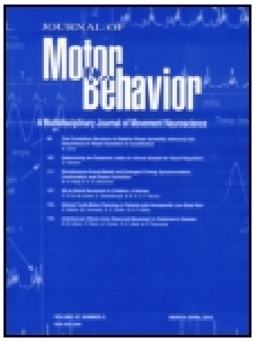

Journal of Motor Behavior

ISSN: 0022-2895 (Print) 1940-1027 (Online) Journal homepage: http://www.tandfonline.com/loi/vjmb20

Simulating the Impact During Human Jumping by Means of a 4-Degrees-of-Freedom Model With Time-Dependent Properties

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Journal of Motor Behavior, 2001, Vol. 33, No. 3, 286–294

Simulating the Impact During Human Jumping by Means of a 4-Degrees-of-Freedom Model With Time-Dependent Properties

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ABSTRACT. The authors simulated the vertical movements of a jumper and the force time courses by means of a 4-degrees-of-freedom model consisting of 4 masses, springs, and dampers. Of the motions simulated, only that of the mass imitating the trunk corresponded to the measured data. The best fit to the measured force curves were obtained in the simulation in which time-dependent model parameters were used. From the results, the authors concluded that at the beginning of the landing, a jumper behaves like a 2-mass model in which the leg segments (thighs, shanks, and feet) effectively combine into 1 mass. After approximately 60 ms, the connections between the leg segments become more compliant and the jumper behaves like a 4-mass model with a soft coupling between the leg segments. The process is equivalent to an increase of the degrees of freedom of the movements. At the end of the ground contact phase during hopping, the jumper has to contract the muscles in order to reach the envisaged jump height. In the model, that contraction could not be satisfactorily simulated.

Key words: ground reaction force, muscle activity, phase plane, vertical movements

The increased popularity of gymnastics has brought with it an increase in the number of injuries of the lower limb and, in particular, the ankle (Snook, 1979, Teitz, 1983). Özgüven and Berme (1988) calculated that the average college gymnast dismounts in excess of 200 times a week from various exercises. Furthermore, it is important to note that high impact forces are being developed during the ground contact of the feet. Those two conditions could be responsible for the numerous injuries encountered.

In previous research, the landing following a vertical jump has been divided into a passive phase and an active phase (Nigg, Denoth, & Neukomm, 1981; Nigg, Denoth, Neukomm, & Segesser, 1979). The passive phase begins after ground contact and lasts 30–40 ms. Because of the latency time, the leg muscles, which may already be stimulated and cannot change their activity within that short phase, do not actively respond to the sudden increase in the ground reaction force. Dorsiflexion of the ankle joint triggers a stretch reflex, however, resulting in an increase in the electromyographic activity of the gastrocnemius muscle, which can be seen approximately 40 ms after the feet touch down (Dietz, Schmidtbleicher, & Noth, 1979; Gollhofer & Schmidtbleicher 1988). In the active phase, the jumper controls the muscles and thereby the movements of the body in an effort to establish an erect posture or to prepare and to carry out the next take-off during hopping.

To analyze the influence of potential factors on the diminution of the ground reaction force peaks and the transmission of the forces from the feet to the trunk, one can simulate the movements of the human body by using mechanical models. The models used in those simulations are built like simple vibratory systems that are adapted to the properties of the human body. The model described in Fritz (1981) consists of two masses, springs, and dampers. For a similar model, consisting of two masses, a massless landing surface, and two springs and dampers, Mizrahi and Susak (1982) assessed the model's parameters by measuring ground reaction forces and accelerations of the greater trochanter. Özgüven and Berme (1988) measured ground reaction forces during landings from a jump height of 0.45 m onto an "infinitely" stiff surface. From the time course of the forces, they computed the natural frequencies of their 2-degrees-of-freedom (*df*) model and the damping ratios. The simulated forces sufficiently approximated the measured forces in the passive phase only, however. By means of a model consist-

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ing of only one mass and spring, Farley and Morgenroth (1999) showed that during hopping in place at 2.2 Hz, leg stiffness increases with jumping height.

In the above models, the two legs were represented by only one mass. Our aim in the present study was to accurately simulate the vertical movements of both the human trunk and the legs and the ground reaction forces during landing after a jump of 0.45 m height and during hopping. Hopping is a cyclic movement in which during the ground contact phase the deceleration of the downward movement of the body continuously changes into the upward acceleration so that the body can take off for the next flight. We executed the simulations by using a model consisting of four masses connected by springs and dampers, as described in detail by Fritz (1999). The simulated forces were adjusted to the time courses of measured forces during both the passive and active phases of the landing. For both activities, the forces and the movements were measured by Fritz (1999).

Method

Model

The model used in thus study consists of four discrete masses (Figure 1). Left–right symmetry is assumed in the model, and the masses m_1, m_2, m_3, and m_4 represent, respectively, the feet, the shanks, the thighs, and the rest of the body. The masses are vertically connected by viscous dampers and linear springs. Thus, by compressing and extending those elements, the masses can shift toward and away from each other along their vertical axes. Motions in the horizontal direction as well as rotational motions are not possible.

