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Human hopping on damped surfaces: strategies for adjusting leg mechanics

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Fast-moving legged animals bounce along the ground with spring-like legs and agilely traverse variable terrain. Previous research has shown that hopping and running humans maintain the same bouncing movement of the body's centre of mass on a range of elastic surfaces by adjusting their spring-like legs to exactly offset changes in surface stiffness. This study investigated human hopping on damped surfaces that dissipated up to 72% of the hopper's mechanical energy. On these surfaces, the legs did not act like pure springs. Leg muscles performed up to 24-fold more net work to replace the energy lost by the damped surface. However, considering the leg and surface together, the combination appeared to behave like a constant stiffness spring on all damped surfaces. By conserving the mechanics of the leg–surface combination regardless of surface damping, hoppers also conserved centre-of-mass motions. Thus, the normal bouncing movements of the centre of mass in hopping are not always a direct result of spring-like leg behaviour. Conserving the trajectory of the centre of mass by maintaining spring-like mechanics of the leg–surface combination may be an important control strategy for fast-legged locomotion on variable terrain.

Keywords: biomechanics; locomotion; motor control; muscle; spring-mass model

1. INTRODUCTION

Simple models accurately predict the mechanics of animal locomotion (Cavagna *et al.* 1977). For example, a spring-mass model reproduces the centre-of-mass motions of all hopping, running, trotting and galloping animals studied so far (see Blickhan 1989; McMahon & Cheng 1990; Alexander 1992; Blickhan & Full 1993; Farley *et al.* 1993). In this model, a linear 'leg spring' represents the combined actions of all muscles, tendons, and ligaments within the legs in contact with the ground. The leg spring supports a point mass representing the animal's centre of mass.

Recent studies have shown that hopping and running humans maintain similar centre-of-mass motions on a range of elastic surfaces by adjusting leg stiffness. Specifically, humans hopping in place and running forward increase the stiffness of their spring-like stance legs to offset softer surfaces. As a result, they have similar centre-of-mass motions on rigid and soft elastic surfaces (Ferris & Farley 1997; Ferris *et al.* 1998). If hoppers and runners did not increase leg stiffness on softer surfaces, the centre of mass would go through a much larger vertical displacement than on harder surfaces. These studies strongly suggest that maintaining the centre-of-mass motions by conserving the stiffness of the leg–surface combination is an important control strategy in bouncing gaits.

Unlike elastic surfaces, most natural surfaces do not return all of the energy they absorb. These energy-dissipating surfaces absorb mechanical energy when they compress under an animal's foot, but return only some of this energy when they rebound later in the contact phase. Thus, when animals traverse sand or snow, they must perform extra mechanical work to replace the energy dissipated by the surface (Lejeune *et al.* 1998) and therefore consume extra metabolic energy (Givoni & Goldman 1971; Pandolf *et al.* 1976; Zamparo *et al.* 1992). Although human runners perform extra mechanical work on sand, they still use movement patterns that resemble a spring-mass system (Lejeune *et al.* 1998). Little is known about the mechanical strategies used for locomotion on energy-dissipating, damped surfaces.

We hypothesized that when humans hop in place, they adjust their leg mechanics to compensate for changes in surface damping, thereby maintaining the same combined leg–surface stiffness and centre-of-mass motions as on elastic surfaces. To prevent changes due to surface damping, our hypothesis predicts that humans will adjust leg mechanics to counteract slowed surface compression-rebound and surface energy dissipation. The legs must perform extra mechanical work to replace the energy lost to damped surfaces. Otherwise, the person would hop progressively lower on successive hops. We tested this hypothesis by quantifying the centre-of-mass dynamics, leg compression–extension timing and leg mechanical work output for humans hopping in place on a range of damped surfaces.

2. MATERIAL AND METHODS

Eight male subjects (body mass 76.2 ± 1.7 kg, height 176 ± 5 cm, age 28 ± 2 yr; mean ± s.d.) hopped in place (i.e. hopped on the spot) on a surface with adjustable stiffness and damping. We recorded the ground reaction force and surface position data at 1000 Hz. The University of Colorado Human Research Committee approved the protocol, and all subjects gave informed consent.

