The Journal of Experimental Biology 200, 821–826 (1997)
Printed in Great Britain © The Company of Biologists Limited 1997
JEB0645

EFFECT OF REDUCED GRAVITY ON THE PREFERRED WALK–RUN TRANSITION SPEED

RODGER KRAM*, ANTOINETTE DOMINGO AND DANIEL P. FERRIS
Human Biodynamics Department, University of California, Berkeley, CA 94720-4480, USA

Accepted 25 November 1996

Summary

We investigated the effect of reduced gravity on the human walk–run gait transition speed and interpreted the results using an inverted-pendulum mechanical model. We simulated reduced gravity using an apparatus that applied a nearly constant upward force at the center of mass, and the subjects walked and ran on a motorized treadmill. In the inverted pendulum model for walking, gravity provides the centripetal force needed to keep the pendulum in contact with the ground. The ratio of the centripetal and gravitational forces $(mv^2/L)/(mg)$ reduces to the dimensionless Froude number (v^2/gL). Applying this model to a walking human, m is body mass, v is forward velocity, L is leg length and g is gravity. In normal gravity, humans and other bipeds with different leg lengths all choose to switch from a walk to a run at different absolute speeds but at approximately the same Froude number (0.5). We found that, at lower levels of gravity, the walk–run transition occurred at progressively slower absolute speeds but at approximately the same Froude number. This supports the hypothesis that the walk–run transition is triggered by the dynamics of an inverted-pendulum system.

Key words: biomechanics, locomotion, gait, Froude number, human, gravity, reduced gravity.

Introduction

Terrestrial animals walk at slow speeds and run at faster speeds. Walking is classically defined as a gait in which at least one leg is in contact with the ground at all times (Hildebrand, 1985). In contrast, running involves aerial phases when no feet are in contact with the ground. When a person begins walking and gradually increases their speed, they prefer to switch to a run at one particular speed. This gait transition occurs because intuitively it feels easier to run than to walk, even though it is possible to walk faster than the preferred transition speed. In this study, we seek a more quantitative explanation for the human walk–run transition.

Margaria (1938) was among the first investigators to quantify that it is metabolically more expensive for humans to walk than to run at speeds faster than $2\,\mathrm{m\,s^{-1}}$. This speed approximately corresponds to the observed gait transition speed, leading to the idea that there is a metabolic trigger for the walk–run transition. A number of studies have recently scrutinized this idea, including Hreljac (1993*b*), Mercier *et al.* (1994) and Minetti *et al.* (1994). These three studies draw different conclusions from very similar data. The different conclusions seem to be due to the different methods of determining the preferred transition speed. Whether metabolic energy cost provides the trigger for the human walk–run transition remains open to interpretation and further experimentation.

Metabolic triggers for gait transitions have also been investigated in quadrupedal animals. Hoyt and Taylor (1981) showed that, during unconstrained overground running at preferred speeds, horses choose the gait that minimizes metabolic energy cost. However, their experiments did not measure the preferred transition speeds between gaits. Farley and Taylor (1991) showed that the trot–gallop transition speed is not triggered metabolically but rather mechanically. They found that horses switch from a trot to a gallop at a critical level of the vertical ground reaction force. However, the walk–trot transition in quadrupeds is probably not triggered by the same mechanism since peak ground reaction forces increase when a quadrupedal animal switches from a walk to a trot (Cavagna *et al.* 1977). Hreljac (1993*a*) found that humans also experience increased forces when they switch to a run and rejected the idea that peak ground reaction forces trigger the walk–run transition.

It seems possible that stride length or some other kinematic variable might be a limitation at fast walking speeds that could be overcome by switching to a run. Hreljac (1995*a*) examined a host of kinematic variables to determine whether a critical value was reached at fast walking speeds and was then decreased by switching to a run. The only kinematic variable that he identified as a trigger for the walk–run transition was the maximum ankle angular velocity (dorsiflexion) required to prevent toe drag during the early part of the swing phase. He found that the maximum ankle angular velocity increases with walking speed and that, by switching to a run, it is abruptly reduced. When his subjects walked uphill, they switched from

---

*e-mail: rkram@garnet.berkeley.edu.

a walk to a run at different speeds but at the same maximum ankle angular velocity. Hreljac (1995*a*) speculated that the tibialis anterior muscles were experiencing local fatigue.