In the human body, the angle between two adjacent body segments—for example, the thigh and the shank (Figure 2)—is reduced or enlarged by the contraction of the muscles and in response to external forces. Thereby, the antagonistic muscles are stretched so that they passively exert forces, which decelerates the movements. The springs and dampers of the conceptual model illustrated in Figure 2 span like chords between the leg segments. When the angles are changed during the movements, the springs and dampers are tensed or compressed. They resist the deformations by exerting forces similar to those exerted by stretched leg muscles. As in the conceptual model, we simulated the muscles that cross the ankle, the knee, and the hip by using spring and dampers in the model used for the computations.

Mass m_1 is connected to the ground by spring c_1 and damper d_1 (Figure 1). The spring and the damper imitate the plantar tissues of the feet, which are compressed by the ground reaction force. During the flight phase, in which the feet do not touch the ground, the values of the spring and damper are set to zero.

On the basis of the equilibrium between the inertial forces, the forces of the springs and dampers, and the weight forces, one can derive an equation of motion for each mass. The four equations can be combined into the differential matrix equation

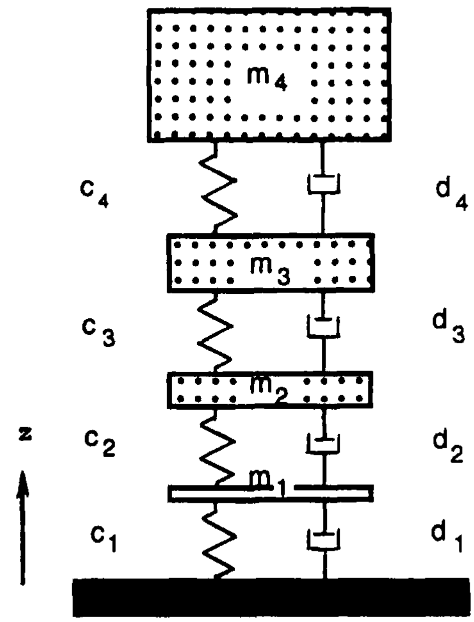

FIGURE 1. Conceptual schematic of the mass–spring–damper model that imitates the jumper during the phase of ground contact (adapted from Fritz, 1999). Masses, m_i, springs, c_i; and dampers, d_i. $i = 1–4$.

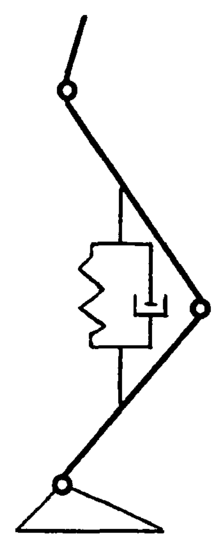

FIGURE 2. Conceptual schematic of the spring and damper spanned like a chord between the thigh–shank angle (adapted from Fritz, 1999).

$$\mathbf{M}\ddot{\mathbf{w}} + \mathbf{D}\dot{\mathbf{w}} + \mathbf{C}\mathbf{w} = \mathbf{f}, \tag{1}$$

where **M**, **D**, and **C** are the matrices of the four masses, the damper, and the spring constants, and **w** and **f** are the arithmetical vectors of the vertical displacements of the masses and the weight forces, respectively.

Mechanical Conditions

In the human system during jumping or hopping, the thighs, shanks, and feet undergo translational and rotational movements. The range of the different movements can be considerable. Nevertheless, one can simulate those movements with the described 4-*df* model under the following conditions:

1. Only the vertical movements of the centers of gravity of the leg segments are simulated by the motions of the model masses.

2. It is assumed in the model that the movements of the segment centers of gravity occur only along the line of action of the vertical ground reaction force. That assumption means that during a flexion of the legs, the joints move in the horizontal direction away from that line.

Mathematical Solutions

One can transform the differential matrix equation by substituting **q**, which is a combination of the displacement vector **w** and the velocity $\dot{\mathbf{w}}$,

$$\mathbf{q} = \begin{vmatrix} \mathbf{w} \\ \dot{\mathbf{w}} \end{vmatrix}, \qquad (2)$$

into the first-order matrix equation

$$\dot{\mathbf{q}} = \mathbf{A}\mathbf{q} + \mathbf{h}, \qquad (3)$$

with **A** and **h** as the state matrix of the system and the extended vector of the weight forces, respectively.

One can solve the first-order matrix equation by using numerical integration. The numerical integration has the advantage over other solutions that the coefficients of the state matrix **A** need not be constant during the simulated movements. In the present study, we integrated the equation by means of a fourth-order Runge–Kutta equation (see mathematics textbooks).

Model Parameters

By using anthropometric data from Dempster (1955), we computed the quantities of the model masses for a jumper with a mass of 74 kg. For the simulation of the landing after a jump, we assessed a first set of the spring values on the basis of the following information:

1. When landing after a jump of 0.45 m height, the first peak of the ground reaction force can amount to about seven times the body weight (Özgüven & Berme, 1988). If only the feet (≈ 3% of the total body mass) are decelerated, the deceleration will be greater than 200 g. A value of that magnitude has not been previously reported in the literature. As a result, in the model the feet and the shanks are connected by a stiff spring c_2 so that they behave like nearly one mass. The deceleration of the combined mass is reduced to the more realistic value of 50 g. For example, the tibia experiences maximal accelerations of 10.6 g during running (Lafortune, 1991).

