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The effects of gravity on human walking: a new test of the dynamic similarity hypothesis using a predictive model

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SUMMARY

The dynamic similarity hypothesis (DSH) suggests that differences in animal locomotor biomechanics are due mostly to differences in size. According to the DSH, when the ratios of inertial to gravitational forces are equal between two animals that differ in size [e.g. at equal Froude numbers, where Froude = velocity^2/(gravity $\times$ hip height)], their movements can be made similar by multiplying all time durations by one constant, all forces by a second constant and all linear distances by a third constant. The DSH has been generally supported by numerous comparative studies showing that as inertial forces differ (i.e. differences in the centripetal force acting on the animal due to variation in hip heights), animals walk with dynamic similarity. However, humans walking in simulated reduced gravity do not walk with dynamically similar kinematics. The simulated gravity experiments did not completely account for the effects of gravity on all body segments, and the importance of gravity in the DSH requires further examination. This study uses a kinematic model to predict the effects of gravity on human locomotion, taking into account both the effects of gravitational forces on the upper body and on the limbs. Results show that dynamic similarity is maintained in altered gravitational environments. Thus, the DSH does account for differences in the inertial forces governing locomotion (e.g. differences in hip height) as well as differences in the gravitational forces governing locomotion.

Key words: stride length, Froude number, force-driven harmonic oscillator, inertial properties.

INTRODUCTION

The dynamic similarity hypothesis (DSH) (Alexander, 1976; Alexander and Jayes, 1983) is one of the most general and useful principles in animal locomotion, allowing researchers to compare movement patterns in taxa that differ greatly in size. The DSH is the dynamic analog of geometric similarity and suggests that the biomechanics of geometrically similar animals can be made identical by multiplying all time durations by one constant, all forces by a second constant and all linear distances by a third constant. Support for the DSH in empirical comparisons of gait indicates that locomotor differences are largely explained by differences in size (Alexander and Jayes, 1983). Thus, the DSH allows researchers to explore underlying rules that govern animal locomotion (e.g. Alexander and Jayes, 1983) and also provides a basis for understanding the evolutionary importance of deviations from dynamic similarity (e.g. Raichlen, 2006).

Alexander noted that dynamic similarity is only possible, and therefore only testable, when two animals have equal ratios of the inertial and gravitational forces governing locomotion (Alexander, 1976; see also Alexander and Jayes, 1983). For terrestrial locomotion, the inertial force is generally assumed to be the centripetal force that acts on an animal as it vaults over its stance leg, which acts as an inverted pendulum (see Donelan and Kram, 1997). Therefore, the ratios of inertial to gravitational forces in two animals are equal when they walk at the same Froude number [velocity^2/(gravity $\times$ hip height)]. Although many researchers rely on the DSH in studies of comparative biomechanics, recent work has questioned its validity (see Donelan and Kram, 1997; Donelan and Kram, 2000). The purpose of the present study is to test the DSH using a predictive kinematic model to assess its utility in understanding human locomotion.

Most tests of dynamic similarity examine the impacts of changes in inertial forces on dynamic similarity (e.g. through differences in limb length in comparative studies) (see Alexander and Jayes, 1983; Alexander and Maloiy, 1984; Gatesy and Biewener, 1991; Bullimore and Burn, 2006). The DSH has been broadly supported by studies showing that animals that differ in size generally use equal relative stride lengths (stride length divided by hip height) when walking at the same Froude numbers and they transition from a walk to a run at equal Froude numbers (Alexander and Jayes, 1983). Donelan and Kram, noting the importance of gravity in the DSH, suggested that dynamic similarity should account for locomotor differences not only due to size but also due to changes in gravitational environments (Donelan and Kram, 1997). Thus, as gravitational forces change, individuals walking at the same Froude numbers should continue using equal relative stride lengths and should transition from a walk to a run at the same Froude numbers.

In an innovative test of the effects of gravity on the DSH in humans, Donelan and Kram used a treadmill that alters the effects of gravity on locomotion by introducing an adjustable upward force on the body through a harness system attached to the torso (Donelan and Kram, 1997; Donelan and Kram 2000; see also Kram et al., 1997). Results from these earlier studies showed that humans deviated from dynamic similarity as gravity was reduced. As gravity decreased, humans walked with relatively shorter strides (Donelan and Kram, 1997), and the walk–run transition occured at higher Froude numbers in very low gravitational fields (Kram et al., 1997). Thus, the DSH may not be a governing principle of animal locomotion and should be used with caution (Donelan and Kram, 2000).

