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THE EFFECT OF REDUCED GRAVITY ON THE KINEMATICS OF HUMAN WALKING: A TEST OF THE DYNAMIC SIMILARITY HYPOTHESIS FOR LOCOMOTION

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Summary

To gain insight into the basic principles that govern the biomechanics of locomotion, we investigated the effect of reduced gravity on walking kinematics. We hypothesized that humans walk in a dynamically similar fashion at combinations of speed and simulated gravity that provide equal values of the Froude number, v^2/gL_{leg}, where v is forward speed, g is gravitational acceleration and L_{leg} is leg length. The Froude number has been used to predict the kinematics and kinetics of legged locomotion over a wide range of animal sizes and speeds, and thus provides a potentially unifying theory for the combined effects of speed, size and gravity on locomotion biomechanics. The occurrence of dynamic similarity at equal Froude numbers has been attributed previously to the importance of gravitational forces in determining locomotion mechanics. We simulated reduced gravity using a device that applies a nearly constant upward force to the torso while subjects walked on a treadmill. We found that at equal Froude numbers, under different levels of gravity ($0.25g$–$1.0g$), the subjects walked with nearly the same duty factor (ratio of contact time to stride time), but with relative stride lengths (L_s/L_{leg}, where L_s is stride length) that differed by as much as 67 %, resulting in the rejection of our hypothesis. To understand the separate effects of speed and gravity further, we compared the mechanics of walking at the same absolute speed at different levels of gravity ($0.25g$–$1.0g$). In lower gravity, subjects walked with lower duty factors (10 %) and shorter relative stride lengths (16 %). These modest changes in response to the fourfold change in gravity indicate that factors other than gravitational forces are the primary determinants of walking biomechanics.

Key words: biomechanics, walking, locomotion, gravity, bipeds, humans, Froude number.

Introduction

Speed, size and gravity all affect the way animals walk and run. Quadrupeds walk at slow speeds, trot at moderate speeds and gallop at fast speeds. Similarly, bipeds change from a walk to a run to increase speed. The mechanics of locomotion also depends on the size of the animal. For example, at $1\,\mathrm{m\,s^{-1}}$, a horse prefers to walk, a small dog would choose to trot and a mouse would gallop (Heglund and Taylor, 1988). Likewise, a small child must run to keep up with an adult who is walking at a comfortable pace. Animals also adjust the way they move under different levels of gravity. In reduced gravity, humans switch from a walk to a run at slower speeds (Kram *et al.* 1997), and at faster speeds humans prefer to ‘lope’, a run with an extended aerial phase (He *et al.* 1991; Newman *et al.* 1994). Similarly, the kinematics of intertidal crab locomotion in the reduced-gravity underwater environment is different from their kinematics on dry land (Martinez *et al.* 1995).

Alexander and Jayes (1983) dynamic similarity hypothesis provides a potentially unifying theory for the combined effects of speed, size and gravity on locomotion biomechanics. Dynamic similarity is an extension of the simple and familiar concept of geometric similarity. Objects are geometrically similar if their corresponding linear dimensions can be made equal by multiplying them by the same constant. This concept is easily envisioned using an example of two boxes. If one is twice as wide as the other, it must also be twice as long and twice as high for the boxes to be geometrically similar.

Movements, just like shapes, may be similar. Two moving bodies are dynamically similar if the motion of one can be made identical to that of the other by multiplying all linear dimensions by one constant, time intervals by another constant and forces by a third constant (Duncan, 1953). For example, two simple pendulums of different lengths move in a dynamically similar manner when they swing through equal angles in the same gravitational field.

The motion of a body is governed by the forces acting upon it. The ratio of the forces acting on two bodies must be equal for the objects to be dynamically similar. Movements that are governed by gravitational forces, including swinging

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pendulums, cannot be dynamically similar unless the ratio of their inertial force to their gravitational force is equal (Duncan, 1953). In the case of the pendulum, the inertial force is the centripetal force. The dimensionless ratio of centripetal force to gravitational force is termed the Froude number, *Fr*:

$$Fr = (mv^2/r)/(m\boldsymbol{g}), \qquad (1)$$

where m is mass, v is velocity, r is radius and $\boldsymbol{g}$ is gravity. This equation reduces to:

$$Fr = v^2/\boldsymbol{g}r. \qquad (2)$$

Dynamic similarity may also apply to more complicated movements such as legged locomotion. For example, consider the locomotion of a mouse and horse. While they move very differently at the same absolute speed, the locomotor movements of a mouse and a horse may be similar at the same relative speed (e.g. a comfortable walking speed). To explore the incidence of dynamic similarity in animal locomotion, it is important to define explicitly what constitutes dynamically similar locomotion.