Similarly, Minetti *et al.* (1994) suggested that a critical angle between the thighs may be a kinematic trigger for the walk–run transition. They asserted that the walk–run transition occurs at different inclines when a 'structural limit' is reached at a particular maximum inter-thigh angle. However, the maximum inter-thigh angle was different at different inclines.

While plausible, these kinematic rationales could only explain the walk–run transition and not the run–walk transition that occurs when speed is gradually decreased. At the run–walk transition, both the maximum ankle angular velocity and the maximum inter-thigh angle increase. It is possible that there are different triggers for each transition, but perhaps there is a simpler mechanism that explains both.

The simplest mechanical model for a walking biped is an inverted pendulum that idealizes the total body mass to a point mass on a rigid massless leg (Alexander, 1977). This model considers walking to be a series of vaults over rigid legs. Force platform and kinematic measurements for humans and a variety of bipedal walking birds are consistent with this model (Cavagna *et al.* 1977). No mechanical energy is needed to maintain the movements of an ideal pendulum because kinetic and gravitational potential energy fluctuations are equal in magnitude and exactly 180 ° out of phase. In humans, the pendulum-like mechanism conserves approximately 70 % of the mechanical energy from step to step at the preferred walking speed (approximately $1.3\,\mathrm{m\,s^{-1}}$) (Cavagna *et al.* 1976). Pendulum-like exchange diminishes at faster walking speeds because of a mismatch in the magnitudes and phases of the fluctuations of the two forms of mechanical energy. Thus, at non-optimal speeds, the muscles must provide additional mechanical power. It may be that the walk–run transition occurs because the inverted pendulum becomes ineffective at conserving mechanical energy compared with the elastic spring mechanisms that conserve mechanical energy in running gaits (Cavagna *et al.* 1977).

The major force that determines the inverted-pendulum-like movements during walking is gravity, which must be at least equal to the centripetal force needed to keep the center of mass traveling along a circular arc. The centripetal force needed is equal to mv^2/L, where m is body mass, L is leg length (hip height) and v is forward speed. In this model, walking above a critical speed is impossible because the gravitational force would be less than the centripetal force required, and the feet would lose contact with the ground. The ratio between the centripetal force and the gravitational force, $(mv^2/L)/m\boldsymbol{g}=v^2/\boldsymbol{g}L$, can be thought of as a dimensionless speed. For historical reasons, the ratio is usually referred to as a Froude number (Alexander, 1989). Above a Froude number of 1.0, walking is impossible for this simple inverted-pendulum model. This equation suggests that animals with longer legs would switch from a walk to a run at faster speeds than animals with shorter legs, and this is borne out by empirical data for a variety of species (Heglund and Taylor, 1988). Note that mass (but not gravity) cancels out of this equation.

In general, humans and other bipedal animals (e.g. birds) prefer to switch from a walk to a run at a Froude number of approximately 0.5 (Alexander, 1977, 1989; Gatesy and Biewener, 1991; Hreljac, 1995*b*; Thorstensson and Roberthson, 1987). However, the inverted-pendulum model does not *a priori* predict that bipeds should switch from a walk to a run at the particular Froude number of 0.5.

The Froude number has only three components: velocity, leg length and gravity. As described above, several groups of investigators have compared the walk–run transition speeds of individuals and species with widely different leg lengths. One way to test further the idea that the gait transition occurs at a particular Froude number is to alter gravity. We conducted the following experiments that simulated locomotion in reduced gravity. We hypothesized that, at reduced levels of gravity, the walk–run transition speed would occur at a slower absolute forward speed but at the same Froude number ($v^2/\boldsymbol{g}L$).

Materials and methods

Preliminary procedures

Nine subjects volunteered to participate in this experiment (seven males and two females, average leg length 0.89±0.043 m; average mass 63.8±7.73 kg; means ± S.D.). Before the experiments, the subjects gave their informed consent after reading a description of the purpose, basic procedures and risks of the experiment. We emphasized that we were looking for their *preferred* gait transition speed, as opposed to the maximum speed of walking or the minimum speed of running. The subjects participated in three separate sessions described below. The first and second sessions familiarized the subjects with the treadmill and the reduced gravity simulator. During the third session, we determined the preferred gait transition speed at different levels of reduced gravity.