Gravity and swing phase

One critique of these studies, fully acknowledged by the authors, is that their novel experimental design did not alter the gravitational environment for the limbs during swing phase (Donelan and Kram, 1997; Donelan and Kram, 2000). Gravity should have an important effect on swing phase, and possibly on overall stride kinematics, because limbs act somewhat like suspended pendula (see Hildebrand, 1985). Therefore, the duration of swing phase is related to limb mass distribution and gravity, and the natural period of the limb (T) is:

$$T = 2\pi\sqrt{\frac{d}{\boldsymbol{g}}} \quad (1)$$

where $\boldsymbol{g}$ is gravitational acceleration (9.81 m s^{-2} on earth) and d is the length of the limb pendulum (m):

$$d = \frac{I}{mL} \ . \quad (2)$$

In Eqn 2, I is the limb's mass moment of inertia about the hip joint (kg m^{-2}), m is the limb's mass (kg) and L is the distance of the limb's center of mass from the hip joint (m). If all else is equal, a relatively long swing period (due to either a relatively large d or to reduced $\boldsymbol{g}$) will lead to a relatively long stride period (the sum of swing and stance durations) and a relatively low stride frequency (the reciprocal of stride duration). Since velocity (**v**) is equal to the product of stride length and stride frequency, low stride frequencies lead to long strides at a given speed.

Both comparative and experimental studies support these connections between pendular limb swing and stride lengths and stride frequencies (Inman et al., 1981; Martin, 1985; Holt et al., 1990; Skinner and Barrack, 1990; Steudel, 1990; Mattes et al., 2000; Raichlen, 2004; Raichlen, 2005; Raichlen, 2006). For example, when weights were affixed to the ankles of dogs and humans, leading to a large d and, therefore, a longer natural swing period, stride lengths increased and stride frequencies decreased (Inman et al., 1981; Martin, 1985; Holt et al., 1990; Skinner and Barrack, 1990; Steudel, 1990; Mattes et al., 2000). Comparative studies of natural variation in limb mass distribution also support the links between limb swing and overall stride kinematics (Preuschoft and Gunther, 1994; Raichlen, 2004; Raichlen, 2005; Raichlen, 2006). Animals with large values of d due to heavy muscles in the hands and feet (such as primates with grasping extremities) use relatively longer strides and lower stride frequencies than animals with more proximally concentrated limb mass (Raichlen, 2004; Raichlen, 2005; Raichlen, 2006).

It is important to note that gravity can still play a role in determining limb swing even if the limbs do not swing as completely passive pendula. Holt and colleagues introduced a model that predicts kinematics at preferred walking speeds by assuming that the limb acts like a force-driven harmonic oscillator (FDHO) during swing phase, accounting for not only gravitational forces but also for some muscle action during swing (Holt et al., 1990). This model considers the limb to be a mostly passive pendulum but does include a constant to account for the damping effects of muscles and tendons and provides a driving force. The FDHO successfully predicts stride frequencies and stride lengths at preferred walking speeds under a variety of conditions including forwards and backwards walking (Holt et al., 1990; Schot and Decker, 1998) and walking with ankle weights (Holt et al., 1990). Thus, experimental studies, comparative biomechanics and biomechanical models support the hypothesis that the limbs swing as suspended pendula assisted by some degree of muscular action and under the influence of gravity.

The present study examines the effects of gravity on dynamic similarity using a very simple kinematic model that links limb mass distribution and swing kinematics to overall locomotor kinematics as a function of speed and gravitational forces. The model presented here expands on the FDHO to predict stride lengths over a range of speeds and explicitly predicts the walk–run transition speed. The model will therefore examine the parameters that deviated from dynamic similarity in previous reduced gravity experiments (Donelan and Kram, 1997; Kram et al., 1997). I use the model presented here to test the hypothesis that humans do in fact walk with dynamic similarity in reduced gravity once the effects of altered gravity on limb swing are considered. Additionally, since previous studies have altered gravitational forces for the upper body but not the limbs (Donelan and Kram, 1997; Kram et al., 1997; Donelan and Kram, 2000), the model is used to examine the kinematic effects of altering gravitational acceleration on the body alone in order to compare model predictions against previous treadmill studies.