2. The mass of the feet and shanks together corresponded to the lower mass in the model of Özgüven and Berme (1988), which amounted to 16% of total body weight. Therefore, we set spring c_1 to same value as Özgüven and Berme had set the spring connecting the lower mass with the ground.

3. The value of spring c_4 resulted from the observation that the trunk (m_4) reaches its maximal displacement shortly after the ground reaction force reaches its second peak value. The time between the first ground contact and the maximal displacement equals a quarter of the vibration period.

4. During the landing, the movements of the thighs are similar to those of the trunk. As a result, spring c_3, which is loaded by masses m_3 and m_4 has to be stiffer than spring c_4, which is loaded by mass m_4.

Starting with that a priori parameter set, the values of the springs and dampers were varied until the difference between the simulated time courses of the displacements and the ground reaction force and measured curves was minimized. A sufficient result was obtained when the simulated and the measured curves were similar in shape. In a second set of constants, spring c_3 was much stiffer, so the feet, the shanks, and the thighs built nearly one mass. With the second set especially, the passive peak force should be fitted by the simulated force. From the two parameter sets, we derived a further set in order to simulate the time courses of hopping.

Simulations were also carried out with time-dependent spring and damper values. With those values, one should be able to simulate the changes of the leg muscles activities. During the first 25 ms, the values were kept constant. In the following 40 ms, the values were allowed to vary with the time. Then 65 ms after ground contact, the values were kept constant again. The time intervals were chosen according to the latency time (passive phase) and the electromechanical delay of the muscles. The variation of the values were described by simple nonlinear equations. For mass m_i (i = 1–4), the values of the four springs are given by the following three equations:

$$c_{i\text{hard}} = \text{const.} \quad \text{for } t \leq 0.025 \text{ s.} \qquad (4)$$

$$c_{it} = c_{i\text{soft}} - \frac{c_{i\text{soft}} - c_{i\text{hard}}}{0.04^2} \times [0.065 - (t / x)^2 \quad \text{for } t < 0.065 \text{ s.} \qquad (5)$$

$$c_{i\text{soft}} = \text{const.} \quad \text{for } t \geq 0.065 \text{ s.} \qquad (6)$$

The index *hard* means that masses m_2 and m_3 are connected by a stiff spring, which results in a hard landing with high ground reaction forces and only small flexions in knee and hip joints, as described in the next section. The index *soft* indicates a more compliant spring between the two masses. The time dependence of the four damper values also corresponds to the three equations.

Results

Using the model parameter values listed in Table 1, we simulated the vertical displacements of the four masses and the ground reaction force for the landing after a jump from a height of 0.45 m. On the left side of Figure 3 are shown the time courses resulting from the simulation in which we used in the model a soft spring between masses m_2 and m_3 (see also the third column of Table 1). At initial ground contact, the accelerations of the masses amount to –9.81 m/s^2 and the velocities to –2.9 m/s. After 40 ms, masses m_1 and m_2 reach their maximal displacements. Masses m_3 and m_4 follow, with a time delay of 80 ms. After 600 ms, the displacements of the four masses reach a steady-state value, which results from the compression of the springs by the weight forces. The ground reaction force reaches its highest value (4.2 × body weight [BW]) after 40 ms and then decreases to a minimal value that is less than the weight of the imitated body. Simultaneously with the achievement of steady-state displacements, the ground reaction force equals the body weight.

When we simulated the landing with the second parameter set, the differences between the displacement curves of masses m_1, m_2, and m_3 were found to be small (see parameter values in the fourth column of Table 1 and the right side

TABLE 1
Model Parameters for the Landing and for Hopping

Index i	Mass m (kg)	Landing		Hopping
		Soft	Hard	
		Spring c (N/m)		
1	2.1	105,000	105,000	105,000
2	6.7	300,000	250,000	260,000
3	14.3	22,000	420,000	32,000
4	51.0	12,000	3,000	20,000
		Damper d (Ns/m)		
1		250	250	115
2		150	150	150
3		1,000	380	340
4		1,400	600	440

Note. This model is adapted from Fritz, 1999.