Alexander and Jayes (1983) interpret the dynamic similarity criteria of equal lengths, time intervals and forces as forming five requirements.

(1) Dynamically similar animals must move their legs with the same phase relationships. This refers to the relative timing of limb movements and often defines a gait. If a quadruped's two front feet contact the ground at the same time, the front limb cycles are in phase. If one front foot hits the ground one-quarter of the stride period after the other front foot, the front limb phase relationship is 0.25. In quadrupeds, a gallop has a different phase relationship from a trot, which has a different phase relationship from a walk. In normal bipedal locomotion, the left leg cycle is 180 ° out of phase with the right leg cycle. As a result, the phase relationship is the same (0.5) for both walking and running during a symmetrical bipedal gait.

(2) The corresponding feet of dynamically similar animals must have equal duty factors. The duty factor is the fraction of the stride time that a foot is in contact with the ground. In bipedal walking, the duty factor is always greater than 0.5 because at least one foot is always in contact with the ground.

(3) Dynamically similar animals must have equal relative stride lengths. Stride length (L_s) is the distance between two consecutive ground contacts of the same foot. Relative stride length is this distance divided by the leg length of the animal. Leg length is usually defined as the standing hip height.

(4) The corresponding feet of dynamically similar animals must exert forces that are equal multiples of body weight at corresponding points in the stride (e.g. mid-stance).

(5) Dynamically similar animals must have mechanical power outputs proportional to the product of body weight and forward speed. This is also interpreted as requiring dynamically similar animals to have equal metabolic costs of transport. The metabolic cost of transport is the amount of energy required to move a unit of body weight a unit distance.

Alexander and Jayes (1983) hypothesized that animals meet these five criteria for dynamic similarity of locomotion when they travel at speeds that translate to equal values of a horizontal Froude number:

$$Fr = v^2/\boldsymbol{g}L_{\text{leg}}, \qquad (3)$$

where L_{leg} is the leg length. To test their hypothesis, they gathered empirical data for small and large animal species over a wide speed range, and these data suggested that their hypothesis is generally true. Their relationship has been used to analyze locomotion mechanics in a wide variety of fields including anthropology, human locomotion biomechanics, paleontology, pediatrics, robotics and zoology (Alexander, 1976, 1984, 1989, 1991; Alexander and Jayes, 1980; Alexander and Maloiy, 1984; Bennett, 1987; Cavagna *et al.* 1983; Cavanagh and Kram, 1989; Gatesy and Biewener, 1991; Kram *et al.* 1997; McGeer, 1990, 1992; Moretto *et al.* 1996; Muir *et al.* 1996; Wagenaar and Beek, 1992; Zani and Claussen, 1994; Zijlstra *et al.* 1996).

The Froude number describes the motion of pendulums, and the simplest mechanical model for a walking biped is an inverted pendulum (Cavagna *et al.* 1977). This model idealizes the mass of the body as a point mass on a rigid massless leg and considers a walk as a series of vaults over these strut-like legs. This mechanism conserves mechanical energy by exchanging kinetic and potential energy within each stride. The effective conservation of mechanical energy also appears to minimize the metabolic energy required for walking (Cavagna *et al.* 1977). Pendulum mechanics are governed by gravity and, as a result, dynamic similarity requires equal Froude numbers.

To gain insight into the basic principles that govern the biomechanics of locomotion, we investigated the effect of reduced gravity on walking kinematics. We tested the hypothesis that humans walk in a dynamically similar fashion when walking at speeds and simulated gravities that provide equal values of the horizontal Froude number. The occurrence of dynamic similarity at equal Froude numbers is attributed to the importance of gravitational force in determining the kinematics and kinetics of animal movements (Alexander and Jayes, 1983). An additional goal of the present study was to determine the separate effects of speed and gravity on walking kinematics.

Materials and methods

Subjects

Ten human subjects volunteered to participate in this experiment (five male, five female; mean leg length 0.88±0.05 m; mean mass 60.6±9.2 kg; mean ± S.D.). We measured leg length as the height to the greater trochanter of the femur while the subjects stood. Before the experiments, the subjects gave their informed consent after reading a description of the purpose, basic procedures and risks of the experiment.

This protocol was approved by the university committee for the protection of human subjects.

Kinematic analysis

The subjects walked on a Quinton 18-60 motorized treadmill. We used a J. C. Labs, Inc. (Mountain View, CA, USA) HSC 250 video camera to record the trials from a sagittal view at 200 fields s^{-1}. The time was displayed on each video field. From the video tapes, we obtained the mean stride time and duty factor for 10 strides in each trial and, knowing the treadmill speed, converted stride time into stride length.

