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LEG STIFFNESS AND STRIDE FREQUENCY IN HUMAN RUNNING

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Abstract—When humans and other mammals run, the body's complex system of muscle, tendon and ligament springs behaves like a single linear spring ('leg spring'). A simple spring–mass model, consisting of a single linear leg spring and a mass equivalent to the animal's mass, has been shown to describe the mechanics of running remarkably well. Force platform measurements from running animals, including humans, have shown that the stiffness of the leg spring remains nearly the same at all speeds and that the spring–mass system is adjusted for higher speeds by increasing the angle swept by the leg spring. The goal of the present study is to determine the relative importance of changes to the leg spring stiffness and the angle swept by the leg spring when humans alter their stride frequency at a given running speed. Human subjects ran on treadmill-mounted force platform at 2.5 m s^{-1} while using a range of stride frequencies from 26% below to 36% above the preferred stride frequency. Force platform measurements revealed that the stiffness of the leg spring increased by 2.3-fold from 7.0 to 16.3 kN m^{-1} between the lowest and highest stride frequencies. The angle swept by the leg spring decreased at higher stride frequencies, partially offsetting the effect of the increased leg spring stiffness on the mechanical behavior of the spring–mass system. We conclude that the most important adjustment to the body's spring system to accommodate higher stride frequencies is that leg spring becomes stiffer.

Keywords: Locomotion; Spring–mass model, Elastic energy; Biomechanics; Motor control.

INTRODUCTION

When animals run, they bounce along the ground using musculoskeletal springs to alternately store and return elastic energy (Cavagna *et al.*, 1964, 1977). Muscles, tendons and ligaments can all behave as springs, storing elastic energy when they are stretched and returning it when they recoil (Alexander, 1988). During running, this complex system of musculoskeletal springs behaves much like a single linear spring (the 'leg spring'). In fact, a simple spring–mass model (Fig. 1), consisting of a single linear leg spring and a mass equivalent to the animal's mass, has been shown to describe and predict the mechanics of running remarkably well (Alexander, 1992; Alexander and Vernon, 1975; Blickhan, 1989; Blickhan and Full, 1993; Cavagna *et al.*, 1988; Farley *et al.*, 1991, 1993; He *et al.*, 1991; Ito *et al.*, 1983; McGeer, 1990; McMahon and Cheng, 1990; Thompson and Raibert, 1989).

How can a simple spring–mass system be adjusted to operate at different running speeds? As animals run faster, the vertical excursion of the center of mass during the stance phase decreases, and the time that each foot is on the ground decreases. In the spring–mass model, these changes could be the result of an increased stiffness of the leg spring or an increased angle swept by the leg spring during the ground contact phase. By increasing the angle swept by the leg spring, the vertical excursion of the center of mass and the ground contact time can be reduced without changing the stiffness of the leg spring. Biomechanical studies have shown that as animals run faster, the body's spring system is adjusted to bounce off the ground in less time by increasing the angle swept by the leg spring during the ground contact phase rather than by increasing the stiffness of the leg spring (Farley *et al.*, 1993; He *et al.*, 1991). The stiffness of the leg spring remains nearly the same at all speeds in a variety of animals including running humans, hopping kangaroos and trotting horses (Farley *et al.*, 1993; He *et al.*, 1991).

Although the stiffness of the leg spring remains the same at all speeds during forward running, experimental evidence shows that it is possible for humans to alter the stiffness of their leg spring. When humans hop in place and vary their hopping frequency, the stiffness of the leg spring can be changed by as much as twofold to accommodate different hopping frequencies (Farley *et al.*, 1991). Similarly, when humans bounce vertically on a compliant board, the stiffness of the leg spring can change by twofold in response to changes in knee angle (Greene and McMahon, 1979). Finally, when humans run with increased knee flexion ('Groucho Running'), the stiffness of the leg spring appears to decrease (McMahon *et al.*, 1987). These studies clearly demonstrate that it is possible to change the stiffness of the leg spring during bouncing movements.