Reduced gravity simulator

To simulate reduced gravity, we constructed an apparatus similar to that described by He *et al.* (1991). The device applied a nearly constant upward force to the center of mass of the subject (Fig. 1). To create the upward force, we used a series of compliant rubber spring elements that were stretched to a length much greater than the vertical oscillations of the person. The force in a Hookean spring is equal to $k\Delta x$, where k is the spring constant (in $\mathrm{N\,m^{-1}}$) and Δx is the change in length. Because of the large stretch in the springs, the small movements of the person when walking or running in the springs caused only a small fluctuation in the spring force. A force transducer in series with the springs indicated that the fluctuations were less than $\pm 0.03\,\boldsymbol{g}$ for all levels of simulated gravity. Here, and throughout: $\boldsymbol{g}$ means number of times normal Earth gravity ($9.81\,\mathrm{m\,s^{-2}}$). These fluctuations are almost negligible for the $0.8\,\boldsymbol{g}$ condition, but represent a significant fluctuation at the simulated $0.1\,\boldsymbol{g}$ condition. The saddle only pulled vertically and did not impart any substantial torque on the body because it acted vertically very near the center of mass.

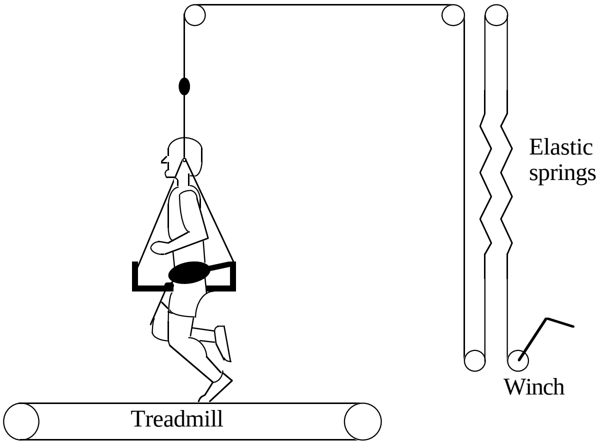

Fig. 1. Reduced gravity simulator. This device applied a nearly constant upward force to the subject's center of mass. The harness consisted of a bicycle saddle attached to a U-shaped section of polyvinyl chloride pipe (total mass 1.74 kg). A wide padded belt held the subject at a comfortable location on the saddle. Upward forces applied to the subject were measured using a force transducer. Two spring elements were arranged in series, connected by cables and separated by a pulley. To increase the amount of tension, additional rubber springs were added in parallel. Additional springs were only added when the force of the original springs became inadequate, in order to maximize spring length and keep the force fluctuations as small as possible. A hand winch reeled in a cable connected to the springs, allowing us to control the length of the springs.

Data collection

Prior to actual data collection, subjects participated in two sessions to allow familiarization with treadmill locomotion and the reduced gravity simulator. In the first session, the subjects walked and ran on the motorized treadmill at comfortable speeds (approximately 1.5 $\mathrm{m\,s^{-1}}$ and approximately 3 $\mathrm{m\,s^{-1}}$, respectively) for 30 min at 1.0 $\boldsymbol{g}$ (where $\boldsymbol{g}$ is 'normal gravitational acceleration') – alternating between speeds every 5 min. The data of Schieb (1986) indicate that this amount of treadmill experience is more than adequate for accommodation to treadmill locomotion and that kinematic variables do not change further with more experience. During the second session, the subjects completed eight trials that lasted 5 min each: each trial consisted of walking and running at both 1.0 $\boldsymbol{g}$ and 0.5 $\boldsymbol{g}$ and was then repeated. This completed the familiarization phase.

Because different investigators have used different protocols to measure the preferred walk–run transition speed, we describe our methods in detail. At the beginning of the third session, the experimenter measured the subject's mass and leg length (height to the greater trochanter of the femur). The subject then warmed-up by walking and running at 0.5 $\boldsymbol{g}$ for 5 min each in the reduced gravity simulator. Next, the subject walked and ran at 1.0 $\boldsymbol{g}$, and then rested for approximately 5 min before starting the experimental procedures. To obtain a preliminary estimate of the walk–run transition speed, the subject walked on the treadmill while the speed was steadily increased, and the experimenter noted the transition speed. To find the transition speed more precisely, we used a procedure similar to that used by Hreljac (1993*b*). The speed of the treadmill belt was adjusted to a constant walking speed that was comfortable for the subject and at least 0.3 $\mathrm{m\,s^{-1}}$ below the approximated transition speed. Treadmill belt speed was verified with a stopwatch during each trial. After 30 s, we asked the subject if they preferred to walk or run. There was no time limit on deciding which gait was preferred. The treadmill speed was then increased by 0.1 $\mathrm{m\,s^{-1}}$, and we repeated the process of measuring the treadmill speed and the preferred gait until the subject preferred to run for three consecutive increments in speed. The first speed at which the subject preferred to run was deemed the preferred transition speed. After completing the process at 1.0 $\boldsymbol{g}$, we repeated the entire procedure at 0.8, 0.6, 0.5, 0.4, 0.2 and 0.1 $\boldsymbol{g}$.