Statistical analysis

In all instances, we used repeated-measures analysis of variance (ANOVA) to determine statistical significance. Our criteria for significance was $P<0.05$.

Reduced gravity simulator

We simulated the effect of reduced gravity on the center of mass using a device that applies a nearly constant upward force to the torso (Fig. 1). The subjects straddled a well-cushioned bicycle saddle attached to a lightweight section of polyvinyl chloride pipe. To create the upward force, we stretched spring elements (made of rubber tubing) to over three times their original length of 2 m. We simulated different levels of gravity by changing the length of the spring elements using a hand winch. To maximize spring stretch, additional parallel springs were only added when the force of the original springs became inadequate. The force in a Hookean spring is equal to the product of the spring constant (k), and the change in length (Δx). As a result of the spring's low stiffness and large stretch, the tension fluctuations caused by the vertical oscillations of the subject's center of mass during walking were small. A Kistler model 9212 force transducer in series with the springs indicated that such fluctuations were less than $0.03\boldsymbol{g}$ for all levels of simulated gravity. We positioned the reduced gravity simulator over the treadmill. This type of simulator has been used in previous studies (Farley and McMahon, 1992; He *et al.* 1991; Kram *et al.* 1997).

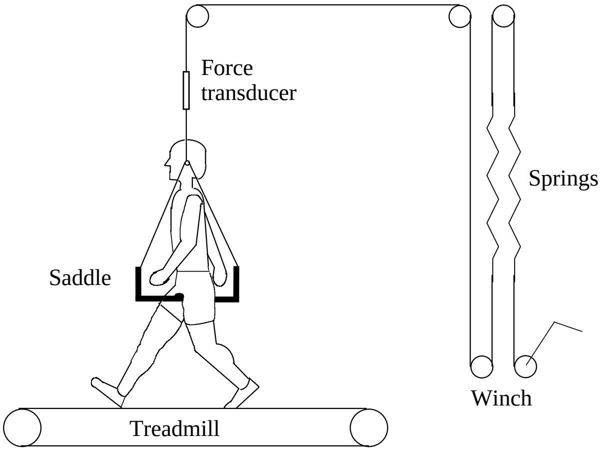

Fig. 1. Reduced gravity simulator. This device applies a nearly constant upward force to the subject's torso. The force is applied to the subject through a saddle constructed from a bicycle seat attached to a U-shaped plastic pipe support. Two spring elements are arranged in series, connected by cables and separated by pulleys. One end of the spring element system is attached by cable to the force transducer and saddle. The other is attached by cable to a hand winch. The length of the spring elements can be changed using the hand winch. Changing the length of the rubber spring elements varies the level of simulated gravity. Additional parallel springs are only added when the force of the original springs becomes inadequate, thus maximizing spring stretch and minimizing the force fluctuation of the springs.

All techniques for simulating reduced gravity involve compromises (Davis and Cavanagh, 1993). Our method of reduced gravity simulation applies vertical force only to the torso and, as a result, the limbs still experience Earth gravity. One might imagine that this would not accurately simulate limb swing in reduced gravity. However, the combined results of Roberts (1963) and Boda *et al.* (1996) indicate that leg swing is not determined solely by passive pendulum mechanics (see Discussion for further explanation). A forward-leaning posture has been noted in previous descriptions of gait in reduced gravity (Davis and Cavanagh, 1993). We did not measure forward lean, but our simulation technique does not restrict the subjects' ability to lean forward.

Unlike other systems, our reduced gravity simulator is very practical as it is both comfortable and can be rapidly adjusted to different levels of gravity. In addition, energetic and biomechanical results from our simulation technique are similar to those of other simulation methods including water immersion, supine lower body negative pressure, supine cable suspension and parabolic flight (Boda *et al.* 1996; Davis and Cavanagh, 1993). Since our experiments were designed to elucidate the general physical principles that govern legged locomotion and because we have examined large changes in the apparent gravity, inaccuracies due to our simulation would not change our general conclusions.

Preliminary procedures

We first habituated the subjects to treadmill walking. The habituation period was designed to exceed the minimum time necessary for habituation to treadmill walking as described by Wall and Charteris (1981). In normal gravity, all subjects walked for 5 min at five speeds (0.75, 1.0, 1.25, 1.5 and 1.75 $\mathrm{m\,s}^{-1}$).

The subjects demonstrated almost immediate habituation to treadmill walking. The changes in duty factor and relative stride length from the first 10 strides to the first 10 strides of the sixth minute were less than 1 % (differences were not significant, $P=0.65$, $P=0.36$, respectively). Stride-to-stride variation decreased with habituation time. The coefficient of variation for duty factor was 2.1 % for the first 10 strides and 1.6 % for the first 10 strides of the sixth minute. Similarly, the coefficient of variation decreased from 3.6 % to 2.1 % for relative stride length.

