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Running in the real world: adjusting leg stiffness for different surfaces

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A running animal coordinates the actions of many muscles, tendons, and ligaments in its leg so that the overall leg behaves like a single mechanical spring during ground contact. Experimental observations have revealed that an animal's leg stiffness is independent of both speed and gravity level, suggesting that it is dictated by inherent musculoskeletal properties. However, if leg stiffness was invariant, the biomechanics of running (e.g. peak ground reaction force and ground contact time) would change when an animal encountered different surfaces in the natural world. We found that human runners adjust their leg stiffness to accommodate changes in surface stiffness, allowing them to maintain similar running mechanics on different surfaces. These results provide important insight into the mechanics and control of animal locomotion and suggest that incorporating an adjustable leg stiffness in the design of hopping and running robots is important if they are to match the agility and speed of animals on varied terrain.

Keywords: biomechanics; locomotion; motor control; spring–mass model; leg spring; muscle

1. INTRODUCTION

Tendons and ligaments serve as excellent elastic energy stores during running gaits. They stretch and recoil with each step, reducing the work required from the muscles and lowering the metabolic cost of locomotion (Cavagna *et al.* 1977; Alexander 1988). The central nervous system (CNS) coordinates the actions of the many muscles in the stance limb with the actions of the tendons and ligaments so that the overall system behaves similarly to a single mechanical spring during running (He *et al.* 1991; Farley *et al.* 1993). In fact, the simplest model of a running animal is a spring–mass system consisting of a linear spring representing the stance limb (i.e. the leg spring) and a point mass equivalent to body mass (Blickhan 1989; McMahon & Cheng 1990) (see figure 1).

The stiffness of the leg spring (k_{leg}) is a key parameter in determining the dynamics of running. Leg stiffness influences many kinematic variables such as stride frequency and ground contact time (t_c) (McMahon & Cheng 1990; Farley & Gonzalez 1996). Experimental evidence has shown that leg stiffness is independent of both forward speed (He *et al.* 1991; Farley *et al.* 1993) and simulated gravity level (He *et al.* 1991), suggesting that inherent properties of the musculoskeletal system determine an animal's choice of leg stiffness. This idea is supported by recent studies revealing that the muscles of running turkeys undergo very little change in length during ground contact (Roberts *et al.* 1997). Thus, the tendon may contribute most of the compliance of the muscle–tendon unit (Alexander 1988) and greatly influence leg stiffness.

In the natural world, animals encounter many surfaces that compress under their feet. These compliant surfaces are like another spring in series with the runner's spring–mass system (McMahon & Greene 1978, 1979). If an animal used the same leg stiffness on all surfaces, the dynamics of running would be affected by surface stiffness. For example, if leg stiffness was invariant, the vertical excursion of the centre of mass during a stride of running would be greater on a compliant surface owing to surface compression. However, recent studies have revealed that humans are capable of adjusting leg stiffness during bouncing gaits. Leg stiffness is adjusted to achieve different stride frequencies at the same speed (Farley *et al.* 1991; Farley & Gonzalez 1996) or to accommodate differences in surface stiffness during hopping in place at a designated frequency (Ferris & Farley 1997). Based on the findings from these studies, we hypothesized that runners would adjust leg stiffness to accommodate different surface stiffnesses, allowing them to run in a similar manner on all surfaces. If runners do not adjust their leg stiffness when running on different surface stiffnesses, then their ground contact time and centre of mass displacement will increase as surface stiffness decreases.

2. METHODS

To test our hypothesis, we studied five human subjects (mean body mass 56.3 kg, s.d. 6.8 kg) as they ran at $5 \mathrm{~m~s^{-1}}$ on a rubber track (18 m) with a force platform (AMTI, Inc.) mounted below it. Preliminary experiments revealed that the basic trends for leg stiffness adjustment for different surfaces stiffnesses were the same regardless of running speed. As a result, we chose to focus on one speed ($5 \mathrm{~m~s^{-1}}$). Subjects ran on tracks of four different stiffnesses. All subjects were instructed to run down the track at the designated speed and were given several practice runs on

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each surface stiffness. Two infrared sensors were placed on the sides of the force platform (2 m apart) to determine the speed of the runner. Only trials within 5% of the designated speed were accepted. The data for three trials were averaged for each surface stiffness for each subject.