The goal of the present study is to determine the relative importance of changes to the leg spring stiffness and the angle swept by the leg spring in adjusting the behavior of the spring–mass system when humans alter

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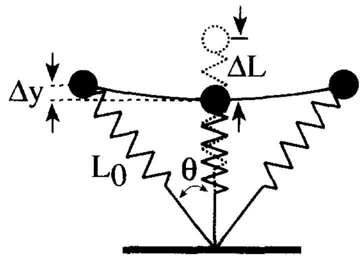

Fig. 1. Running is modeled as simple spring–mass system bouncing along the ground (McMahon and Cheng, 1990). The model consists of a mass and a single leg spring (which connects the foot and the center of mass of the animal). This figure depicts the model at the beginning of the stance phase (leftmost position), at the middle of the stance phase (leg spring is oriented vertically) and at the end of the stance phase (rightmost position). The leg spring has an initial length, L_0, at the beginning of the stance phase, and its maximal compression is represented by ΔL. The dashed spring–mass model shows the length of the uncompressed leg spring. Thus, the difference between the length of the dashed leg spring and the maximally compressed leg spring represents the maximum compression of the leg spring, ΔL. The downward vertical displacement of the mass during the stance phase is represented by Δy and is substantially smaller than ΔL. Half of the angle swept by the leg spring during the ground contact time is denoted by θ.

their stride frequency at a given running speed. It is well known that changing stride frequency at a given running speed has strong effects on energetic cost (Hogberg, 1952; Cavanagh and Williams, 1982), impact forces on the musculoskeletal system (Clarke *et al.*, 1983), and mechanical power of the center of mass and limbs (Cavagna *et al.*, 1991; Kaneko *et al.*, 1987). Based on previous studies, we predict that when stride frequency is increased, the spring–mass system will be adjusted using one or both of the following mechanisms: (1) increasing the stiffness of the leg spring; and (2) increasing the angle swept by the leg spring.

METHODS

Four male subjects (average mass 73.4 ± 8.3 kg and average leg length of 0.97 ± 0.03 m, mean ± S.D.) between the ages of 21 and 29 yr volunteered to participate in this study. They were in good health and were experienced treadmill runners. Informed consent was obtained from the subjects, and the experimental protocol was approved by the Human Subjects Committee at Harvard University.

At the beginning of the experiments, each subject performed 10 min runs on two separate days to determine the preferred stride frequency for running at 2.5 m s^{-1}. The running speed of 2.5 m s^{-1} was chosen because it was low enough that a large range of stride frequencies above and below the preferred frequency could be sustained. In subsequent experiments, each subject ran at nine stride frequencies: the preferred, four below the preferred (− 5, − 11, − 18 and − 26%) and four above the preferred (+ 17, + 25, + 30 and + 36%). Throughout this paper, 'Δ stride frequency' and 'ΔSF' will represent the percent difference in stride frequency from the preferred stride frequency. We defined a stride as the time from the footfall of one leg to the next footfall of the same leg. On average, the preferred stride frequency was 1.33 ± 0.09 stride per second (mean ± S.D.). In all trials, including the trials at the preferred frequency, the subjects matched their footfalls to a metronome while they ran on a motorized treadmill. Each subject required about two 1-h practice sessions to learn to match the frequency of the metronome to within 1%. At each frequency, the properties of the musculoskeletal spring system were analyzed using force platform measurements in order to address the question of whether the stiffness of the leg spring can be adjusted to accommodate a range of stride frequencies at a given speed.

The vertical ground reaction force during running was measured using a treadmill-mounted force platform (Kram and Powell, 1989). A strain-gauged force platform (model OR6-5-1, Advanced Mechanical Technology, Newton, MA) was mounted under the tread belt (Kram and Powell, 1989). The cross-talk from a horizontal force to the vertical was less than 1%. The natural frequency of vertical vibration of the force platform mounted in the treadmill was 160 Hz. The force signal was sampled at 1 kHz.