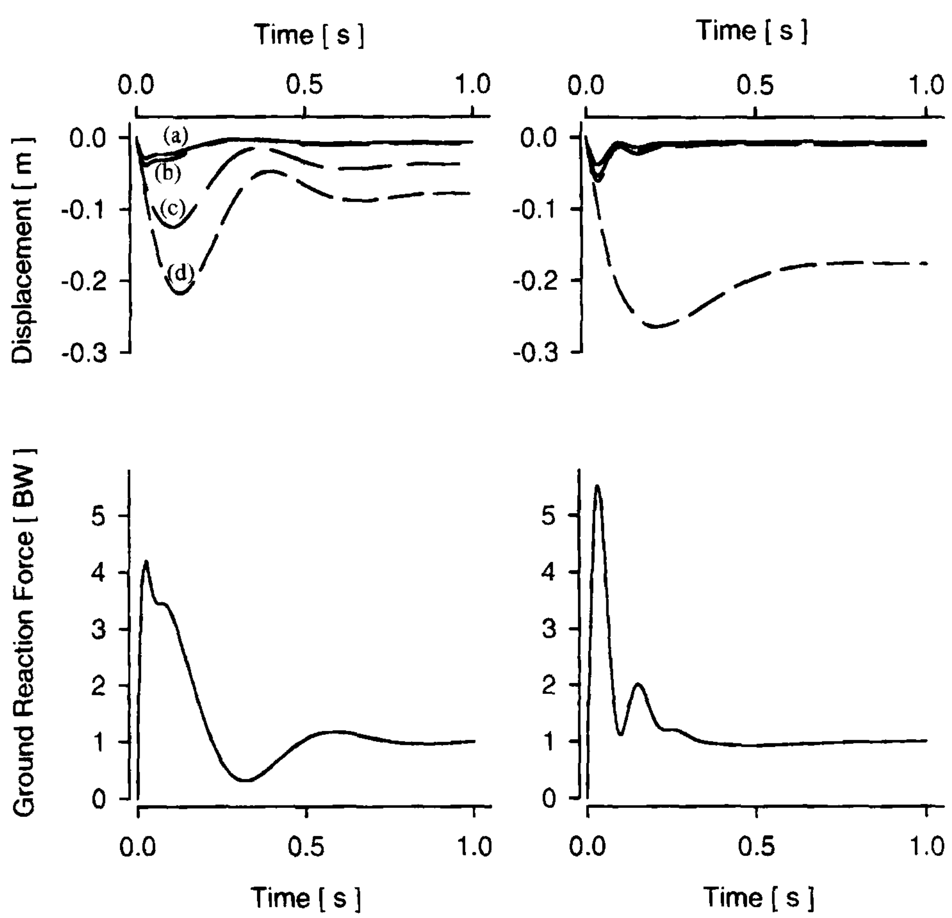

FIGURE 3. Time courses of the displacements and the ground reaction force during landing after a jump, simulated with the time-invariant model parameters. **Left**. Soft spring between masses m_2 and m_3; c_3 = 22,000 N/m. **Right**. Hard spring between masses m_2 and m_3; c_3 = 420,000 N/m. BW = body weight. (a) represents mass m_1; (b) represents mass m_2; (c) represents mass m_3; and (d) represents mass m_4.

of Figure 3). Mass m_4 produces a displacement pattern similar to that of a 1-*df* model containing a single mass, spring, and damper. The ground reaction force increases to a maximal value of 5.5 BW within 30 ms. In contrast to the plateau in the force curve of the previous simulation, a second peak (2 BW) is present. In addition, there is no time when the ground reaction force has a value lower than the body weight.

The time courses plotted in Figure 4 resulted from the simulation with the time-dependent parameters. On the basis of the time relation given by Equations 4, 5, and 6, we allowed the parameters to change from the values in the fourth column of Table 1 to the values in the third column during the (simulated) landing event. The resulting displacements were similar to those illustrated in Figure 3 (left side), except that the ground reaction force rises to the first peak of 5.6 BW after 30 ms. A second peak value of 2.6 BW occurs at 110 ms, and the force decreases to the minimal value of 0.5 BW at 330 ms. After 750 ms, the ground reaction force equals body weight. The phase-plane relations between the velocities and the displacements of each mass are illustrated on the right side of Figure 4. After the initial ground contact, mass m_1 starts to decelerate its downward motion. The velocity of mass m_4 decreases to –3.0 m/s. It is clear from this figure that the velocities of the four masses are zero not only at the end of the landing but also when the masses pass their greatest displacements. During that upward motion, the velocities of the masses reach about 0.9 m/s.

In our simulation of a hopping activity, the four masses move nearly synchronously (Figure 5; see parameters listed in the last column of Table 1). The displacements increase from mass m_1 to m_4. The initial ground contact lasts 255 ms. Then, the masses carry out a second flight phase of 345 ms during which they reach only one third of the preceding jump height. During the first ground contact, the reaction force reaches its first peak (3.7 BW) within 18 ms. When the masses reach their maximal displacements, the force increases to a second peak value of 4.2 BW. The impulse transmitted to the masses by that force–time course is small, however; therefore, in the second and the further flight phases, the masses do not reach the jump height of the former phase again.