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Table 1. Subject data for an elastic surface and four damped surfaces.
(Values are means (s.e.m.) for all subjects. An asterisk (*) denotes a significant difference from the elastic surface. Simulation data are for a spring-mass model on the most damped surface, using the leg stiffness from the elastic surface (see § 2). The simulation demonstrates the effect of surface damping when it is not offset by adjusting lesg mechanics. Centre of mass is abbreviated to COM.)

	subject data					
hopping parameters	elastic				most damped	simulation
surface damping (Ns m^{-1})	NA	582	1145	1634	2073	2073
surface stiffness (kN m^{-1})	30.3	27.8	22.0	16.2	13.3	13.3
COM mechanical energy dissipated (%)	1.6 (0.1)	29.0 (1.0)*	54.1 (2.3)*	69.0 (2.9)*	72.4 (3.1)*	84.0 (1.2)*
surface energy dissipated per hop (J)	1.8 (0.2)	27.7 (1.5)*	51.7 (3.2)*	65.9 (3.4)*	69.7 (3.5)*	95.4 (0.6)*
time of maximum surface compression (ms)	158 (4)	167 (5)*	175 (6)*	189 (6)*	199 (7)*	221 (2)*
downward COM displacement—contact (cm)	11.4 (0.2)	11.1 (0.2)	10.4 (0.2)*	10.4 (0.1)*	10.3 (0.2)*	8.9 (0.2)*
upward COM displacement—aerial (cm)	2.6 (0.3)	2.7 (0.3)	3.1 (0.4)	3.0 (0.4)	2.8 (0.4)	no aerial phase
contact time (ms)	319 (7)	326 (6)*	321 (9)	332 (9)*	334 (10)*	no aerial phase
maximum leg compression (cm)	5.2 (0.2)	5.1 (0.2)	4.9 (0.2)	5.5 (0.2)*	6.0 (0.2)*	3.8 (0.1)*
leg length at take-off relative to touchdown (cm)	0.4 (0.1)	1.7 (0.2)*	3.1 (0.3)*	3.8 (0.3)*		
peak vertical force (N)	2035 (43)	1963 (50)	1933 (63)*	1914 (64)*	1876 (57)*	1436 (7)*
negative leg work (J)	42 (1)	34 (2)*	31 (2)*	36 (1)*	40 (2)	27 (1)*
positive leg work (J)	45 (1)	64 (2)*	87 (3)*	105 (4)*	112 (4)*	19 (1)*
net leg work (J)	3 (1)	30 (2)*	56 (4)*	70 (5)*	72 (4)*	−8 (0)*

Subjects hopped in place on a lightweight surface (3.7 kg) that was supported by steel springs (Century Springs, Inc.) and a bi-directional linear hydraulic damper (Taylor Devices, Inc.) and was mounted on a force platform (AMTI, Inc.). The surface deck was a 60cm × 60cm fibreglass and aluminium honeycomb sandwich panel (Goodfellow, Inc.) that linear bearings (INA, Inc.) constrained to move only vertically. For five levels of surface damping, we used a computer simulation of a spring-mass model landing on each damped surface (see final paragraph of this section) to choose surface stiffness values that maintained peak surface compression at 6.0 cm during the model's contact time (see table 1). In the experiments, peak surface compression varied between 6.0 cm and 6.5 cm on all surfaces. We measured the surface compression with a linear potentiometer (Omega, Inc.). We controlled the peak surface compression to isolate the leg adjustments to changes in surface damping. We altered the surface stiffness by changing the number of springs in parallel supporting the surface. We determined the surface stiffness from the slope of the static force–displacement relation ($r^2 = 0.99$) over the force range measured during hopping (0–2.5 kN). We determined the linear damping (b_{damper}; $r^2 = 0.98$) of the damper using ramp tests (Instron, Inc) over the range of velocities measured during hopping (0.03–0.60 m s^{-1}). In each ramp test, the damper was lengthened and compressed at a constant velocity. We varied the surface damping (b_{surface}) by changing the fulcrum position of a 50 cm lever positioned between the linear damper and the hopping surface and using the equation:

$$b_{\mathrm{surface}} = b_{\mathrm{damper}} \times (R_{\mathrm{damper}}/R_{\mathrm{surface}})^2, \tag{2.1}$$

where R_{damper} and R_{surface} were the distances from the damper and surface to the fulcrum, respectively. Thus, a given surface damping (b_{surface}) resulted in a damper force on the hopping surface (F_{surface}) directly proportional to surface velocity (v_{surface}) and in the opposite direction of surface movement based on the equation: $F_{\mathrm{surface}} = b_{\mathrm{surface}} \times v_{\mathrm{surface}}$. We maintained the temperature of the damper between 21 °C and 22 °C by using a surface thermocouple (Omega, Inc.) and a copper coil circulating ice water. This 1 °C temperature variation changed the damping coefficient by less than 13 N s m^{-1} (less than 2.2% of b_{surface}).