The spring–mass model that was used to analyze the mechanics of running consisted of a mass and a single linear massless 'leg spring' (Fig. 1; Farley *et al.*, 1993; He *et al.*, 1991; McMahon and Cheng, 1990). The stiffness of the leg spring, k_{leg}, was defined as the ratio of the force in the spring, F, to the displacement of the spring, ΔL, at the instant when the leg spring was maximally compressed:

$$k_{leg} = F/\Delta L. \quad (1)$$

The leg spring was maximally compressed at the middle of the stance phase when the leg spring was oriented vertically, and thus, F corresponded to the peak vertical ground reaction force.

The peak displacement of the leg spring, ΔL, was calculated from the maximum vertical displacement of the center of mass, Δy, the initial length of the leg spring, L_0 (measured as the vertical distance from the ground to the greater trochanter during standing), and half of the angle swept by the leg spring while it was in contact with the ground, θ (Fig. 1; McMahon and Cheng, 1990):

$$\Delta L = \Delta y + L_0(1 - \cos\theta). \quad (2)$$

The vertical displacement of the center of mass, Δy, was calculated by integrating the vertical acceleration twice as described in detail elsewhere (Blickhan and Full, 1992; Cavagna, 1975). From geometric considerations (Fig. 1), an equation for calculating θ from the time of foot contact with the ground, t_c, the forward speed, u, and L_0 was obtained:

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

The vertical motions of the system during the ground contact phase can be described in terms of the 'vertical stiffness', k_{vert}. The vertical stiffness, k_{vert}, does not correspond to any physical spring in the model. Rather, k_{vert} describes the vertical motions of the center of mass during the ground contact time and is important in determining how long the spring–mass system remains in contact with the ground. The effective vertical stiffness was calculated from the ratio of the force, F, to the vertical displacement of the center of mass, Δy, at the moment when the center of mass reached its lowest point:

$$k_{vert} = F/\Delta y. \quad (4)$$

The center of mass reached its lowest point at the same time as the leg spring was maximally compressed.

In the spring–mass model, the effective vertical stiffness, k_{vert}, is determined from a combination of the stiffness of the leg spring, k_{leg}, half the angle swept by the leg spring, θ, and the force in the spring, F. Equation (4) can be rewritten to show the interrelationship between these aspects of the system by defining Δy in terms of F, k_{leg}, L_0 and θ [equation (2)]:

$$k_{vert} = F/[(F/k_{leg}) - L_0(1 - \cos\theta)]. \quad (5)$$

Equation (5) shows that when the leg spring is oriented vertically ($\theta = 0°$) during the entire time that it is in contact with the ground (e.g. during hopping or running in place), $k_{vert} = k_{leg}$. As θ increases above zero (e.g. during forward locomotion), k_{vert} increases relative to k_{leg}. This can be observed in that the vertical displacement of the center of mass, Δy, decreases relative to the displacement of the leg spring, ΔL, when the angle swept by the leg spring is greater. In addition, analysis of equation (5) shows that k_{vert} will increase if k_{leg} increases. A detailed discussion of the concept of the vertical stiffness is included in McMahon and Cheng (1990).