Finally, in Figure 6 we show the displacement and the force curves resulting from a hopping simulation in which we used the time-dependent parameters. Those parameters

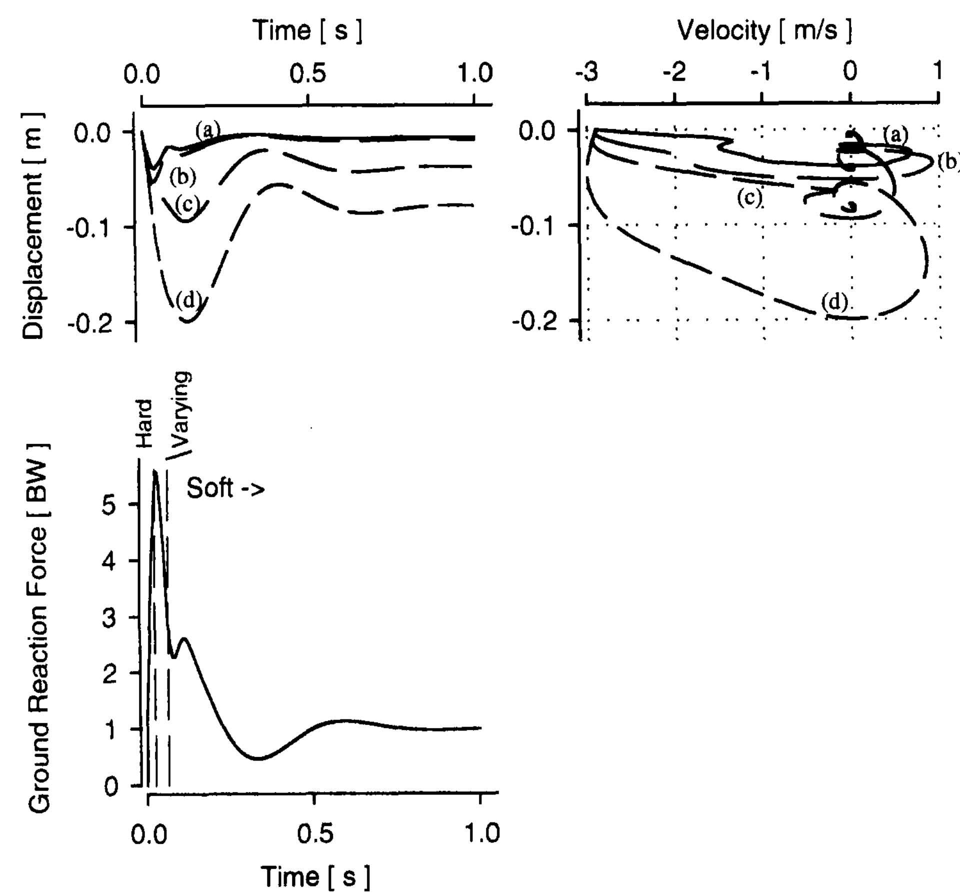

FIGURE 4. Time courses of the displacements and the ground reaction force during the landing after a jump and phase plane between the displacements and the velocities, as simulated with the time-dependent model parameters (line assignments as in Figure 3).

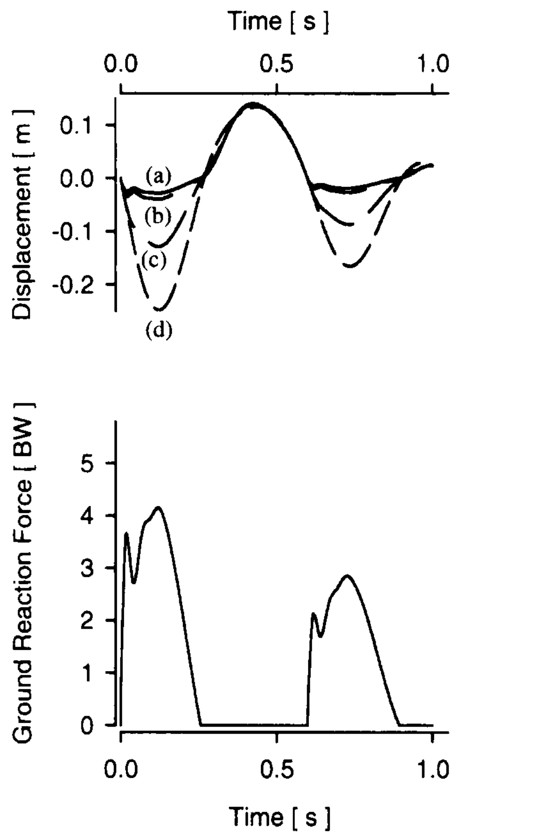

FIGURE 5. Time courses of the displacements and ground reaction force during hopping, as simulated with the time invariant model parameters (line assignments as in Figure 3).

were again derived from Equations 4, 5, and 6. During the first 25 ms, the value of spring c_3 is 3.3 times the value listed in the last column of Table 1, and the corresponding ratio of spring c_4 is 4. The values of the dampers d_1 and d_4 are also elevated during the 25-ms period. When we used those modified values, the first force peak was 4.5 BW, which results in a stronger deceleration of the masses and thus a reduced downward displacement compared with the simulation shown in Figure 5. The stronger deceleration also results in reduced upward displacements during the flight phase. In the phase plane, the increase of the velocities of the masses during ground contact and the decrease during the flight phase can be seen. After passing the top of the flight path, the four masses have nearly the same velocities.