Results

At lower levels of gravity, the walk–run transition occurred at progressively slower absolute speeds (Table 1; Fig. 2). At 1.0 $\boldsymbol{g}$, the average transition speed was 1.98 $\mathrm{m\,s^{-1}}$, which corresponded to an average Froude number ($v^2/\boldsymbol{g}L$) of 0.45. We

Table 1. *Walk–run transition speed and Froude number of humans at different gravity levels*

Gravity ($\boldsymbol{g}$)	Transition speed ($\mathrm{m\,s^{-1}}$)	Froude number	Predicted transition speed ($\mathrm{m\,s^{-1}}$)	% Difference from prediction
1.0	1.98 (±0.038)	0.45 (±0.02)	1.98	–
0.8	1.84 (±0.049)	0.49 (±0.03)	1.77	4
0.6	1.65 (±0.066)	0.53 (±0.04)	1.54	7
0.5	1.55 (±0.067)	0.56 (±0.05)	1.40	11
0.4	1.39 (±0.062)	0.56 (±0.05)	1.25	11
0.2	1.18 (±0.073)	0.83 (±0.10)	0.89	34
0.1	0.97 (±0.075)	1.13 (±0.17)	0.63	54

Froude number ($v^2/\boldsymbol{g}L$) was calculated from transition speed (v, in $\mathrm{m\,s^{-1}}$), simulated gravity level ($\boldsymbol{g}$, number of times normal Earth gravity, 9.81 $\mathrm{m\,s^{-2}}$) and leg length (L, in m).

Predicted transition speeds were based on the Froude number found at 1.0 $\boldsymbol{g}$ and the average leg length (L=0.89 m).

Values are means (±S.E.M.) for nine subjects.

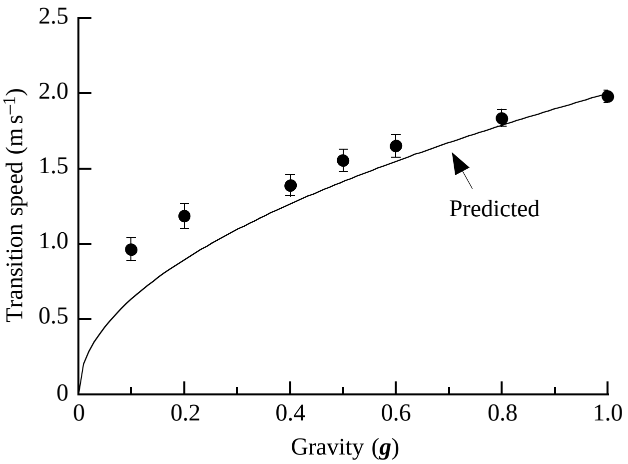

Fig. 2. The mean walk–run transition speed was slower at lower levels of simulated reduced gravity. The subjects preferred to switch gaits at approximately 1.98 m s^{-1} during locomotion at normal earth gravity (1.0 **g**), but at 0.1 **g** they chose to switch at less than half that speed, 0.97 m s^{-1}. The solid line is the predicted transition speed for reduced gravity trials based on a constant Froude number equal to the Froude number at 1.0 **g**. Error bars indicate ± 1 S.E.M., *N*=9.