Next, we familiarized the subjects to walking in the reduced gravity simulator. The subjects walked for 5 min in normal gravity ($1.0\boldsymbol{g}$) and in conditions simulating 0.75, 0.50 and $0.25\boldsymbol{g}$. At each level of simulated gravity, the subjects walked at speeds that equated to a Froude number of 0.25. The subjects demonstrated a brief period of accommodation to walking in simulated reduced gravity. At the lowest level of gravity, the changes in duty factor and relative stride length from the first 10 strides to the first 10 strides of the sixth minute were +2.8 % (not significant, P=0.12) and –8.0 % (P=0.001) respectively. However, after 1 min of walking at $0.25\boldsymbol{g}$, the average duty factor was within 1 % of its final value (not significant, P=0.28) and the relative stride length was only 3 % longer than its final length (P=0.007). As with treadmill habituation, stride-to-stride variation decreased with habituation time. The coefficient of variation decreased from 6.6 % to 3.1 % for duty factor and from 3.8 % to 3.0 % for relative stride length. We concluded that 1 min was sufficient to familiarize subjects to treadmill walking in each level of simulated reduced gravity. During the experimental trials, we analyzed the kinematics only after subjects had walked for 1 min at each speed and level of simulated gravity.

Experimental protocol

To test our hypothesis, subjects walked in normal gravity and in conditions simulating 0.75, 0.50 and $0.25\boldsymbol{g}$. At each level of simulated gravity, the subjects walked at speeds corresponding to four Froude numbers (0.1, 0.2, 0.3 and 0.4) (see Table 1). To understand the separate effects of speed and gravity, we examined the kinematics of walking at matched speeds. At each level of gravity, subjects walked at four matched speeds (0.25, 0.50, 0.75 and 1.0 m s^{-1}) (see Table 2). It was not possible to have matched walking speeds greater than 1.0 m s^{-1} because at low gravities, the walk–run transition speed approaches 1.0 m s^{-1} (Kram *et al.* 1997). In total, each subject walked at 32 different combinations of speed and gravity.

Results

As the dynamic similarity hypothesis predicts, at equal Froude numbers, but different levels of gravity, the subjects walked with nearly the same duty factors (Fig. 2A). While the differences in duty factor at different levels of gravity were statistically significant (P=0.006), the difference in duty factor between $0.25\boldsymbol{g}$ and $1.0\boldsymbol{g}$ was only 2 %.

In contradiction to the dynamic similarity hypothesis, at equal values of the Froude number, but different levels of gravity, the subjects walked with very different relative stride lengths (Fig. 2B) (P<0.0001). The increase in relative stride length between $0.25\boldsymbol{g}$ and $1.0\boldsymbol{g}$ ranged from 55 to 67 %. The mean duty factors and relative stride lengths at equal Froude numbers are presented in Table 1.

At matched absolute speeds, subjects walked with a lower duty factor at lower gravities (P<0.0001) (Fig. 3A). The decrease in duty factor between $1.0\boldsymbol{g}$ and $0.25\boldsymbol{g}$ ranged from 8 to 14 %.

At lower levels of simulated gravity, the subjects significantly decreased their relative stride length (P<0.0001) (Fig. 3B). The decrease in relative stride length between $1.0\boldsymbol{g}$ and $0.25\boldsymbol{g}$ ranged from 9 to 37 %. The mean duty factors and relative stride lengths at matched absolute speeds are presented in Table 2.