Discussion

In Figures 3–6, we have plotted the simulated displacement–time curves of the four masses. Regarding the sequence of the maxima and minima, there was sufficient correspondence between those curves and the measured movement, which resulted in similarly shaped curves. As an example of measured movements in Figure 7, the curves of Fritz (1999) are shown. The simulated curves show the displacements of the center of gravity of the masses in relation to initial values, which were set to zero for the four masses. During measurements, the movements of markers fixed at the leg joints and the trunk are normally recorded (as was done by Fritz, 1999). The marker movements are described as the displacements of the markers relative to a reference point, for example, a point on the ground. As a result, it is difficult to compare model data with the data of human subjects. The closest relationship between those data would be between the displacements of mass m_4 and the movements of the iliac crest, because a marker at the iliac crest nearly represents the center of gravity of the body.

During the simulated landing, there are great differences between the motions of masses m_1 and m_2 and those of mass m_4 (Figures 3 and 4). As a characteristic feature of the motions, the peaks of the displacements of the two lower masses (m_1 and m_2) are smaller than the corresponding peak of mass m_4, with a ratio of about 0.04 m to 0.20 m. The time delay between those peaks is 100 ms. The relationships between the displacements and the velocities are drawn in the phase-plane diagram in Figure 4, and they are consistent with the results of Minetti, Ardigò, Susta, and Catelli (1998). From the diagram one can see that the velocities increase to zero when the masses rise to their peak displacements. Because the displacements of the lower masses are smaller than that of mass m_4, the lower masses have to decelerate over a shorter distance, and the magnitude of the deceleration is forced to be larger. During hopping, the differences between the peak displacements are relatively large (Figures 5 and 6). However, the masses reach their maximal displacements at nearly the same time. The four masses move with the same rhythm. As a result, less energy is dissipated, and the masses are able to take off for the next flight phase.

By comparing the measured and simulated ground reaction force curves, we found a relation between the sequence of the force maxima and minima in the passive and the active phases (Figure 8). Considering the entire landing phase, the time course of the simulated ground reaction force (Figure 3, left side) sufficiently corresponded with measured courses given by Fritz (1981); Minetti et al. (1998); Natrup, Peikenkamp, and Nicol (1993); and Nigg et al. (1979). In the force–time curve of Fritz (1999; Figure 7, left side), the body weight is not reached at the end of the trial. That finding may have resulted from the subjects' incomplete performance of the jumping task. However, the comparison between that force curve and the simulated curve resulted in a correlation of $r = .75$ ($p < .001$). In each of the experimental studies, the force–time courses were characterized by a peak after about 30 ms, a second peak or plateau, and a minimal force during the deceleration of the upward movement. In contrast, the first peak of the simulated force when using the soft spring was much lower than the average peak measured by Özgüven and Berme (1988) for the same drop height (ratio 4.2 to 5.9 BW). In the model with the second set of parameters, including the stiff spring

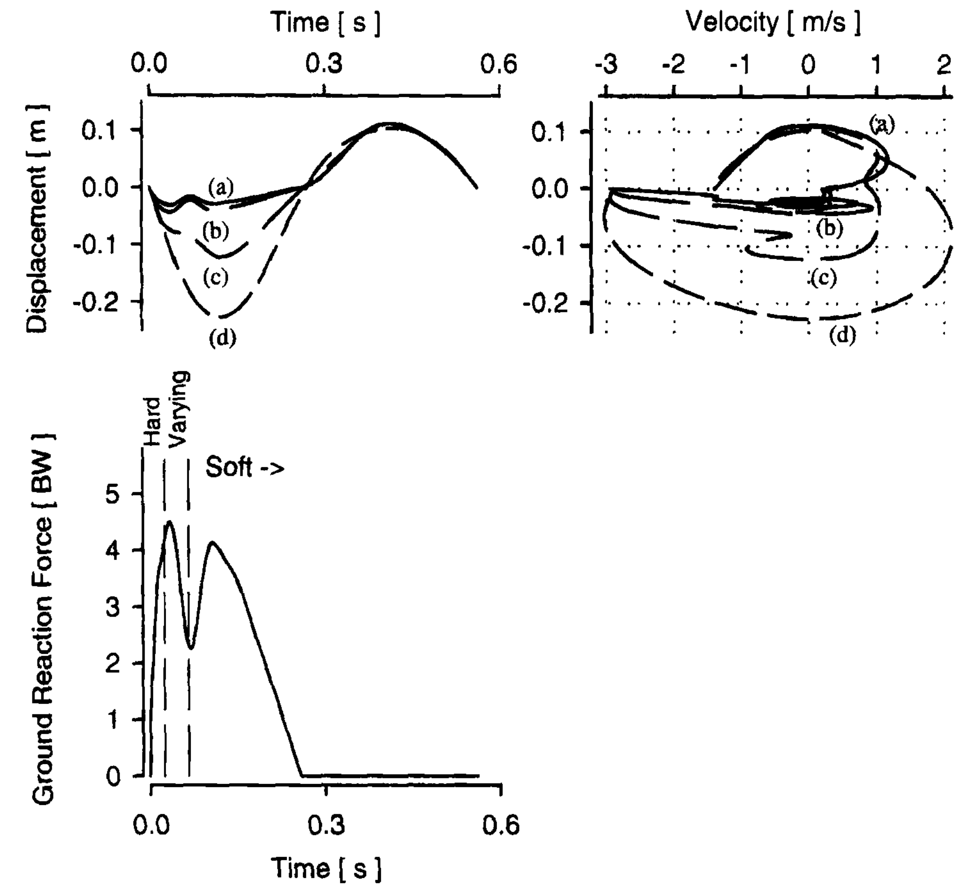

FIGURE 6. Time courses of the displacements and the ground reaction force during hopping and phase plane between the displacements and the velocities, as simulated with the time-dependent model parameters (line assignments as in Figure 3). BW = body weight.