The damped surfaces differed dramatically from the elastic surface in compression timing and energy dissipation. The surface natural frequency slowed from 3.1 Hz to 0.2 Hz between the elastic surface and the most damped surface. The elastic surface dissipated only 3% of the mechanical energy that it absorbed, whereas the most damped surface dissipated 77% (table 1).

Subjects hopped in place on an elastic surface (i.e. damper removed) and four damped surfaces. All subjects hopped barefoot on two legs, matching a metronome beat at 2.2 Hz (approximately preferred frequency; Melville-Jones & Watt 1971; Farley *et al.* 1991). Pilot data showed that preferred frequency varied by less than 0.2 Hz across the range of damped surfaces. Therefore, we chose to fix the hopping frequency at 2.2 Hz to eliminate a slight change in frequency that might have confounded the interpretation. It is important to note that subjects have a range of mechanical strategies available to them for hopping at a set frequency. For example, they can vary the contributions of the contact time and aerial time to the hop period by dramatically changing leg mechanics (Farley & Morgenroth 1999).

We gave subjects three instructions about how to hop: (i) follow the metronome beat; (ii) leave the ground between hops; and (iii) clasp hands behind the back. Subjects hopped to their 'preferred height' in the aerial phase. We felt preferred height hopping most accurately reproduced sustained locomotion on natural terrain outside the laboratory. During each trial, subjects hopped for 30 s after matching the metronome beat, and subsequently, we collected data for 10 s. Trial order progressed from the least to most damped surface, followed by the elastic surface. Subsequently, trials were repeated in reverse order, and we averaged the data from both trials on each surface to control for fatigue. For each trial, we analysed five consecutive hops that were within 5% of the 2.2 Hz hopping frequency. We tested for differences among the five surfaces with a repeated-measures ANOVA and a Tukey *post-hoc* test ($p < 0.05$). All values are mean and s.e.m.

We corrected for surface inertia and then calculated the centre-of-mass vertical displacement, leg length change, leg work and surface energy dissipation. To determine the net vertical force acting on the legs, we first subtracted the inertial force due to surface acceleration (less than 4% of peak vertical force in all cases) from the total vertical ground reaction force. Next, we calculated the centre-of-mass vertical displacement by twice integrating its vertical acceleration (obtained from the net vertical force) with respect to time (Cavagna 1975). We determined leg compression (i.e. the reduction in distance between the centre of mass and the surface) during the contact phase by subtracting the surface displacement from the centre-of-mass displacement. We calculated the negative and positive mechanical work done by the legs by integrating the net vertical force with respect to leg compression. Similarly, integrating the net vertical force with respect to surface displacement yielded the mechanical energy absorbed and returned by the surface.

We calculated the overall 'vertical stiffness' of the leg and surface combination (k_{vert}) from the net force (F_{peak}) at the peak vertical displacement of the centre of mass (Δy; Ferris *et al.* 1998):

$$k_{\mathrm{vert}} = F_{\mathrm{peak}}/\Delta y. \tag{2.2}$$

Similarly, we calculated leg stiffness on the elastic surface by dividing F_{peak} by peak leg compression. It is reasonable to calculate leg stiffness and vertical stiffness in the manner described because both force–displacement relations are linear ($r^2 > 0.97$ in all cases).

We used a computer simulation to quantify how the adjustments made by the subjects for surface damping affected centre-of-mass dynamics. The simulation predicted the centre-of-mass trajectory that would have occurred with no adjustment of leg mechanics to offset surface damping. We assumed that if subjects did not adjust their leg behaviour to overcome surface damping, their legs would behave like a spring with the same leg stiffness as on the elastic surface. The simulation consisted of a spring-mass model with the leg stiffness from the elastic surface landing on the most damped surface (see table 1 for surface damping and stiffness). We ran computer simulations using the leg stiffness and touchdown velocity from each trial for each subject on the elastic surface (The Mathworks, Inc., MATLAB 6.1, ode113, time-step = 0.001 s, absolute error = 10^{-8}). Average initial conditions were leg stiffness, $36.8 \pm 1.5\ \mathrm{kN\ m^{-1}}$ and touchdown velocity, $0.68 \pm 0.03\ \mathrm{m\ s^{-1}}$. For each simulation, we calculated the error by comparing the trajectory of the model's point mass (COM) to the trajectory of the subject's centre of mass on the elastic surface ($\mathrm{COM_{ref}}$) at each time step:

$$\%\ \mathrm{error} = \left(\sqrt{\Sigma(\mathrm{COM} - \mathrm{COM_{ref}})^2/\Sigma(\mathrm{COM_{ref}})^2} \right) \times 100. \tag{2.3}$$

We also used equation (2.3) to calculate the difference between each subject's centre-of-mass trajectory on the most damped (COM) and elastic surface ($\mathrm{COM_{ref}}$). Finally, we used a similar simulation to predict the centre-of-mass trajectory when the leg and surface combination were represented by a single spring with stiffness k_{vert} (equation (2.2)). We used equation (2.3) to find the difference between the predicted trajectory (COM) and each subject's trajectory ($\mathrm{COM_{ref}}$) on all surfaces.

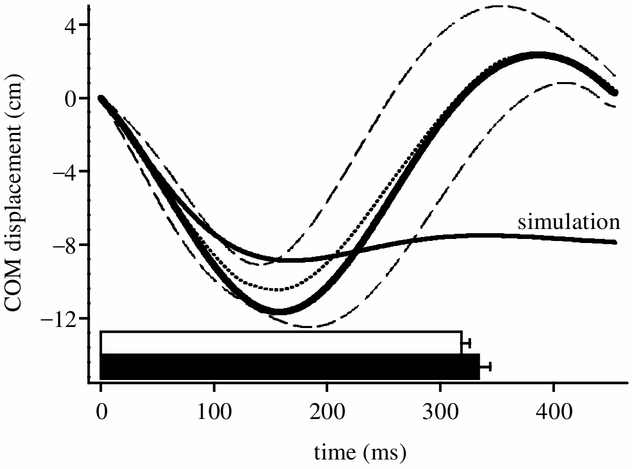


Figure 1. Average centre-of-mass vertical displacement versus time for all subjects on the elastic surface (thick line) and most damped surface (dotted line with 95% confidence intervals demarked by dashed lines). Displacement is expressed with respect to touchdown. A complete hop from one touchdown to the next is shown. White and black horizontal bars denote the average contact time for the elastic and most damped surface, respectively. Hoppers maintain almost the same centre-of-mass trajectory regardless of surface damping. 'Simulation' denotes the trajectory that the centre of mass would have followed if leg mechanics were the same on the most damped surface as on the elastic surface.

3. RESULTS

Hopping subjects maintained almost the same centre-of-mass motions on all surfaces despite large differences in surface damping (i.e. 3–77% energy dissipation; table 1). During the ground contact phase, the centre of mass moved downward by only 10% less on the most damped surface than on the elastic surface. During the aerial phase, the centre of mass moved upward by the same amount on all surfaces (table 1; figures 1 and 2). Although the surfaces compressed and rebounded more slowly with greater damping, the feet remained on the surface for almost the same amount of time (table 1). Overall, the centre-of-mass trajectory on the most damped surface differed by only 10% from the trajectory on the elastic surface (figure 1; equation (2.3)). In contrast, our simulation indicated that if the subjects had not changed their leg behaviour to overcome surface damping, the centre-of-mass trajectory would have differed by 85% from the elastic condition (figure 1).

Hoppers maintained a similar centre-of-mass trajectory on all damped surfaces by altering the timing of leg compression and extension to counteract the slower surface movements. With greater surface damping, the surface compressed and rebounded more slowly. For example, the most damped surface reached its lowest point 41 ± 7 ms later than the elastic surface (figure 2; table 1). The legs compensated almost perfectly for the slower compression