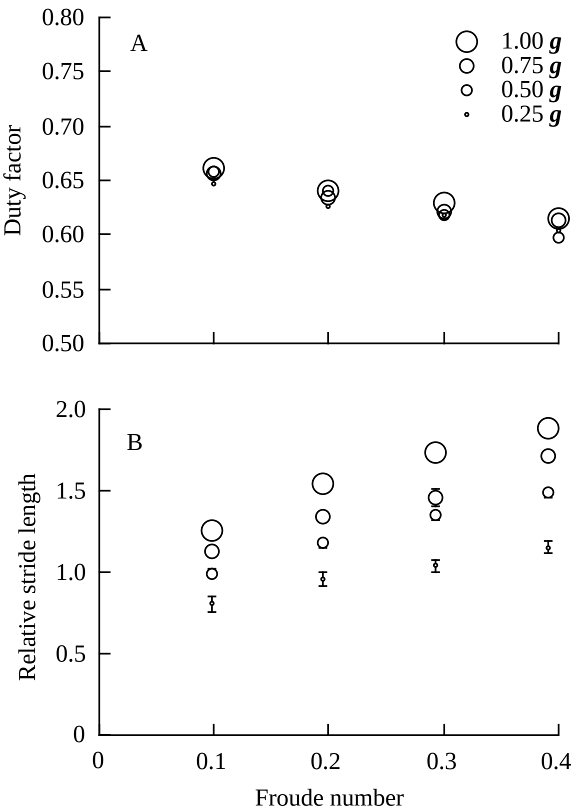

Fig. 2. (A) At different combinations of speed and gravity, but equal Froude numbers, subjects walked with nearly the same duty factor. For clarity, error bars are not shown (see Table 1). (B) Subjects walked with very different relative stride lengths at equal Froude numbers. The size of a symbol indicates the magnitude of simulated gravity as in A. Error bars indicate ±1 S.E.M., N=10. Some error bars are smaller than the symbols.

Discussion

Alexander and Jayes (1983) defined five requirements for dynamically similar locomotion. Their hypothesis predicts that these requirements will be met when animals walk with equal values of the Froude number. Our experiments provide a kinematic test of the dynamic similarity hypothesis by investigating the first three requirements. We assess the fifth requirement below by re-analyzing data available in the literature.

The first prediction of the dynamic similarity hypothesis is that humans walk with the same phase relationships at equal Froude numbers. In quadrupeds, the phase relationship differs between gaits (e.g. trot and gallop). However, during normal bipedal walking, the left leg cycle is always 180 ° out of phase with the right leg cycle. As a result, the phase relationship of

Table 1. *Duty factor, relative stride length and average speed at equal Froude numbers*

		Froude number			
Gravity		0.1	0.2	0.3	0.4
1.00***g***	*Df*	0.66±0.01	0.64±0.01	0.63±0.01	0.62±0.01
	L_s/L_{leg}	1.26±0.01	1.54±0.03	1.74±0.02	1.89±0.03
	v (m s^{-1})	0.93	1.31	1.61	1.86
0.75***g***	*Df*	0.66±0.01	0.63±0.01	0.62±0.01	0.61±0.01
	L_s/L_{leg}	1.12±0.02	1.34±0.03	1.46±0.06	1.71±0.03
	v (m s^{-1})	0.80	1.14	1.39	1.61
0.50***g***	*Df*	0.66±0.01	0.64±0.01	0.62±0.01	0.60±0.01
	L_s/L_{leg}	0.99±0.03	1.18±0.02	1.35±0.03	1.48±0.03
	v (m s^{-1})	0.66	0.93	1.14	1.31
0.25***g***	*Df*	0.65±0.01	0.63±0.01	0.62±0.01	0.60±0.01
	L_s/L_{leg}	0.81±0.05	0.96±0.04	1.04±0.04	1.15±0.03
	v (m s^{-1})	0.46	0.66	0.80	0.93

The duty factors (*Df*), relative stride lengths (L_s/L_{leg}) at different levels of gravity and Froude numbers are shown.
Values are means ± S.E.M., *N*=10.
Each subject walked at a different absolute speed for each trial. The mean speeds (v) for the 10 subjects are shown for reference.

symmetrical human locomotion is 0.5 at all speeds. The subjects fulfilled the first requirement of the dynamic similarity hypothesis by walking symmetrically at all combinations of speed and gravity. Kram *et al.* (1997) provided further support for this prediction by demonstrating that, in simulated reduced gravity, humans change gait, from a walk to a run, at similar Froude numbers.

The second prediction of the dynamic similarity hypothesis is that humans will walk with equal duty factors at equal Froude numbers. We found that at different combinations of speed and gravity, but equal Froude numbers, humans walk with only slightly different (2 %) duty factors, thus lending support to the dynamic similarity hypothesis (Fig. 2A).

The third prediction is that relative stride lengths are the same at equal Froude numbers. However, humans walk with very different relative stride lengths at equal Froude numbers (Figs 2B, 3B). The dynamic similarity hypothesis would predict an increase in relative stride length to almost 2 leg lengths for walking at 1.0 m s^{-1} in 0.25***g*** (Fig. 3B). In fact, subjects decreased their relative stride length to just over 1 leg length. Thus, our data differ from that predicted by the dynamic similarity hypothesis in both magnitude and direction.

In addition to the kinematic predictions, Alexander and Jayes (1983) make kinetic predictions for dynamic similarity locomotion. The dynamic similarity hypothesis predicts that, at equal Froude numbers, humans will exert equal forces at corresponding points in a stride. We did not measure ground reaction forces, and there are only limited force data for walking in simulated reduced gravity available in the literature (Newman *et al.* 1994; Letko, 1973). More such data are necessary to evaluate this prediction sufficiently.