We obtained a range of surface stiffnesses by changing the number of rubber layers comprising the track. The stiffness of the running surface was calculated from the slope of its force versus displacement relation (linear fit $R^2 > 0.90$ for forces up to the peak vertical ground reaction force) as determined by a materials-testing machine and the areas of the subjects' shoe soles. Surface stiffness is proportional to loading area for a point elastic surface like the rubber track (Nigg & Yeadon 1987). For the purpose of our analysis, surface stiffness was used to calculate the surface compression at the middle of the ground contact phase (Δy_{surf}). High-speed video (200 Hz) of the trials showed that the entire shoe sole was in contact with the track at the middle of the ground contact phase for all runners. While it is likely that the centre of pressure was located underneath the metatarsal heads at mid-stance (Cavanagh & Lafortune 1980), we decided to use each subject's shoe-sole area as the surface loading area because it provided the most conservative estimate of surface stiffness for the purpose of testing our hypothesis. Using a portion of each subject's sole area instead of the entire sole area would have led to lower surface stiffness values. Given our calculation technique, this would not have affected our vertical stiffness values, but would have led to the calculation of a greater leg stiffness adjustment for reasons outlined in § 3. Thus, using a smaller foot area would not have affected our overall conclusions, but it would have magnified the extent of leg stiffness adjustment. As a result, using the entire sole area to calculate surface stiffness was the most conservative approach to testing our hypothesis. The stiffness of a given surface differed among the subjects because of variation in shoe size.

The damping properties of the surface were estimated from steel-shot drop-tests as detailed by Nigg & Yeadon (1987). The amount of energy dissipated by the surface during the runner's stance phase was then estimated from computer simulations (Working Model 4.0, fourth-order Kutta–Merson integration, time-step = 0.001 s). The runner was modelled with a spring–mass system, and the surface was modelled with a spring and dashpot in parallel. We calculated the energy dissipated by the dashpot over the ranges of leg stiffnesses, surface stiffnesses, and landing velocities used in our study. The total energy dissipated by the surface dashpot was less than 2% of the energy of the runner's centre of mass for most of the trials and was less than 4% at its highest. Thus, we concluded that the surface energy losses were negligible for the purpose of our study.

The vertical motions of the spring–mass system during the ground contact phase can be described in terms of an 'effective vertical stiffness' (k_{vert}) (McMahon & Cheng 1990). The effective vertical stiffness does not correspond to any physical spring in the runner or the model. Rather, it describes the vertical motions of the centre of mass during the ground contact phase and is extremely important in determining the time of ground contact. Effective vertical stiffness is calculated from the ratio of the force (F_{peak}) to the vertical displacement of the centre of mass (Δy) at the moment when the centre of mass reaches its lowest point:

$$k_{vert} = F_{peak}/\Delta y. \quad (1)$$

The peak ground reaction force occurs at the same time as the centre of mass reaches its lowest point during running

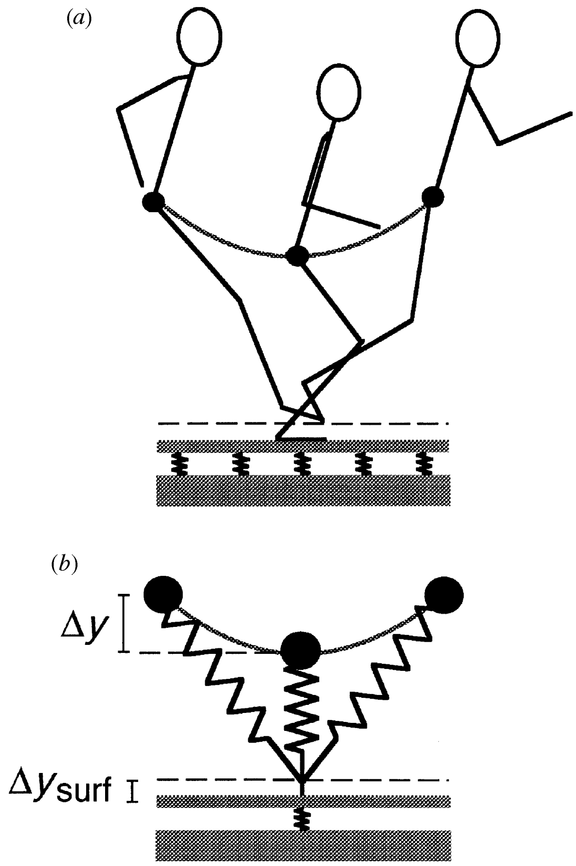

Figure 1. The spring–mass model. (*a*) Stick figure of a human runner and (*b*) the spring–mass model, both on a compliant surface. A total of three different times during ground contact are shown: at first contact, at the middle of the stance phase, and at last contact. The model consists of a point mass equivalent to body mass and a single linear spring representing the leg. The surface essentially adds a spring in series with the spring–mass system of the runner. The compression of the surface (Δy_{surf}) contributes to the vertical displacement of the centre of mass during ground contact (Δy).