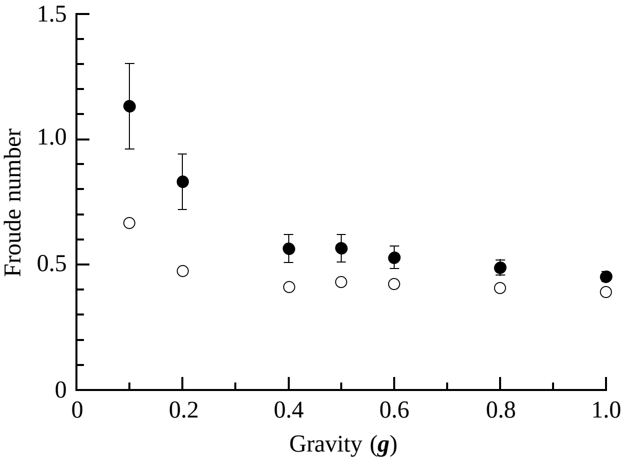

Fig. 3. The dimensionless Froude number, the ratio of the centripetal and gravitational forces at the preferred walk–run transition speed, is plotted *versus* the gravity level (filled symbols). From 1.0 to 0.4 **g**, the gait transition occurred at a fairly constant Froude number (0.45 to 0.56). However, at very low gravity levels, subjects switched gaits at substantially higher Froude numbers. At the lowest simulated gravity level of 0.1 **g**, the Froude number at the transition was 1.1, a value that is theoretically impossible for a single point mass rigid leg model. The open symbols represent estimated ‘adjusted’ Froude numbers for a more complicated model of walking that incorporates the additional downward force provided by the swing leg. This model is described in the text. Note that this modification of the model results in nearly constant Froude numbers for the walk–run transition speed over a tenfold range of gravities. Error bars indicate ± 1 S.E.M., *N*=9.

calculated the absolute speed that corresponds to a Froude number of 0.45 for each level of gravity and plotted this prediction as the solid line in Fig. 2. Above 0.2 **g**, this prediction was within 11 % of the actual preferred transition speed, although it represented a systematic underprediction.

At 0.2 and 0.1 **g**, the preferred speeds were substantially higher than predicted. This dramatic difference from the prediction is addressed below. Fig. 3 (filled symbols) and Table 1 present the data in a different form. These data indicate that the Froude number at the preferred transition speed increased only moderately from 1.0 to 0.4 **g** and then increased substantially at 0.2 and 0.1 **g**.

Discussion

The main purpose of this study was to examine whether inverted-pendulum mechanics trigger the walk–run transition speed. In general, our data support the hypothesis that, in reduced gravity, the walk–run transition occurs at a slower absolute speed but at a similar Froude number. Over the tenfold range of gravities, the walk–run transition speed decreased by more than 50 %. Given these large changes, our empirical results are remarkably close to the predictions of a simple inverted-pendulum model for walking.

However, our findings show that at lower levels of simulated reduced gravity (0.1 and 0.2 **g**) the equal Froude number prediction did not hold. This could be due to a number of factors. First, we considered whether our method of simulating reduced gravity was inadequate at very low levels of gravity. Our simulation did not alter the way in which the limbs swing passively in a real reduced-gravity situation. At normal Earth gravity, the dominant downward acceleration force on the body is gravity. However, an additional downward acceleration is caused by any swinging of the arms and legs. At normal gravity, these swinging-induced accelerations are small relative to gravity. At the lower levels of gravity we simulated in this study, the limb accelerations were relatively substantial. For example, we estimated that at a simulated gravity of 0.2 **g**, the peak limb acceleration force was equivalent to approximately 0.16 **g**. These estimates were made by measuring the vertical ground reaction force under one foot while the subject swung their arms and opposite leg through a similar arc and at the same frequency as that used during walking. At mid-stance, the downward vertical force is equal to the sum of gravity and the inertial force of the swinging limbs. Although there is evidence that the leg is swung passively at the preferred speed of walking in normal gravity (Basmajian and De Luca, 1985), leg swing is an active process at faster speeds. In a real reduced-gravity environment (e.g. on the moon), the leg would swing more slowly if it were a passive process. However, we suspect that leg swing would be an active process at faster than preferred walking speeds in true reduced gravity.

The divergence of empirical results from the prediction at low simulated gravity may be due to the simplifying assumptions of the inverted-pendulum model of walking. Perhaps the model should be modified to account for the leg-swing-induced accelerations introduced above. If we consider the 0.2 **g** example with 0.16 **g** of peak leg-swing-induced acceleration, then the true peak effective $\boldsymbol{g}$ is 0.36. If we substitute $0.36\boldsymbol{g}$ for the '$0.2\boldsymbol{g}$' condition, we obtain an 'adjusted' Froude number (Fr') of 0.44, almost exactly the 0.45 value found at $1.0\boldsymbol{g}$. We carried out similar calculations for all levels of gravity and plotted the modified results in Fig. 3 (open symbols). These calculations suggest that a more accurate model of walking should include accelerations of the leg and arms of appropriate mass and inertia. Thus, we feel that our simulation is a good simulation of an actual reduced-gravity environment, but that the peak downward acceleration is not simply equal to gravity.