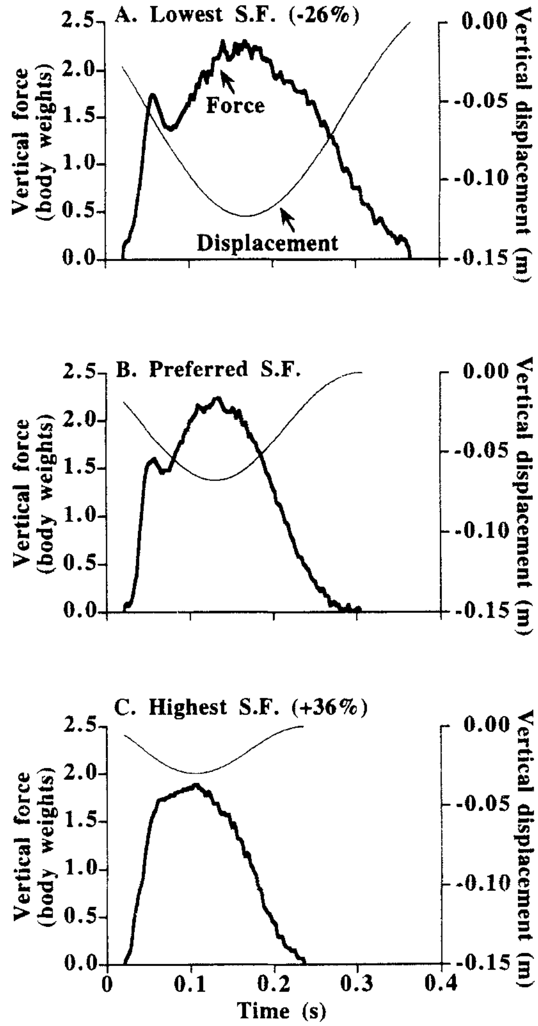

Fig. 2. Vertical ground reaction force (thick line) and vertical displacement (thin line) as a function of time during the ground contact phase for: (A) the lowest stride frequency, (B) the preferred stride frequency, and (C) the highest stride frequency. Note that the general pattern of vertical ground reaction force and displacement was similar for all stride frequencies suggesting that a spring-like gait was used at all stride frequencies. However, the time of foot–ground contact and the magnitude of the vertical displacement both decreased at higher stride frequencies. These are typical data from a 67 kg subject with a leg length of 0.94 m.

RESULTS

The general pattern of vertical force application to the ground and of vertical displacement of the center of mass was similar at all stride frequencies suggesting that a 'spring-like' gait was used over the range of stride frequencies (Fig. 2). The vertical ground reaction force began to rise as the foot hit the ground and reached an initial peak within the first 0.035 s of the ground contact phase. This initial peak was associated with the heel hitting the ground at the beginning of the ground contact phase. After the initial peak, the vertical force smoothly increased to a midstep maximum that occurred at the same time as the center of mass reached its lowest point. Then, during the second half of the ground contact phase, the center of mass moved upward, and the vertical force smoothly decreased, reaching zero as the foot left the ground.

The vertical displacement of the center of mass and the ground contact time decreased at higher stride frequencies, showing that there were substantial adjustments to the mechanical behavior of the musculoskeletal spring system when stride frequency was altered (Fig. 2). First, as stride frequency was increased, the vertical displacement of the center of mass during the ground contact phase, Δy, decreased substantially (Figs 2 and 6B). Between the lowest and highest frequencies, Δy decreased by 76% (0.107 ± 0.011 m at the lowest frequency to 0.025 ± 0.001 m at the highest frequency, mean of all subjects $\pm$ S.E.M.). In addition, as frequency was increased, the time that a foot was on the ground (the ground contact time, t_c) decreased by 32% (Figs 2 and 3; 0.365 ± 0.009 s at the lowest frequency to 0.248 ± 0.008 s at the highest frequency, Fig. 3). These observations suggest that there were substantial changes to the vertical stiffness to accommodate changes in stride frequency.

The slope of the relationship between the vertical force and the vertical displacement of the center of mass increased at higher stride frequencies, suggesting that the

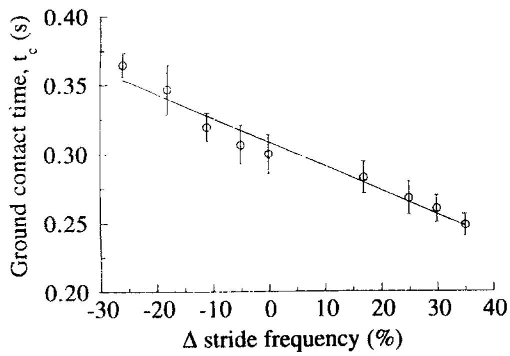

Fig. 3. The time of foot–ground contact (the ground contact time, t_c) decreased at higher stride frequencies ($F_{8,24} = 29.7$, $P < 0.01$, ANOVA), suggesting that there were substantial adjustments to the mechanical behavior of the spring–mass system to accommodate changes in stride frequency. In this graph and others, 'Δ stride frequency' represents the percent difference in stride frequency from the preferred stride frequency. Each point represents the mean for all subjects, and each error bar represents the standard error of the mean. The line is the least-squares linear regression.