MATERIALS AND METHODS

Model assumptions

The model developed in the present study predicts stride length and the walk–run transition speed based only on limb inertial properties and hip height. There are three primary assumptions involved in the model. The first assumption is that swing phase follows the FDHO model, where limb swing was modeled as a suspended pendulum, taking into account muscle and tendon damping of the oscillating limb (Holt et al., 1990). The second assumption is that step length (the distance traveled during stance phase) remains constant over all walking speeds and is equal to 95% of hip height. This value is the maximum step length used during walking in humans that still minimizes energy costs (see Srinivasan and Ruina, 2006). Finally, it is assumed that at the walk–run transition velocity, stance duration and swing duration are equal. When walking, duty factor (stance duration/stride duration) is always greater than 0.50 (i.e. there is no aerial phase); when running, duty factor is less than 0.50, indicating an aerial phase. Thus, the walk–run transition should occur when duty factor is 0.50 (i.e. equal stance and swing durations).

Model development

Based on the assumption that the limbs swing as FDHOs, the period of the limb is calculated following Turvey et al. (Turvey et al., 1988; see also Holt et al., 1990) as:

$$T = 2\pi\sqrt{\frac{md^2}{(md\boldsymbol{g} + \mathrm{k}b^2)}} \quad (3)$$

where k is the spring constant that represents the composite stiffness of limb muscles and tendons that dampen and drive limb oscillations (N m^{-1}) and b is the distance of the composite spring from the hip (m). Turvey and colleagues (Turvey et al., 1988; see also Holt et al., 1990) found, experimentally, that kb^2, across mammals, is always some multiple of the gravitational forces (mgd) acting on the limb, and thus the equation is reduced by assuming a constant ratio of kb^2 to $m\boldsymbol{g}d$. It is important to note that the value of this ratio is somewhat arbitrary, may differ among gaits and taxa and is found by comparing model predictions to experimental data (see Turvey et al., 1988). The value that best fit human walking data in the present study (see Results) was 3.5, and thus, Eqn 3 is reduced as follows:

$$T = 2\pi\sqrt{\frac{md^2}{(md\boldsymbol{g} + \mathrm{k}b^2)}} = 2\pi\sqrt{\frac{md^2}{(4.5md\boldsymbol{g})}} = 2\pi\sqrt{\frac{d}{(4.5\boldsymbol{g})}} \quad (4)$$

Because Eqn 4 represents one full oscillation, limb swing duration, (t_{sw}), is half this value:

$$t_{sw} = \pi\sqrt{\frac{d}{4.5\boldsymbol{g}}} \; . \quad (5)$$

Stance duration (t_{st}) is calculated by first assuming that step length (L_{st}; distance traveled during stance phase) does not change with speed and is equal to:

$$L_{st} = t_{st}\mathbf{v}\,. \quad (6)$$

According to the second assumption of the model, human step lengths are equal to 95% of limb length (h) (see Srinivasan and Ruina, 2006). Thus, t_{st} at any given velocity ($\mathbf{v}$) is calculated from Eqn 6:

$$t_{st} = L_{st}\mathbf{v}^{-1} = 0.95h\mathbf{v}^{-1}\,. \quad (7)$$

All other spatio–temporal kinematic variables are calculated from t_{st} and t_{sw} at a given velocity. Stride duration (SD) is calculated as the sum of swing and stance durations. Stride frequency (f) is the reciprocal of stride duration. Finally, stride length (SL) is the product of SD and $\mathbf{v}$:

$$SD = t_{st} + t_{sw}\,, \quad (8)$$

$$f = 1/SD\,, \quad (9)$$

$$SL = \mathbf{v}SD\,. \quad (10)$$

By combining Eqns 8–10, SL at a given $\mathbf{v}$ is calculated based solely on h and limb d:

$$SL = \mathbf{v}\left(0.95h\mathbf{v}^{-1} + \pi\sqrt{\frac{d}{4.5\boldsymbol{g}}}\right). \quad (11)$$