c_3, the first force peak reaches 5.5 BW and instead of a plateau a second peak occurs (Figure 3, right side). In addition, the force does drop to a minimal value lower than body weight. Those changes of the parameter values resulted in a correlation of $r = .74$ ($p < .001$). When one compares the two force curves in Figure 3, it becomes clear that during the first 200 ms the ground reaction force simulated with the stiff spring c_3 shows a similar shape as the measured curves and that during the rest of the landing phase our use of the softer spring improved the similarity between the simulated curve and the curves measured during human performance.

The comparison of the two force curves (Figure 3) and the human data leads to the following observations:

- At the beginning of the landing, a jumper behaves like a two-mass vibratory model. The relatively big mass created by combining the thighs, the shanks, and the feet has a larger deceleration magnitude than the mass of the upper body. That results in a higher peak force than is seen when (simulated) leg segments are connected by softer springs. In the model, we simulated that behavior by means of the stiff springs between masses m_1 and m_2 and between m_2 and m_3.
- The stiff connections between the thighs, the shanks, and the feet reduce the magnitude of deceleration of those segments. Thus, the resultant deceleration will be lower than 50 g.
- After approximately 60 ms, the connection between the leg segments appears to become more compliant. Now, the jumper behaves like a four-mass model. That behavior corresponds to the simulation with the soft springs.

When we applied those observations, the jumper seemed to change from a two-mass to a four-mass system as the landing progressed. That finding corresponds to an increase in the degrees of freedom of the movement. During the passive phase of the landing, the stiffness of the legs is produced by pre-activated muscles. The high ground reaction force leads to dorsiflexion of the ankle and flexion of the knee and hip. At the beginning of the active phase, the muscles can influence the flexion in each joint of the legs. In that way, the jumper can extend the duration of the landing, can reduce the ground reaction force, and can control his or her posture.

In an effort to simulate variation in muscle forces by the model, we carried out the third simulation of the landing phase by using time-dependent values of the springs and

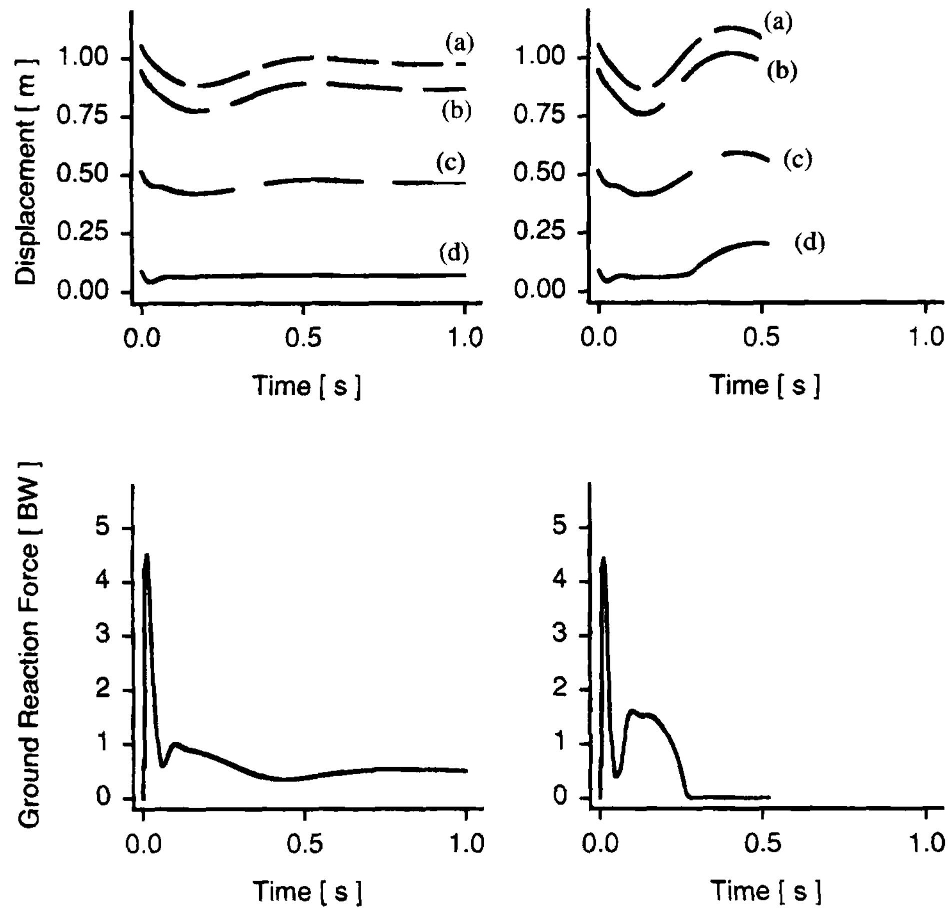

FIGURE 7. Time courses of the vertical displacements of four body markers and the ground reaction force measured by Fritz (1999) during the landing (**left**) and during hopping (**right**). (**a**) iliac crest, (**b**) hip, (**c**) knee, and (**d**) ankle. BW = body weight.