(McMahon & Cheng 1990; He *et al.* 1991; Farley & Gonzalez 1996).

On a non-compliant surface, the combination of leg stiffness and half the angle swept by the leg during ground contact (θ) establishes a runner's effective vertical stiffness (McMahon & Cheng 1990). On a compliant surface, the effective vertical stiffness is also affected by surface stiffness because the surface compresses under the runner's foot, contributing to the vertical displacement of the runner's centre of mass (see figure 1). As a result, effective vertical stiffness on a compliant surface is determined by the combination of surface stiffness, leg stiffness, and half the angle swept by the leg during ground contact. To run similarly on different surfaces, as we predict in our hypothesis, runners would have to adjust leg stiffness so that their effective vertical stiffness remained the same on all surfaces.

We calculated the effective vertical stiffness of the runners on all of the surfaces from the peak ground reaction force (F_{peak}) and the maximum vertical displacement of the centre of mass. The maximum vertical displacement of the runner's centre of mass (Δy) was the difference between the height of the centre of mass at ground contact and the height of the centre of mass at the middle of the stance phase. It was calculated by twice integrating the centre of mass vertical acceleration with respect to time (Cavagna 1975). The centre of mass vertical acceleration was

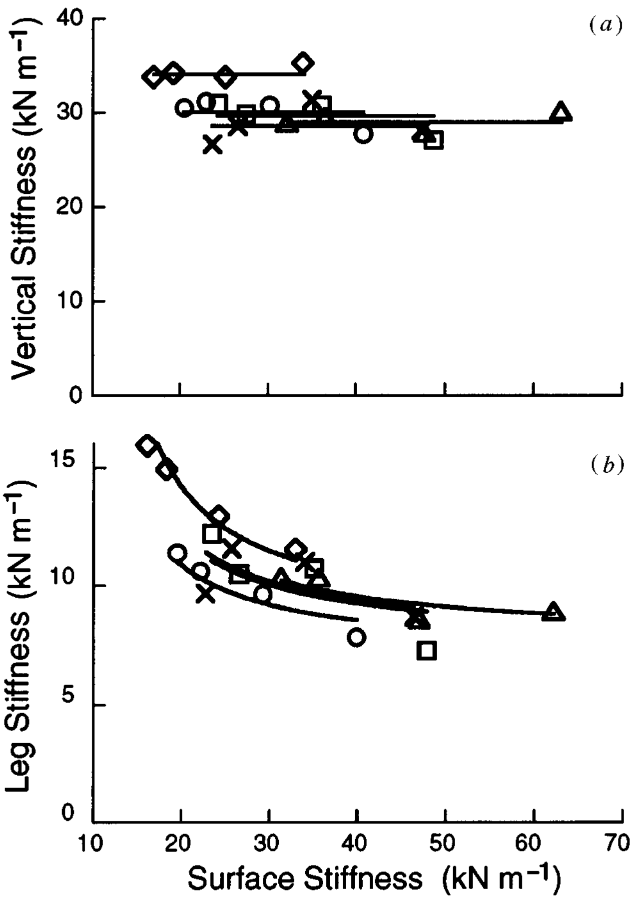

Figure 2. Effective vertical stiffness and leg stiffness versus surface stiffness. (*a*) Each runner maintained the same vertical stiffness on all the surfaces (repeated measures ANOVA, $p=0.6014$). Each type of symbol represents the data for a single subject. Lines represent the mean vertical stiffness for all the surfaces for each subject. (*b*) Each runner increased leg stiffness to accommodate reductions in surface stiffness ($p=0.0183$). Leg stiffness increased by as much as 68% between the most stiff surface and the least stiff surface. Lines are theoretically predicted leg stiffnesses required to maintain a constant vertical stiffness on all the surfaces.

