less at take-off in the constrained jump? To understand this, we need to realize that the motion of the segmental mass centers has a circular component. This circular component involves centripetal accelerations, which have a negative contribution to the upward acceleration of the center of mass. The muscle forces, by producing angular accelerations of the segments, have a positive contribution to the upward acceleration of the center of mass. In the constrained jump, this latter contribution became insufficient in a configuration in which the hip joint was less extended than in the maximum-height jump (Fig 3), mostly because the forces of the hip joint muscles had dropped too far (Fig. 5). This latter drop, in turn, was caused by the rapid increase of the angular velocity of hip extension in the constrained jump.

CONCLUSION: In this simulation study, it has been shown that a premature activation of soleus has a dramatic effect on vertical jumping performance. This effect was attributed primarily to a drop in the work output of glutei and hamstrings. In the jump with premature activation of soleus, the glutei dissipated energy early in the push-off, and both glutei and hamstrings generated less energy during shortening because their shortening velocities increased too quickly.

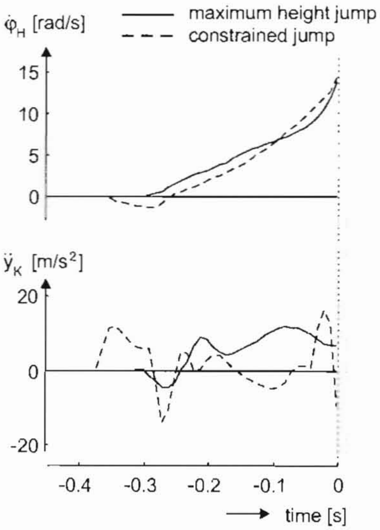


Figure 5. Time histories are presented for the angular velocity of hip extension (top) and the vertical acceleration of the knee joint (bottom), for the maximum-height jump and the constrained jump of the simulation model. Time is expressed relative to take-off (t=0).

These detrimental effects were explained by the effects of premature rotation of the foot on the motion in the hip joint. The analysis presented in this paper shows how the timing of the activation of one muscle can affect the work output of other muscles, and clarifies why coordination is so important in explosive movements such as jumping.

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