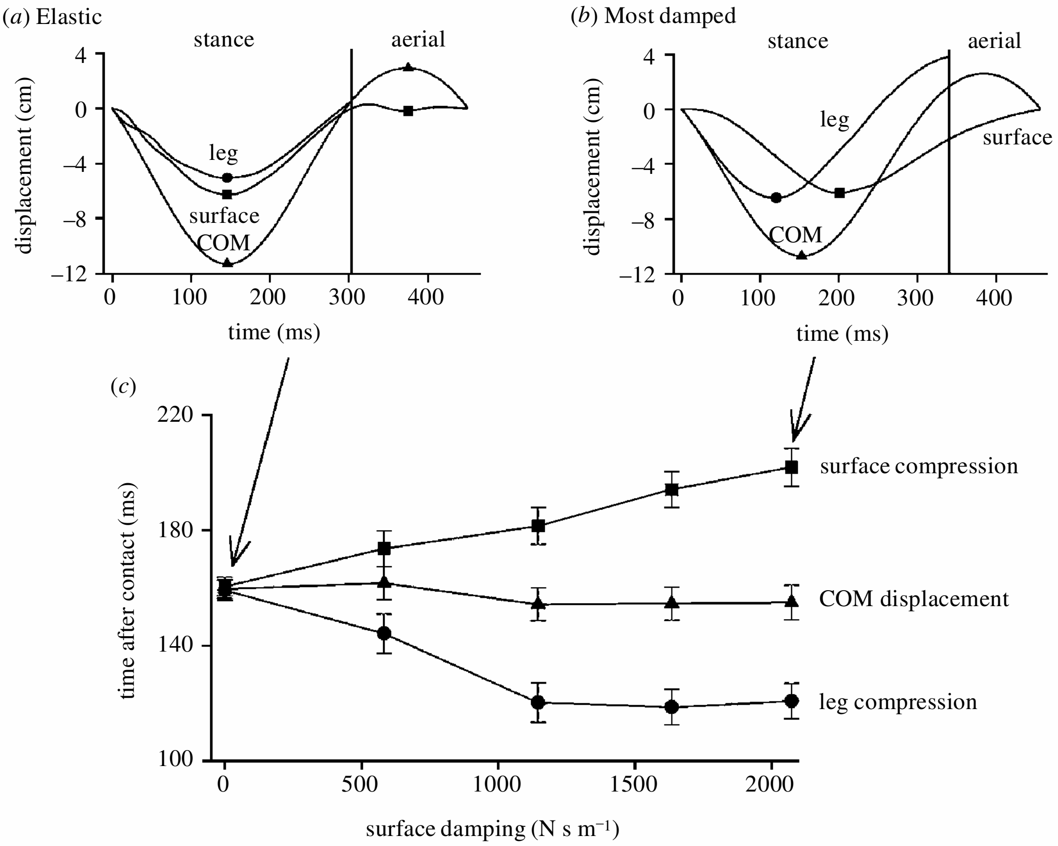


Figure 2. Centre-of-mass vertical displacement ('COM'; filled triangles), leg compression ('leg'; filled circles) and surface compression ('surface'; filled squares) relative to touchdown for a typical trial on the (*a*) elastic surface and (*b*) most damped surface. A complete hop is shown from one touchdown to the next. (*c*) Time intervals after touchdown for peak downward centre-of-mass displacement, peak leg compression and peak surface compression for all subjects (mean ± s.e.m.) versus surface damping. As surface damping increases, peak surface compression occurs later ($p < 0.05$), peak leg compression occurs earlier ($p < 0.05$) and peak centre-of-mass displacement occurs at the same time ($p > 0.05$).

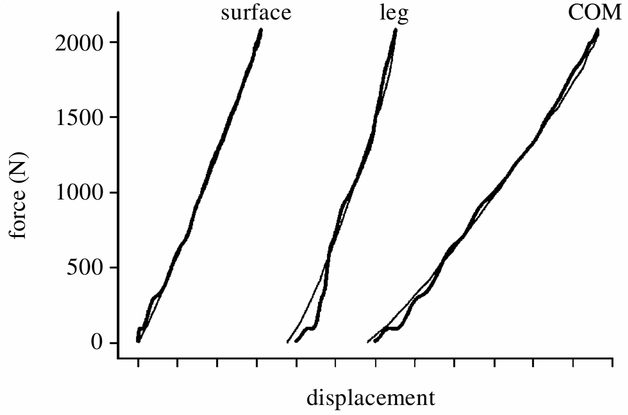
of the most damped surface by reaching their maximum compression 38 ± 6 ms *earlier* than on the elastic surface (figure 2). As a result, the centre of mass reached its minimum height at almost the same time after touchdown regardless of surface damping (figure 2).