Table 2. *Duty factor and relative stride lengths at matched walking speeds*

		Velocity (m s^{-1})			
Gravity		0.25	0.50	0.75	1.00
1.00***g***	*Df*	0.77±0.01	0.71±0.01	0.68±0.01	0.66±0.01
	L_s/L_{leg}	0.79±0.03	0.98±0.02	1.15±0.02	1.31±0.02
0.75***g***	*Df*	0.75±0.01	0.69±0.01	0.67±0.01	0.65±0.01
	L_s/L_{leg}	0.64±0.02	0.92±0.03	1.10±0.02	1.27±0.02
0.50***g***	*Df*	0.71±0.01	0.67±0.01	0.65±0.01	0.64±0.01
	L_s/L_{leg}	0.61±0.03	0.88±0.03	1.06±0.03	1.23±0.03
0.25***g***	*Df*	0.66±0.01	0.64±0.01	0.62±0.01	0.59±0.01
	L_s/L_{leg}	0.57±0.06	0.82±0.05	1.01±0.04	1.20±0.03

The duty factors (*Df*) and relative stride lengths (L_s/L_{leg}) at different levels of gravity and matched speeds are shown.
Values are means ± S.E.M. for 10 subjects.

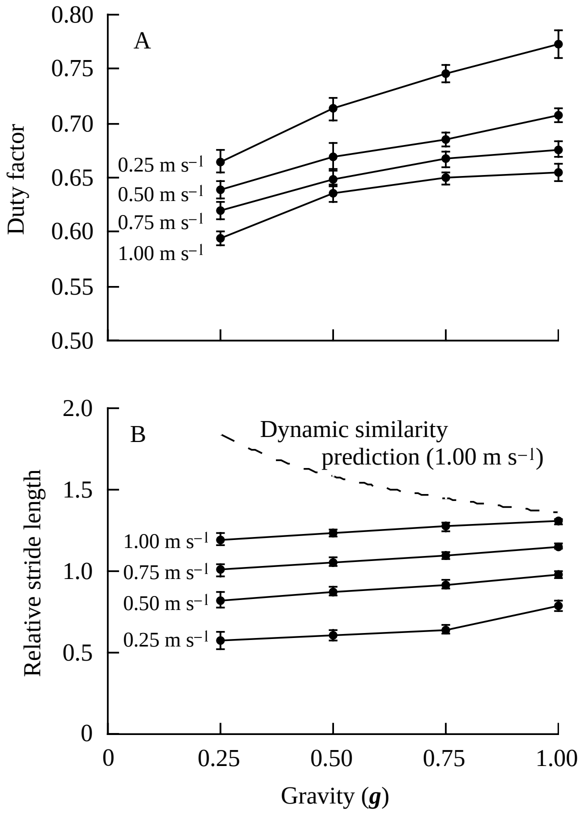

Fig. 3. (A) At all speeds, duty factors were significantly smaller at lower levels of gravity. (B) Relative stride lengths were slightly shorter at lower levels of gravity. The broken line represents the predicted relative stride length based on the dynamic similarity hypothesis of Alexander and Jayes (1983) for walking at 1 m s^{-1}. Values are means ±1 S.E.M., N=10.

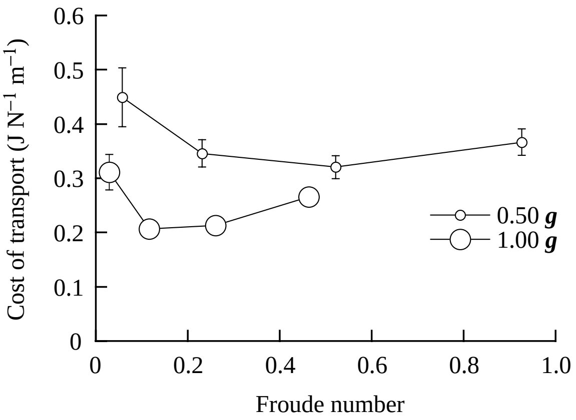

Fig. 4. Cost of transport as a function of Froude number. Data are from Farley and McMahon (1992). Subjects did not walk with equal costs of transport at equal Froude numbers, nor was the cost of transport minimized at the same Froude number. Because gravity was varied, we calculated the cost of transport per unit body weight rather than using the more conventional unit of body mass. The size of the symbols indicates the level of simulated gravity. Values are means ± S.E.M., N=4. Some error bars are smaller than the symbols.

Finally, the dynamic similarity hypothesis predicts that humans walk with equal metabolic costs of transport at equal Froude numbers and that the cost of transport will be minimized at the same Froude number. Farley and McMahon (1992) investigated the energetics of walking in reduced gravity using a simulator similar to that used in the present study. Analysis of their data (Fig. 4) demonstrates that, at similar Froude numbers, the cost of transport at 0.5***g*** is as much as 62 % greater than at 1.0***g***. Fig. 4 also demonstrates that the metabolic cost of transport is minimized at very different values of the Froude number for the two levels of simulated gravity used. Note that we have calculated the cost of transport per unit body weight, where body weight is the product of mass and the simulated level of gravity. Although not used here, mechanical power estimates using a force platform as an ergometer (Cavagna, 1975) might provide additional insight into pendulum mechanics and mechanical energy recovery during walking in reduced gravity.