Since the walk–run transition occurs when swing and stance durations are equal, the walk–run transition velocity ($\mathbf{v}_{wr}$) is:

$$\mathbf{v}_{wr} = L_{st}t_{sw}^{-1} = 0.95h\left(\pi\sqrt{\frac{d}{4.5\boldsymbol{g}}}\right)^{-1}. \quad (12)$$

Altering gravitational fields

If the dynamic similarity hypothesis is correct, when gravitational acceleration is altered in the model, predicted relative stride lengths should be equal at the same Froude numbers. In order to predict the effects of altered gravity on kinematics and test for dynamic similarity, model parameters are first converted into dimensionless numbers. Thus, a given velocity is converted into a Froude number (Fr) (dimensionless velocity):

$$Fr = \frac{\mathbf{v}^2}{\boldsymbol{g}h} \; . \quad (13)$$

Stride length is converted to a dimensionless value (dSL) as:

$$dSL = \frac{SL}{h} \; . \quad (14)$$

Substituting Eqns 11 and 13 into Eqn 14, dSL is calculated at any given velocity:

$$dSL = \frac{\left(\overbrace{\pi\sqrt{\frac{d}{4.5\boldsymbol{g}}}}^{\mathrm{a}} + \overbrace{\frac{0.95h}{\sqrt{\boldsymbol{g}hFr}}\right) * \sqrt{\boldsymbol{g}hFr}}^{\mathrm{b}}}{h} \; . \quad (15)$$

From Eqn 15, it is clear that gravity plays a major role in determining dSLs at a given speed in two ways (denoted by the curved braces above): (a) by changing the calculation of swing duration, and (b) by changing calculation of velocity from Froude numbers. To predict the effects of reduced gravitational forces on locomotion, the gravitational acceleration constant, g, is changed to some fraction of earth's gravitational acceleration; if gravitational forces influence both the limbs and the body, $\boldsymbol{g}$ is changed in both places in the equation (i.e. a and b in Eqn 15). Altering gravitational forces in the velocity calculations alone (b in Eqn 15) will model the limbs swinging in earth's gravity, while the rest of the body experiences a different gravitational field.

Testing the model: sample

To test the model, stride lengths were predicted for a sample of humans and were measured during treadmill walking. A sample of 11 individuals (five males, six females; see Table 1) volunteered to participate in this project. All subjects gave informed consent and all procedures were approved by the University of Arizona Human Subjects Committee. Each subject performed a series of treadmill walking trials at three speeds (1.0, 1.5 and 2.0 $\mathrm{m\,s^{-1}}$). Pressure-sensitive footswitches were attached to the underside of their feet at the heel and hallux (Delsys, Inc., Boston, MA, USA) to determine the time of touch-down and toe-off. Stride duration was calculated as the time elapsed between two successive touch-downs of the same foot. Using treadmill velocity, stride lengths were calculated as the product of velocity and stride duration. Limb inertial properties were calculated from limb length and body mass after Winter (Winter, 1990).

Hypothesis testing

The effects of reduced gravity on walking were predicted by changing the gravitational acceleration constant in the model. Two cases were modeled: (1) changing the gravitational acceleration constant for both the limbs and the body (i.e. a and b in Eqn 15) and (2) changing the gravitational acceleration constant for the body only (i.e. b in Eqn 15). The effects of gravity were modeled in subjects over a range of Froude numbers (Fr=0.1, 0.2, 0.3, 0.4) at four different gravitational accelerations (% of earth's $\boldsymbol{g}$=100, 75, 50, 25). Model predictions were compared to previous studies in which gravity was altered for the entire body including the legs (Newman, 1996) and for the upper body only (Donelan and Kram, 1997; Kram et al., 1997).