In addition to adjusting leg compression–extension timing, hoppers performed dramatically more positive work to replace the mechanical energy dissipated by the damped surfaces (table 1). The elastic surface dissipated almost no mechanical energy, and thus, the legs produced almost no net work. On the elastic surface, the negative mechanical work performed by the legs during landing almost equalled the positive mechanical work performed during take-off. In contrast, to replace the energy dissipated by the damped surfaces, the legs produced net positive work by slightly decreasing negative work (−5%) and dramatically increasing positive work (+150%). Thus, net leg work increased by 24-fold between the elastic surface and the most damped surface (table 1). Subjects increased positive leg work for damped surfaces primarily by extending the legs up to 65% farther during take-off than the legs compressed during landing (table 1). As a result, leg length at take-off exceeded leg length at landing by up to 4 cm. In contrast, on the elastic surface the legs extended only 8% further than they compressed (table 1; figure 3).

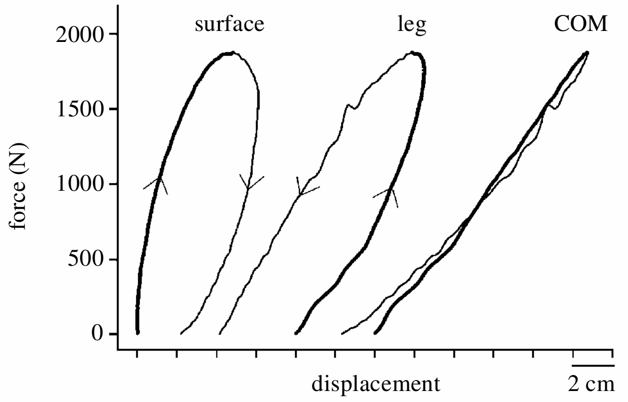
On damped surfaces, the adjustments to leg compression timing and work output caused the combination of the legs and surface to behave like the same linear spring as on the elastic surface. On the elastic surface, the surface and legs each independently behaved like linear springs, resulting in a spring-like force–displacement relation for the leg–surface combination (figure 3*a*). The damped surfaces dissipated energy, and did not behave even remotely like the elastic surface. Surprisingly, hoppers maintained spring-like behaviour of the leg–surface combination on all of the damped surfaces by using non-spring-like leg behaviour that compensated for the non-spring-like surface behaviour (figure 3*b*). Thus, the force–displacement relation for the leg–surface combination remained the same over a wide range of surface damping (figure 3*c*). In fact, a spring-mass model with a constant stiffness spring representing the leg–surface combination predicted the centre-of-mass motions with less than 10% error (6.4 ± 0.5%; equation (2.3)) on all surfaces.

4. DISCUSSION

Our results support the hypothesis that human hoppers adjust leg mechanics to overcome surface damping, thereby maintaining the same combined leg–surface stiffness and centre-of-mass motions. The non-spring-like leg mechanics used on damped surfaces cause the leg–surface combination to behave like a constant stiffness spring regardless of surface damping. Similarly, previous studies (*a*) Elastic



(*b*) Most damped



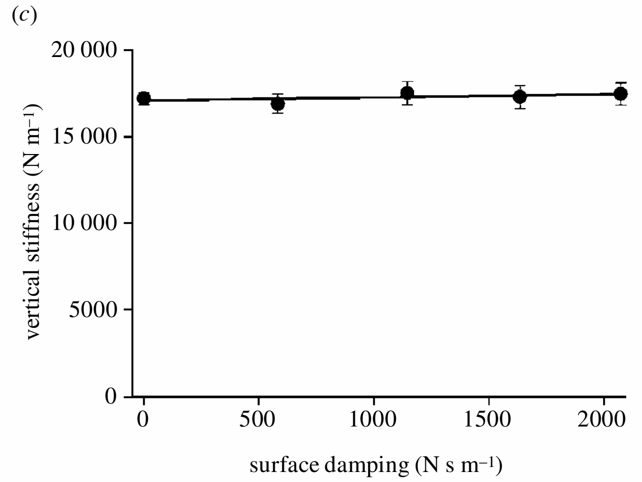


Figure 3. Force versus displacement for the surface, legs and centre of mass during contact from typical trials on (*a*) the elastic surface and (*b*) the most damped surface. During landing (thick lines), the force increases, the surface and centre of mass move downwards, and the legs shorten. During take-off (thin lines), the paths are retraced for the elastic surface but not for the damped surface. (*c*) Vertical stiffness, calculated from the slope of the centre-of-mass force–displacement curve, versus surface damping for all subjects (mean ± s.e.m.). Vertical stiffness remains constant with increased surface damping ($p > 0.05$) because the legs compensate for surface damping.

show that hoppers use the same stiffness of the leg–surface combination on hard and soft elastic surfaces (Ferris & Farley 1997; Farley *et al.* 1998). Taken together, these observations strongly support the idea that hopping humans control the mechanical properties of the leg–surface combination, thereby maintaining centre-of-mass motions.