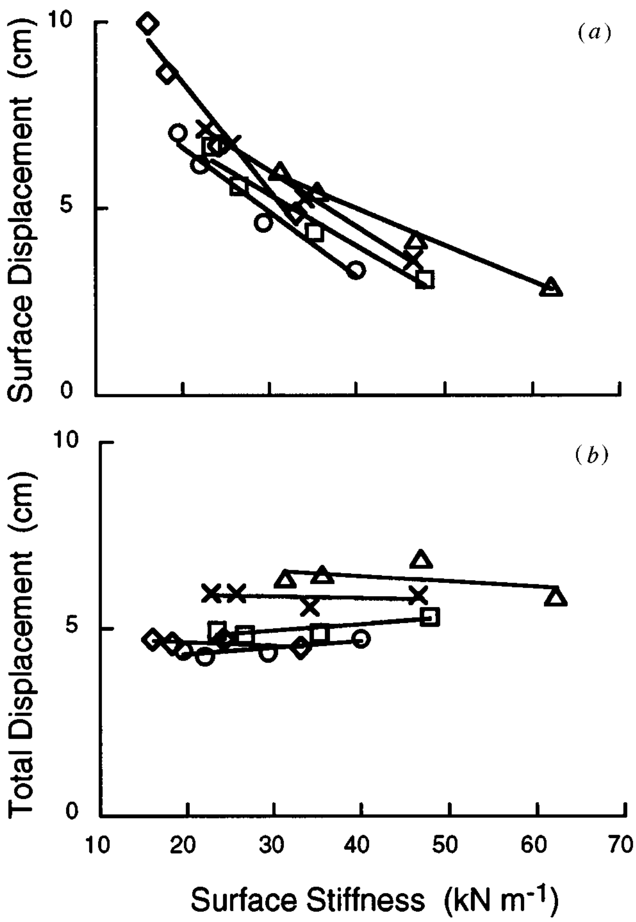

Figure 3. Surface displacement and total vertical displacement versus surface stiffness. (*a*) Surfaces of lower stiffnesses compressed more during the ground contact phase ($p<0.004$). (*b*) Each runner maintained the same total vertical displacement of their centre of mass during ground contact on all the surfaces in spite of greater surface compression on surfaces with lower stiffnesses ($p=0.8189$). This was achieved by increasing leg stiffness on lower stiffness surfaces. (*a*,*b*) Each type of symbol represents the data for a single subject. Lines are linear least squares regressions for each subject.

derived from the vertical ground reaction force. Subsequently, we calculated leg spring compression at midstance (ΔL) from the length of the leg (i.e. distance from greater trochanter to the ground, L_0), the vertical displacement of the centre of mass, the displacement of the surface (Δy_{surf}), and half the angle swept by the leg during ground contact (θ):

$$\Delta L = \Delta y - \Delta y_{\mathrm{surf}} + L_0(1 - \cos\theta). \tag{2}$$

The displacement of the surface was calculated from the ratio of the peak ground reaction force to the surface stiffness. Half the angle swept by the leg during ground contact was calculated from the running speed (u), contact time (t_c), and leg length (L_0):

$$\theta = \sin^{-1}(ut_c/2L_0). \tag{3}$$

Finally, the leg spring compression was used to determine the average leg spring stiffness during ground contact:

$$k_{\mathrm{leg}} = F_{\mathrm{peak}}/\Delta L. \tag{4}$$

The basis for this approach is described in detail elsewhere (He *et al.* 1991; Farley *et al.* 1993; Ferris & Farley 1997). A repeated measures ANOVA was used to determine statistical significance for all variables.

3. RESULTS

The runners maintained the same effective vertical stiffness on all of the surfaces despite a twofold change in surface stiffness ($p=0.6014$; see figure 2*a*). They achieved a constant vertical stiffness by increasing leg stiffness to offset reductions in surface stiffness ($p=0.0183$; figure 2*b*). Leg stiffness increased by as much as 68% between the most stiff surface and the least stiff surface. The magnitude of the increase in leg stiffness differed among the subjects because leg stiffness and surface stiffnesses were different for each subject. The relative magnitude of the leg stiffness adjustment necessary to maintain a constant vertical stiffness depends on the ratio of surface stiffness to leg stiffness (Ferris & Farley 1997). When this ratio is lower, leg stiffness is adjusted to a greater extent. Thus, the subjects running on lower stiffness surfaces (i.e. subjects with smaller feet), or subjects who had higher leg stiffnesses, had to make greater adjustments to leg stiffness. The angle swept by the leg (θ) remained the same for all the surfaces ($p=0.4874$).