We conclude that in simulated reduced gravity humans do not walk in a dynamically similar fashion at equal Froude numbers. We reject this hypothesis primarily on the basis of the departure of the relative stride length data from the predictions of dynamic similarity. Data from the literature on metabolic power output during walking in simulated reduced gravity also cast doubt on the validity of the dynamic similarity hypothesis.

While the Froude number broadly predicts the kinematics and kinetics of animal locomotion over a wide range of body sizes and speeds at Earth gravity (Alexander and Jayes, 1983), it does not describe the effect of gravity on walking mechanics. The Froude number can still be used to predict how walking mechanics change with size at Earth gravity, but we believe that a new theoretical construct is needed to interpret the underlying mechanisms.

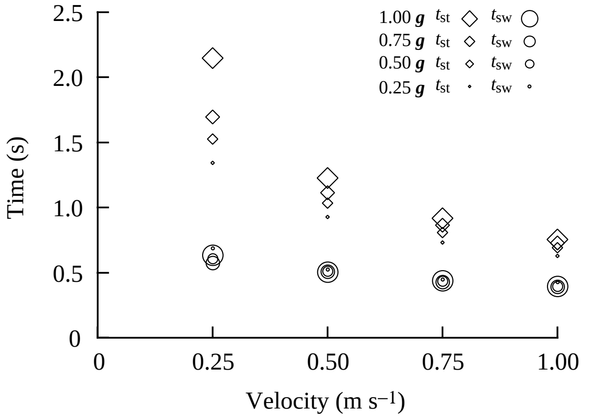

Fig. 5. Stance time (t_{st}) and swing time (t_{sw}) as a function of gravity and velocity. Stance time decreased significantly at lower levels of gravity and faster speeds (P<0.001). Swing time also decreased slightly as speed was increased (P<0.001). However, swing time was unaffected by a fourfold decrease in simulated gravity (P=0.136). Values are means for N=10. The size of symbol indicates the level of simulated gravity.

To investigate the separate effects of speed and gravity, we examined the mechanics of walking at matched speeds over a range of gravities. The effect of decreasing gravity on duty factor was very similar to the effect of increasing speed (Fig. 3A). At the four speeds tested, duty factor decreased by an average of 10 % between 1.0$\boldsymbol{g}$ and 0.25$\boldsymbol{g}$. As speed was increased from 0.25 m s^{-1} to 1.0 m s^{-1}, the mean decrease in duty factor was 12 % at the four levels of gravity tested. Subjects walked with duty factors approaching 0.5 (i.e. near running) with an increase in speed or a decrease in gravity. This corresponds with the findings of Kram *et al.* (1997), who found that the walk–run transition occurs at slower speeds in lower gravity.

Surprisingly, a fourfold reduction in gravity at a given walking speed caused only a small reduction in stride length. At the four speeds tested, the mean decrease in relative stride length between 1.0$\boldsymbol{g}$ and 0.25$\boldsymbol{g}$ was 16 %. To put that change in context, at normal gravity, when speed was decreased from 1.0 m s^{-1} to 0.25 m s^{-1} the relative stride length decreased by 40 %. In short, stride length in walking is influenced much more strongly by speed than by gravity.

Further insight into the interactions among size, speed and gravity is gained by considering stride time. Stride time and stride length determine locomotion speed:

$$v = L_s/t_s\,, \tag{4}$$

where t_s is stride time. As gravity was decreased from 1.0$\boldsymbol{g}$ to 0.25$\boldsymbol{g}$, stride time decreased by an average of only 16 % over the four speeds tested.

We found these small changes in stride time over a fourfold change in gravity intriguing. To explore further, we divided stride time into its components, swing time and stance time. The decreases in stride time, due either to a reduction in gravity or to an increase in speed, occurred almost exclusively because of decreases in stance time (Fig. 5). That is, the swing time was nearly constant. Similar reductions in stance time with increased speed have been reported for quadrupedal walking (Arshavsky *et al.* 1965; Goslow *et al.* 1973). These investigators noted that the increase in speed and the decrease in stance time were similar in magnitude such that the forward distance moved during the stance phase (step length) remained nearly constant. It has been suggested that this indicates that the transition from swing to stance is triggered by a certain hip angle (Grillner and Rossignol, 1978). Our results show that, at a given speed, decreased gravity results in decreased stance time, shorter step length and, therefore, different hip joint angles at the stance–swing transition. A close inspection of the data of Letko *et al.* (1966) also reveals that the stance–swing transition occurs at different hip angles in normal and simulated reduced gravity. It appears that the initiation of the swing phase is not dependent upon hip angle alone.