It is critical to note that maintaining spring behaviour and constant stiffness of the leg–surface combination is not a mechanical necessity when hopping at a given frequency. Humans can hop steadily with non-spring-like behaviour of the leg–surface combination. For example, at slow frequencies on hard surfaces, the legs do not behave even remotely like springs during hopping in place (see fig. 4 in Farley *et al.* 1991). Furthermore, if the leg–surface combination does behave like a spring, it is possible to hop at 2.2 Hz with a range of leg–surface stiffness values by altering the fractions of the hop period spent on the ground and in the air. For example, when subjects increase hopping height at the same frequency, they double the combined leg–surface stiffness, and they are capable of increasing upward centre-of-mass displacement from 2.7 cm to 8.6 cm (Farley & Morgenroth 1999). These examples demonstrate that maintaining a constant stiffness of the leg–surface combination and constant centre-of-mass dynamics, as observed in this study is one of many possible strategies.

Unlike the present study, all previous studies of hopping and running on elastic surfaces of different stiffness have shown that humans maintain spring-like leg behaviour and adjust leg stiffness to conserve centre-of-mass dynamics. By simply increasing leg stiffness on softer elastic surfaces, hoppers and runners reduce leg compression to exactly offset the larger surface compression, thereby maintaining similar centre-of-mass dynamics (Ferris & Farley 1997; Ferris *et al.* 1998, 1999; Kerdok *et al.* 2002). Leg behaviour can remain spring-like because elastic surfaces do not dissipate energy. On elastic surfaces, the maximum leg and surface compression occur simultaneously. On damped surfaces, however, hoppers do not synchronize leg and surface compression. The legs reach maximum compression before the surface reaches maximum compression. Thus, the legs begin extending earlier and produce extra positive leg work to replace the energy lost by damped surfaces. In addition, this timing shift causes the centre of mass to reach its lowest position at the same time in the contact phase as on the elastic surface despite the later peak compression of damped surfaces.

Due to the fundamental mechanical similarities between hopping and running, this study may have implications for running. Our current data lead to the prediction that *runners* on a damped surface will maintain leg compression but increase leg extension, resulting in more extended legs at take-off than at touchdown. Similarly, during uphill running, humans increase positive work by having more extended legs at take-off than at touchdown (Iversen & McMahon 1992). We also predict that runners on damped surfaces will maintain the mechanical behaviour of the leg–surface combination, thereby conserving centre-of-mass motions regardless of surface damping.

Why do hoppers and runners conserve the same bouncing centre-of-mass motions on a range of surfaces? Our data do not support the idea that humans use bouncing gaits because the legs behave like energy-conserving springs. Indeed, the legs do not behave like springs during hopping on damped surfaces, yet the centre of mass follows the same bouncing trajectory as on elastic surfaces.

Alternatively, the progressive decrease in redundancy and step-to-step variability from the muscle activation level to the kinematic level (Winter & Eng 1995) suggest that maintaining a spring-like centre-of-mass trajectory may simplify the control of locomotion. In addition, spring-mass systems may be self-stabilizing, thus requiring less active neural control. Recent research has shown that a spring-mass model self-stabilizes over multiple running steps due to its intrinsic dynamics (Seyfarth *et al.* 2002). Thus, conserving bouncing centre-of-mass motions may minimize the role of active control in producing stable locomotion.

In summary, human hoppers conserve centre-of-mass motions by maintaining the same spring-like behaviour of the leg–surface combination on all surfaces. As surface damping increases, the legs reach peak compression earlier in the contact phase to offset the effect of the slower surface compression on centre-of-mass motions. To replace the energy dissipated by damped surfaces, the legs produce more net work, primarily by increasing positive leg work. Understanding the mechanical adjustments made by animals to traverse energy-dissipating terrain may aid in the design of legged robots, lower-limb prostheses and athletic surfaces.

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