The least stiff surface compressed twice as much under a runner's foot as the most stiff surface ($p<0.0047$; figure 3*a*). However, the total vertical displacement of the runner's centre of mass during ground contact remained the same (mean = 5.3 cm) on all of the surfaces ($p=0.8189$; figure 3*b*). The increased leg stiffness on lower surface stiffnesses caused a reduction in leg compression and a reduction in the vertical displacement of the centre of mass relative to the surface. This offset the increased surface compression and kept the total vertical displacement of the centre of mass the same on all of the surfaces. For some runners, the least stiff surface compressed enough (up to 10 cm) for it to exceed the total vertical displacement of the centre of mass during running. In these extreme cases, leg compression was small enough that the rotation of the leg about the point of ground contact caused the centre of mass to move upward relative to the surface during the first half of the ground contact phase. This remarkable adjustment to the runner's spring–mass system offset the larger surface compression and allowed the total displacement of the centre of mass to remain constant on even the lowest surface stiffnesses.

Because leg stiffness was adjusted to keep vertical stiffness constant, many aspects of running remained the same regardless of surface stiffness. For example, the runners used the same stride frequency and the same time of ground contact on all of the surfaces ($p>0.20$; figure 4*a*,*b*). The peak vertical ground reaction force was also the same (2.92 ± 0.04 times body weight) during running on all of the surfaces ($p=0.4421$). Thus, by adjusting leg stiffness to accommodate surface stiffness, the runners maintained similar locomotion mechanics on different running surfaces.

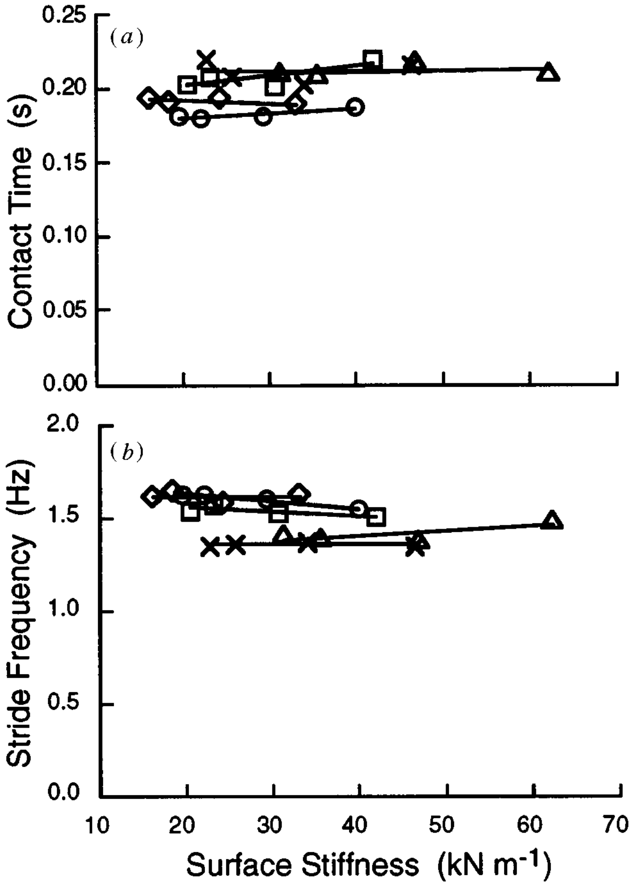

Figure 4. Ground contact time and stride frequency versus surface stiffness. (*a*) Ground contact time was independent of surface stiffness ($p=0.3227$). (*b*) Each runner also maintained the same stride frequency regardless of surface stiffness ($p=0.5783$). (*a*,*b*) Each type of symbol represents the data for a single subject. Lines are linear least squares regressions for each subject.

4. DISCUSSION

McMahon & Greene (1978, 1979) were the first to study the effect of surface stiffness on the biomechanics of running. Their model suggested that tuning the stiffness of a track to complement a runner's stiffness could increase maximal sprinting speed. A key point to their analysis was the assumption that leg stiffness was the same regardless of surface stiffness. This assumption seemed justified at the time, based on the notion that the stretch reflex maintained a constant muscle stiffness (Houk 1976; Nichols & Houk 1976; Hoffer & Andreassen 1981), and it was also supported by results from a related study on rhythmic leg extensions in humans (Greene & McMahon 1979). However, further development of the spring–mass model (McMahon & Cheng 1990), recent advances in reflex modulation (Stein & Capaday 1988; Prochazka 1989; Pearson 1995; Stein *et al.* 1995), and the results from our study indicate that it should be reconsidered.