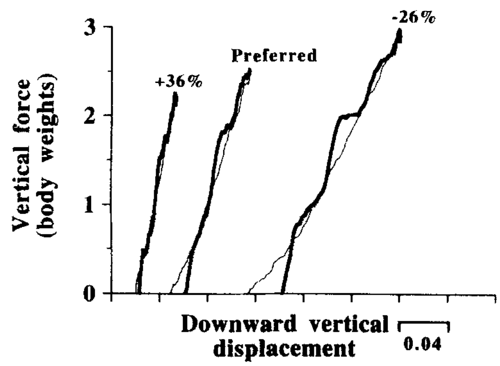

Fig. 5. When a subject was instructed to hit the ground with his forefoot rather than his heel, the general shape of the force–displacement relationship did not change substantially except that the initial force peak nearly completely disappeared. The force–displacement curves are labeled with stride frequencies. The thicker lines represent the landing phase and the thinner lines represent the takeoff phase. The convention used here is that the vertical displacement increases as the center of mass moves downward. The data shown in this figure are from the same subject as the data shown in Figs 2 and 4.

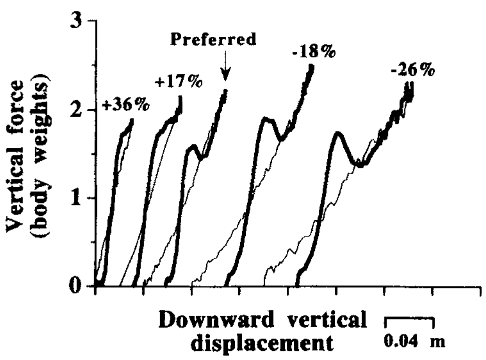

Fig 4. After the force peak there was a nearly linear relationship between the vertical force and the downward vertical displacement during the ground contact phase at all stride frequencies, and the slope of the force–displacement curve increased at higher stride frequencies. This observation suggests that the vertical stiffness of the spring–mass system increased at higher stride frequencies. The force–displacement curves are labeled with stride frequencies. The 'preferred' stride frequency is the one that the subject normally chose to use at this speed, and the other frequencies are labeled with their % difference from the preferred stride frequency. The thicker lines represent the landing phase and the thinner lines represent the takeoff phase. The convention used here is that the vertical displacement increases as the center of mass moves downward. The data shown in this figure are from the same subject and trials as the data shown in Fig. 2. This subject, as well as all of the other subjects, chose to use heel-toe running. The data were similar for all of the subjects.

vertical stiffness, k_{vert}, increased at higher stride frequencies (Fig. 4). Because the vertical stiffness, k_{vert}, of the spring–mass system is important in determining its mechanical behavior, it is instructive to examine the vertical force–displacement relationship to begin to understand the adjustments to the spring–mass system for different stride frequencies. At the preferred stride frequency, the vertical ground reaction force began to rise as the foot hit the ground (thicker line) (Fig.4). It rapidly increased to about 1.6 times body weight (the 'initial force peak') and then decreased slightly. This initial force peak appeared to be associated with heel strike and subsequent deceleration of the shank. Inspection of videotapes of the trials confirmed that the subjects chose to strike the ground first with their heels. After the initial force peak, the vertical force was nearly linearly related to the vertical displacement. The force reached its maximum of about 2.3 times body weight at the same time as the center of mass reached its lowest point. During takeoff (thinner line), the center of mass moved upward as the force smoothly decreased to zero. This general pattern was similar at all stride frequencies, and the slope of the vertical force–displacement relationship increased at higher frequencies.

When a subject ran at each stride frequency while striking the ground with his forefoot rather than his heel, the initial force peak was nearly completely absent (Fig. 5). This observation supports the idea that the initial force peak observed in Fig. 4 was associated with heel strike and subsequent deceleration of the shank. This conclusion is also supported by the observation that the time course of the initial force peak observed in Fig. 4 was short (0.035 s) at all stride frequencies (Fig. 2).