Despite a fourfold change in both speed and gravity, our subjects chose to walk with a near-constant leg swing time (Fig. 5). While this phenomenon is typical of walking at different speeds (Nilsson *et al.* 1985), it is important to note that it is possible to alter leg swing time voluntarily during walking (Cavagna and Franzetti, 1986; Minetti *et al.* 1995). This suggests that swing time may be determined mechanically.

To understand how swing time may be determined mechanically, consider the simple model of walking proposed by Mochon and McMahon (1980). They demonstrated that bipedal walking is possible with legs that swing only as a result of their own inertia. In their 'ballistic walking' model, the swing leg acts as a compound pendulum and swings with its natural period. The natural period of a compound pendulum is proportional to its radius of gyration and inversely proportional to gravity:

$$T \approx (r/\boldsymbol{g})^{0.5}\,, \tag{5}$$

where T is the period (in s) and r is the radius of gyration (in m). The natural period, and thus the swing time, of a passively swinging leg is increased if gravity is decreased. If walking kinematics were determined by the preservation of a passive leg swing, reduced gravity would increase stride time and stride length.

Our method of simulating reduced gravity does not alter the passive leg swing properties as true reduced gravity would. However, there are data from altered gravity experiments that indicate that leg swing in reduced gravity is not passive. For example, parabolic flight has been used to investigate the effect of gravity on walking mechanics (Roberts, 1963). In this simulation technique, experiments are conducted in an aircraft flying along elongated parabolic arcs (Davis and Cavanagh, 1993). At the top of the arc, for a short period, true reduced gravity is achieved. Different levels of gravity are attained by varying the trajectory of the flight. At flight trajectories simulating 0.25$\boldsymbol{g}$, the subjects in Roberts' (1963) experiments increased their swing time by 29 % compared with the 1.0$\boldsymbol{g}$ swing times. The same reduction of gravity on a compound pendulum would double its swing time, indicating that the subjects of Roberts (1963) were no longer swinging their legs passively.

A more recent study (Boda *et al.* 1996) provides another unique test of the passive leg swing assumption of the ballistic walking model. They used an apparatus that simulated normal gravity on the center of mass but eliminated gravitational forces on the legs. Recall that the apparatus in the present study reduced gravity on the center of mass but left the legs in normal Earth gravity. In Boda *et al.* (1996), the subjects walked in a supine position on a vertically mounted treadmill while the upper body was supported by a hammock. The subject's legs are counterbalanced by each other in the vertical direction. A lower body negative pressure (LBNP) chamber pulled the subject towards the treadmill with a force equal to normal Earth gravity. Boda *et al.* (1996) compared the kinematics of walking in this device and of upright walking at Earth gravity. The swing time in normal walking was only 8 % shorter than that for supine LBNP walking, which involves no passive gravitational contribution to leg swing. The results of Roberts (1963) and Boda *et al.* (1996) indicate that swing time is not determined solely by passive pendulum mechanics. Experiments on intact and spinalized quadrupeds also demonstrate near-constant swing times, suggesting that swing time is determined in part by reflexes or spinal networks (Arshavsky *et al.* 1965; Goslow *et al.* 1973; Lovely *et al.* 1990).

Preservation of leg swing time is not merely an isolated phenomenon. It places strong constraints on the overall mechanics of walking. In their mechanical analysis of walking, Mochon and McMahon (1980) noted that neither a compound pendulum model alone nor an inverted pendulum model alone can describe the dynamics of walking adequately. They conclude that the most simple and accurate model of walking is an inverted pendulum representing the stance leg and a compound pendulum representing the swing leg. These pendulums are coupled, in that the mechanics of each affects the other. Modeling walking as the coupling of an inverted pendulum and a time-constrained compound pendulum over a range of sizes, speeds and levels of gravity deserves further investigation.

Our rejection of the dynamic similarity hypothesis does not exclude the possibility that locomotor movements can be dynamically similar at combinations of size, speed and gravity other than the Froude number. It is intriguing that at normal gravity Alexander and Jayes (1983) hypothesis encompasses all gaits because, from a mechanical viewpoint, walking and running are so fundamentally different. Walking is a series of vaults over relatively stiff legs, while running is a bouncing movement in which the legs act like compliant springs (Cavagna *et al.* 1977). We suspect that a single dynamic similarity approach will not describe the interaction of size, speed and gravity adequately for both walking and running.

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