While our study did not examine maximal sprinting speed on compliant surfaces, our findings do suggest an explanation for enhanced running performance on compliant running tracks for middle- and long-distance running events (McMahon & Greene 1978). A runner's leg is stiffer and compresses less when running on a compliant surface compared with running on a hard non-compliant surface. A reduction in leg compression indicates that there is less joint flexion and a straighter limb posture during ground contact (Farley *et al.* 1996). With a straighter limb posture, lower joint moments and muscle forces are required to exert the same ground contact force (Biewener 1989). It is also important to realize that a compliant elastic surface will passively store and return energy with each step, reducing the mechanical work performed by the runner's muscles. For a 70 kg human running at 4.5 m s^{-1}, a compliant elastic track with a stiffness of 195 kN m^{-1} (McMahon & Greene 1979) would store and return about 9% of the 100 J required for each step (Ker *et al.* 1987) assuming a peak vertical ground reaction force of 2.75 body weights (Nilsson & Thorstensson 1989). Thus, a reduction in both muscle force generation and work production may contribute to the enhanced running performance observed on compliant elastic running tracks (McMahon & Greene 1978).

To estimate the adjustments to leg stiffness that occur on athletic surfaces, we calculated the change in leg stiffness required to accommodate the series stiffness of a running track and running shoe. For a runner with a leg stiffness of 18 kN m^{-1}, a track stiffness of 195 kN m^{-1} (McMahon & Greene 1979), and a shoe stiffness of 200 kN m^{-1} (Alexander & Bennett 1989), leg stiffness would have to be increased by 22% to maintain a constant vertical stiffness. The $18\,\mathrm{kN\,m^{-1}}$ reflects the highest published leg stiffness value for a total of seven runners (He *et al*. 1991; Farley & Gonzalez 1996), but it is likely that larger (Farley *et al*. 1993) or stronger (Greene & McMahon 1979) runners have even higher leg stiffnesses and thus, greater adjustments (Ferris & Farley 1997).

Our results also provide important insight into the neural control of locomotion. The changes in leg stiffness and leg compression on different surfaces indicate that the CNS does not rely on a specific pattern of joint dynamics to control running. Joint displacements and joint moments change for different surface stiffnesses, but centre of mass movement and ground contact time remain the same. The invariance of these global running parameters suggests that one or more of them may be controlled by the CNS during running. Alternatively, it is possible that leg stiffness adjustments indirectly result from the control of a lower level neuromuscular parameter (e.g. minimizing muscle fibre displacement during ground contact; (Roberts *et al*. 1997). Further studies exploring the link between muscle–tendon action and leg stiffness should provide a better physiological understanding of leg stiffness adjustments during running.

Regardless of the mechanism, the ability to adjust leg stiffness allows humans to run similarly on different surfaces. Although our study was limited to changes in surface stiffness on compliant elastic surfaces, the sparse data available for locomotion on energy-dissipating surfaces indicate that humans maintain the same stride frequency on hard and sandy surfaces (Zamparo *et al*. 1992). Thus, a similar control of centre of mass movement may also exist on compliant inelastic surfaces, although this would obviously require an increase in muscular work to offset the energy lost owing to surface compression. We did not examine how quickly humans can adjust leg stiffness, but data from running birds suggest that they adjust to a new surface stiffness within a single step (Clark 1988). The ability to adjust leg stiffness quickly would allow animals to maintain dynamic stability when running on varied and unpredictable terrain. In addition, because running robots heavily rely on the elasticity of their spring-like legs and follow similar centre of mass dynamics as animals (Raibert 1986; Raibert & Hodgins 1993; Raibert *et al*. 1993), an adjustable leg stiffness might improve their performance on varied terrain. Besides allowing the robot to accommodate different surface stiffnesses, an adjustable leg stiffness would permit a robot to quickly adjust its stride length to avoid obstacles on rocky and uneven surfaces (Raibert *et al*. 1993; Farley & Gonzalez 1996). For these reasons, an adjustable leg stiffness might help legged robots approach the speed and agility of animals on natural terrain.

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