The simple inverted-pendulum model suggests that a person must run if the Froude number is greater than 1.0. Note that, in Table 1 at $0.1\boldsymbol{g}$, the subjects preferred to switch from a walk to a run at speeds with a Froude number greater than 1 and could have walked substantially faster. This underscores the inadequacy of the simple inverted-pendulum model for walking in low gravity.

The simple inverted-pendulum model identifies the Froude number as an important variable; however, it only predicts the *maximum* walking speed (Froude number=1.0). Many investigators have noted that humans and bipedal birds *prefer* to switch from a walk to a run at a Froude number of 0.5. However, we are aware of no satisfactory model that predicts *a priori* that the transition should occur at a Froude number of 0.5. The most recent relevant modeling attempt was that of Alexander (1992), which included compliant legs with reasonable mass. This model could be modified to predict a transition at a Froude number of 0.5, but only with adjustments that did not seem reasonable to Alexander or to us. A simple mechanical model that predicts a transition at a Froude number of 0.5 remains elusive.

Margaria, Cavagna and many collaborators (Cavagna *et al.* 1976, 1977; Margaria, 1976) have long championed the idea of walking as an inverted pendulum alternately exchanging mechanical energy between gravitational potential and forward kinetic forms. They have supported this idea with empirical data for these energy fluctuations. An ideal pendulum is a conservative system; that is, the sum of gravitational potential energy and kinetic energy is constant. Cavagna *et al.* (1977) quantified the ideal nature of a human inverted pendulum and found that approximately 60–70 % of the mechanical energy is conserved from step to step. At faster walking speeds, the conservation of mechanical energy is greatly diminished.

Running involves a very different system of mechanical energy conservation. During running, gravitational and kinetic energy is stored as elastic potential energy in the muscles and tendons and then returned during each step. The preferred walk–run transition occurs at a speed beyond that predicted by the optimal pendulum-like conservation of mechanical energy. Beyond that speed, elastic energy storage and recovery may conserve more mechanical energy. Alexander's (1992) model uses this same reasoning. A reasonable next hypothesis to test is that the walk–run transition occurs at the speed at which more mechanical energy is conserved by running than by walking. We are currently investigating this idea by examining the fluctuations in mechanical energy during reduced-gravity walking and running. These experiments may provide a mechanistic explanation for why bipeds choose to switch gaits when the Froude number is 0.5 even though it is not a mechanical requirement.

Conservation of mechanical energy would presumably reduce the metabolic cost of locomotion. A metabolic trigger for a gait transition requires that the preferred transition speed should correspond to the speed beyond which it is metabolically cheaper to use a different gait. Although we did not collect metabolic energy data, the data of Farley and McMahon (1992) provide a background for interpreting the present results. Farley and McMahon (1992) examined the energetic cost of walking and running at normal gravity and at three levels of reduced gravity. They found that reducing gravity decreased the energetic cost of running much more than for walking. They attributed this to the different mechanical energy-conserving mechanisms for the two gaits. Farley and McMahon's (1992) data suggest that, below $0.25\boldsymbol{g}$, it is metabolically cheaper to run than to walk at all speeds. We found that at $0.2\boldsymbol{g}$ our subjects preferred to walk rather than run at speeds below $1.2\,\mathrm{m\,s^{-1}}$. Thus, it appears that a completely non-metabolic trigger may exist at low gravity. Because Farley and McMahon did not measure the cost of running below $2.0\,\mathrm{m\,s^{-1}}$, further measurements are needed to confirm this hypothesis.

In summary, we find that, in reduced gravity, humans prefer to switch from a walk to a run at slower absolute speeds. At normal and moderately reduced levels of gravity, the transition is made at mechanically equivalent speeds (i.e. at a Froude number of approximately 0.5). We interpret these results as evidence that the walk–run transition is triggered by the dynamics of an inverted-pendulum system. However, it remains unclear why the transition occurs at that particular dimensionless speed.