The vertical stiffness of the spring–mass system increased at higher stride frequencies, k_{vert} (Fig. 6C). Between the lowest and highest frequencies, k_{vert} increased by 3.5-fold from 15.1 ($\pm$ 0.713 kN m^{-1}) to 52.4 kN m^{-1} ($\pm$ 2.34 kN m^{-1}). Over the range of stride frequencies, peak vertical force, F, only changed slightly but the peak vertical displacement, Δy, decreased substantially. Between the lowest and highest stride frequencies, the

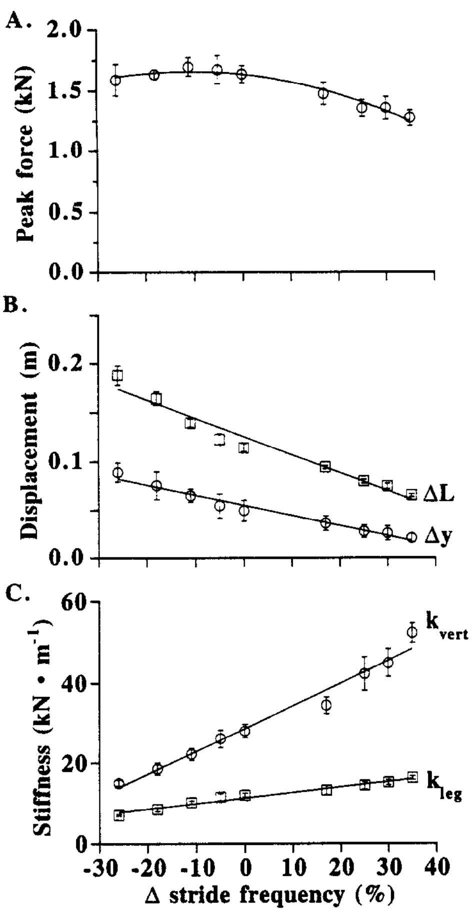

Fig. 6. The leg spring stiffness, $F/\Delta L$, and the vertical stiffness, $F/\Delta y$, increased at higher stride frequencies. (A) The peak force decreased at stride frequencies above the preferred stride frequency ($F_{8,24} = 19.5$, $P < 0.01$, ANOVA). (B) Both the vertical displacement of the center of mass (Δy; $F_{8,24} = 63.4$, $P < 0.01$, ANOVA) and the displacement of the leg spring (ΔL; $F_{8,24} = 106.5$, $P < 0.01$, ANOVA) decreased substantially at higher stride frequencies. (C) Both the vertical stiffness (k_{vert}; $F_{8,24} = 80.4$, $P < 0.01$, ANOVA) and the leg spring stiffness (k_{leg}, $F_{8,24} = 43.5$, $P < 0.01$, ANOVA) increased at higher stride frequencies. In parts A–C, each point represents the mean for all subjects, and each error bar represents the standard error of the mean. Note that the error bars are contained within the points in some instances. The lines are the least-squares regressions.

peak vertical force decreased slightly (− 19%), and the peak vertical displacement, Δy, decreased much more (− 76%, Figs 4, 6A and B).

The vertical stiffness of the spring–mass system increased at higher stride frequencies because the leg spring stiffness increased (Fig. 6C). The leg spring stiffness more than doubled between the lowest frequency (7.03 ± 0.21 kN m^{-1}) and the highest frequency (16.34 ± 0.42 kN m^{-1}). The ratio of the peak force to the peak displacement of the leg spring, $F/\Delta L$, increased at higher stride frequencies mainly because ΔL decreased. Between the lowest and highest stride frequencies, F decreased slightly (− 19%), and ΔL decreased substantially (− 65%, Figs 6A and B).