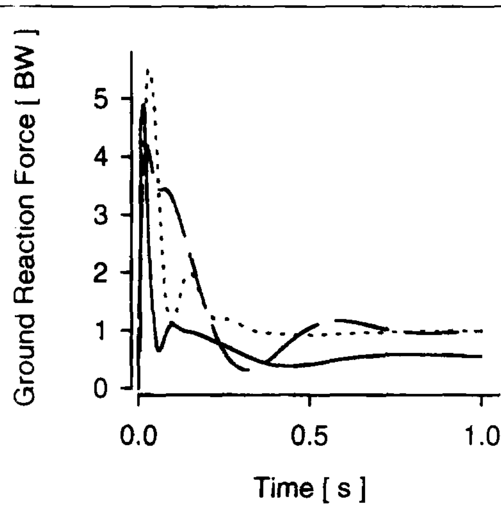

FIGURE 8. Time courses of the vertical ground reaction force during the landing. Solid line represents the curve measured by Fritz (1999) (see also Figure 7, left side); dashed line represents a soft landing (see also Figure 3, left side); and dotted line represents a hard landing (see also Figure 3, right side). BW = body weight.

dampers. The resulting ground reaction force included two peaks and a minimal value before it reached the steady state (Figure 4). The correlation between the simulated force curve and the measured data of Fritz (1999; Figure 7) was $r = .73$ ($p < .001$). The ratios between the passive maxima and minima and between the active maxima and minima of the simulated and the measured forces were 124%, 380%, 262%, and 131%, respectively. The ratios show that during the entire landing phase, the simulated forces were higher than the forces measured by Fritz (1999). The greatest differences were found between the passive minima and the following active maxima. The main advantage of using a time-dependent set of parameters is that one obtains a higher accuracy in simulating the change from the passive to the active phase (compare Figure 3, left side, with Figure 4) as well as the change from the active maximum to the active minimum (compare Figure 3, right side, with Figure 4). One cannot obtain further improvement in simulating the change from the passive to the active phase and thus the activation of the leg muscles and the change of their forces by using the simple Equations 4, 5, and 6. Finally, the first small peak occurring in the initial part of the measured force–time courses of Nigg et al. (1981; Nigg et al., 1979) and Fritz (1981, 1999) was not imitated by the model. That peak is believed to result from the rotation of the feet in the sagittal plane during the period from touch down to heel strike. In contrast to that rotation, mass m_1 in our model can move only in the vertical direction.

The shape of the force curve in Figure 5 corresponds to the time courses measured during hopping (Fritz, 1981, 1999). The differences were given by the simulated force values and by the ground contact time, which was too short. Concerning the force values, we achieved better results by using the simulation with the time-dependent model parameters. The contact time was shorter again. Like the body segments, the model's masses are decelerating during the first half of the contact phase. Then, the masses have to accelerate in order to attain the given jump height. However, the duration of the acceleration phase is too short and thus the velocities of the masses do not reach the required value. Compared with the muscles, the time-invariant springs cannot prolong that phase and thereby they build up additional energy, which is dissipated during the deceleration of the initial upward movement. Thus it became clear that one cannot simulate activities such as the extension of the legs during hopping with models consisting solely of time-invariant elements.

Conclusions

Our comparison of the simulated mass motions and the ground reaction forces with measured data given in the literature lead to the following statements about the activity of the leg muscles:

By the varying their activity, the muscles have to fit the stiffness of the legs to the momentary motion phase or to the aim of the motion. During the active phase of landing, the loosening of the stiff connection between the thighs and the shanks results in an increase in the degrees of freedom of the movements, which allows the jumper to influence his movements. During hopping, the increase of the muscle activities enables the the jumper to take off to the next flight.

In the model, the forces of inertia and the spring and damper forces have the same line of action. During bouncing of the legs, the distances between the joints and the action line of the forces of inertia increase and thus the torques in the joints also increase. To maintain the equilibrium of the torques, one must contract the muscles.

By the contracting of the muscles, mechanical energy is added to the movements of the human body so that during the following flight phase the given jump height can be achieved.

The results of the simulations provided useful hints about aspects of loads in sports activities including repeated landing movements, as occur in volleyball. To reduce the passive peak, a reduced pre-activation of the quadriceps femoris is necessary, which would correspond to a decrease of c_3 in the model. At the same time, knees and ankles should be completely extended so that the landing velocity can be decelerated over a long distance. That means that an athlete should be made aware of the need to control his landing.

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Submitted February 29, 2000
Revised July 12, 2000
Second revision November 11, 2000