This work was supported by the California Space Institute, NASA fellowship NGT-51416, the University of California SROP, URAP and Biology Fellows Program.

References

ALEXANDER, R. MCN. (1977). Mechanics and scaling of terrestrial locomotion. In *Scale Effects in Animal Locomotion* (ed. T. J. Pedley), pp. 93–110. New York: Academic Press.

ALEXANDER, R. MCN. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiol. Rev.* **69**, 1199–1227.

ALEXANDER, R. MCN. (1992). A model of bipedal locomotion on compliant legs. *Phil. Trans. R. Soc. Lond. B* **338**, 189–198.

BASMAJIAN, J. V. AND DE LUCA, C. (1985). Muscles alive: their function revealed by electromyography. Baltimore: Williams & Wilkins.

CAVAGNA, G. A., HEGLUND, N. C. AND TAYLOR, C. R. (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. *Am. J. Physiol.* **233**, R243–R261.

CAVAGNA, G. A., THYS, H. AND ZAMBONI, A. (1976). The sources of external work in level walking and running. *J. Physiol., Lond.* **262**, 639–657.

FARLEY, C. T. AND MCMAHON, T. A. (1992). Energetics of walking and running: insights from simulated reduced-gravity experiments. *J. appl. Physiol.* **73**, 2709–2712.

FARLEY, C. T. AND TAYLOR, C. R. (1991). A mechanical trigger for the trot–gallop transition in horses. *Science* **253**, 306–308.

GATESY, S. M. AND BIEWENER, A. A. (1991). Bipedal locomotion – effects of speed, size and limb posture in birds and humans. *J. Zool., Lond.* **224**, 127–147.

HE, J. P., KRAM, R. AND MCMAHON, T. A. (1991). Mechanics of running under simulated low gravity. *J. appl. Physiol.* **71**, 863–870.

HEGLUND, N. C. AND TAYLOR, C. R. (1988). Speed, stride frequency and energy cost per stride: how do they change with body size and gait? *J. exp. Biol.* **138**, 301–318.

HILDEBRAND, M. (1985). Walking and running. In *Functional Vertebrate Morphology* (ed. M. Hildebrand, D. M. Bramble, K. F. Liem and D. B. Wake), pp. 38–57. Cambridge: Belknap Press.

HOYT, D. F. AND TAYLOR, C. R. (1981). Gait and energetics of locomotion in horses. *Nature* **292**, 239–240.

HRELJAC, A. (1993*a*). Determinants of the gait transition speed during human locomotion: kinetic factors. *Gait Post.* **1**, 217–223.

HRELJAC, A. (1993*b*). Preferred and energetically optimal gait transition speeds in human locomotion. *Med. Sci. Sports Exerc.* **25**, 1158–1162.

HRELJAC, A. (1995*a*). Determinants of the gait transition speed during human locomotion: kinematic factors. *J. Biomech.* **28**, 669–677.

HRELJAC, A. (1995*b*). Effects of physical characteristics on the gait transition speed during human locomotion. *Human Mov. Sci.* **14**, 205–216.

MARGARIA, R. (1938). Sulla fisiologia e specialmente sul consumo energetico della marcia e della corsa a varie velocita ed inclinazioni del terreno. *Atti Accad. Naz. Lincei Memorie*, pp. 299–368. Cited in *Biomechanics and Energetics of Muscular Exercise* (1976), pp. 69–75. Oxford: Clarendon Press.

MARGARIA, R. (1976). *Biomechanics and Energetics of Muscular Exercise*. Oxford: Clarendon Press. 146pp.

MERCIER, J., LE GALLAIS, D., DURAND, M., GOUDAL, C., MICALLEF, J. P. AND PREFAUT, C. (1994). Energy expenditure and cardiorespiratory responses at the transition between walking and running. *Eur. J. appl. Physiol.* **69**, 525–529.

MINETTI, A. E., ARDIGO, L. P. AND SAIBENE, F. (1994). The transition between walking and running in humans: metabolic and mechanical aspects at different gradients. *Acta physiol. scand.* **150**, 315–323.

SCHIEB, D. A. (1986). Kinematic accommodation of novice treadmill runners. *Res. Q. Exerc. Sport* **57**, 49–57.

THORSTENSSON, A. AND ROBERTHSON, H. (1987). Adaptations to changing speed in human locomotion: speed of transition between walking and running. *Acta physiol. scand.* **131**, 211–214.