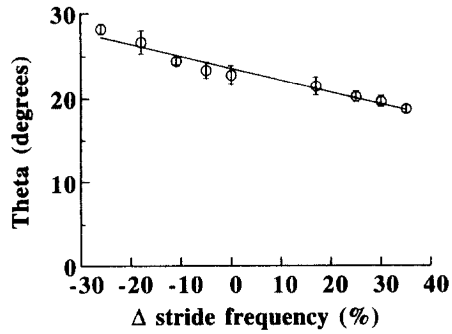

Fig 7. Half the angle swept by the leg spring (θ, see Fig. 1) decreased at higher stride frequencies ($F_{8,24} = 49.3$, $P < 0.01$, ANOVA). This decreased angle swept by the leg spring at higher stride frequencies causes there to be a lower vertical stiffness for a given leg spring stiffness. Thus, the decreased angle swept by the leg spring stiffness partially offset the effects of the increased leg spring stiffness at higher stride frequencies. Each point represents the mean for all subjects, and each error bar represents the standard error of the mean. Note that the error bars are contained within the points in some instances. The line is a linear least-squares regression.

Half the angle swept by the leg spring decreased at higher stride frequencies, partially offsetting the effect of the increase in k_{leg} on k_{vert} (Fig. 7). Between the lowest and the highest stride frequencies, θ decreased from 28.2° (± 0.4°) to 18.7° (± 0.3°). For a given k_{leg}, reducing θ will reduce k_{vert}. Thus, there was a lower k_{vert} for a given k_{leg} at high stride frequencies than there would have been if θ had not decreased at higher stride frequencies.

DISCUSSION

The spring–mass model used to analyze running in this study is the simplest model that can describe the mechanics of running gaits. This model represents the entire mass of the animal as a single point mass and represents the entire musculoskeletal system as a single linear spring. The simplicity of this model contrasts with the complexity of the actual musculoskeletal system. The actual musculoskeletal system consists of a jointed skeleton with muscles, tendons and ligaments acting across nearly every joint. Yet, despite the simplicity of the model, it describes and predicts the mechanics of running in a variety of animals including humans, horses, kangaroos and cockroaches (Blickhan and Full, 1993; Farley *et al.*, 1993; He *et al.*, 1991). This observation shows that the actions of all of the elements of the musculoskeletal system are integrated in such a way that the overall system behaves like a single linear spring during running.

In the present study, we investigate the relative importance of changes to the leg spring stiffness and the angle swept by the leg spring in adjusting the behavior of the spring–mass system when humans alter their stride frequency at a given running speed. We find that when humans increase their stride frequency at a given running speed, the most important adjustment to the body's spring system is that leg spring becomes stiffer. Between the lowest and highest possible stride frequencies, the stiffness of the leg spring more than doubles. As a result, the vertical stiffness of the spring–mass system increases, the vertical displacement during the ground contact phase decreases, and the system bounces off the ground in less time at higher stride frequencies. The angle swept by the leg spring decreases at higher stride frequencies, partially offsetting the effect of the higher leg spring stiffness on the mechanical behavior of the spring–mass system.

These findings about the adjustability of the leg spring during forward running parallel those of an earlier study showing that the stiffness of the leg spring can be altered substantially when humans hop in place at different frequencies (Farley *et al.*, 1991). When humans hop in place, the stiffness of the leg spring increases by about twofold when they increase their hopping frequency by 65%. Similarly, when humans run forward at a given speed, the stiffness of the leg spring increases by about twofold when they increase their stride frequency by 65%. Thus, the relationship between leg stiffness and stride frequency is similar for hopping in place and for forward running. Although our study did not address the issue of the mechanism of stiffness adjustment, earlier studies (Greene and McMahon, 1979; McMahon *et al.*, 1987) suggest that alterations in limb posture may lead to changes in leg stiffness, In addition, it is possible that the stiffness of the leg may be altered by changing the activation of muscles acting about the joints of the leg.

In conclusion, we find that although the leg spring stiffness does not change with speed in forward running, it is possible for leg stiffness to be changed by more than two-fold to accommodate different stride frequencies at a given speed. The adjustability of leg stiffness may be important in allowing the body's spring system to operate on the variety of terrain encountered in the natural world. In addition, our findings suggest that a variable leg stiffness may be an important design parameter for spring-based prostheses for running and for legged robots.

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