RESULTS

Model validation

The model was validated by comparing predicted stride lengths with stride lengths measured during treadmill walking. Predicted stride lengths do not differ significantly from observed stride lengths (t-test, P=0.08). An ordinary least-squares regression line relating

Table 1. Sample description

Subject	Sex	Mass (kg)	Hip height (m)	d*(m)	T† (s)
Subject 1	F	65.91	0.87	0.61	0.74
Subject 2	M	74.55	0.95	0.67	0.77
Subject 3	F	58.18	0.84	0.59	0.72
Subject 4	F	61.36	0.91	0.63	0.75
Subject 5	F	63.64	0.83	0.58	0.72
Subject 6	F	63.60	0.94	0.66	0.77
Subject 7	M	63.62	0.92	0.65	0.76
Subject 8	M	72.72	0.93	0.65	0.77
Subject 9	F	45.00	0.84	0.59	0.73
Subject 10	M	66.82	0.85	0.59	0.73
Subject 11	M	62.72	0.92	0.65	0.76

*d is calculated as distance in meters from the hip joint following equation 2.
†T is the swing period predicted by the force-driven harmonic oscillator (FDHO) in seconds. Note that this value is for one full oscillation, and swing phase duration is half this value.

predicted to observed stride length does not differ significantly from the line of identity (y=x; see Fig. 1). Additionally, if this regression line is forced through the origin (i.e. y-intercept=0; at zero velocity, both predicted and actual stride length must be zero), the slope and 95% confidence intervals (CI) overlap with the line of identity [slope (95% CI)=1.04 (0.07)].

Testing dynamic similarity

Dynamic similarity is maintained across all Froude numbers and gravitational environments when the gravitational acceleration constant is changed for both the limbs and the body (Fig. 2). However, the model predicts lower dimensionless stride lengths in reduced gravity when gravitational forces are altered for the body alone (Fig. 2). This pattern is consistent with the results of previous studies for both walking and running where gravitational forces were altered for the body alone (see Donelan and Kram, 1997; Donelan and Kram, 2001).

Donelan and Kram (Donelan and Kram, 2001) compared relative stride lengths from treadmill experiments with those from a study where locomotion was examined at a constant velocity onboard an airplane flying a parabolic flight path (Newman, 1996). These flights generated true reduced gravity at the apex of each parabola for short periods of time (Newman, 1996; Donelan and Kram, 2001). The model matches the pattern and magnitude of changes in stride lengths in reduced gravity on parabolic flights (Fig. 3). Additionally, model results are similar to those from treadmill experiments when gravitational forces are reduced for the body only (Fig. 3).

Finally, the model predicts that the human walk–run transition should occur at the same Froude number (Fr=0.58) regardless of gravitational environment (Fig. 4). These predicted values are slightly higher than the mean walk–run transition Froude number found in most experimental studies (Fr~0.50) but are within the range of variation in these studies [range=0.37–0.66 (Gatesy and Biewener, 1991; Hreljac, 1995; Diedrich and Warren, 1995; Kram et al., 1997; Rubenson et al., 2004)]. In treadmill experiments (where gravity was reduced for the upper body only), Kram and colleagues (Kram et al., 1997) showed that, as gravity was reduced to very low levels, the walk–run transition occurred at higher Froude numbers (see Fig. 4). When gravitational acceleration is altered in the model for the upper body only, a similar pattern emerges. In this case, the model predicts that humans will transition to a run at higher Froude numbers as the gravitational acceleration constant is reduced.

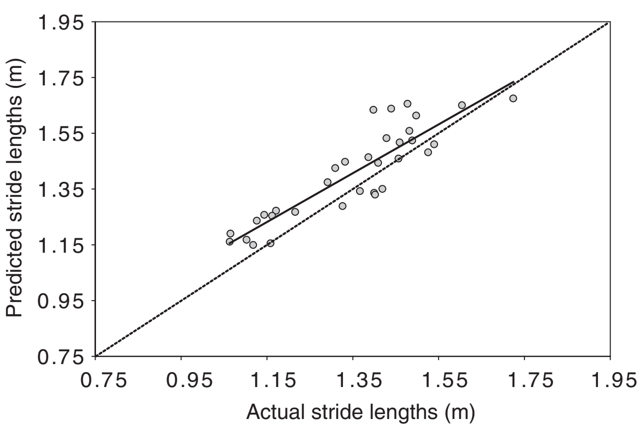

Fig. 1. Comparison of predicted and observed stride lengths in a sample of humans (N=11). The regression line (solid line) relating predicted and observed stride lengths does not differ significantly from the line of identity [slope (95%CI)=0.87(0.16); intercept (95% CI)=0.23(0.23)]. Broken line is the line of identity (y=x).

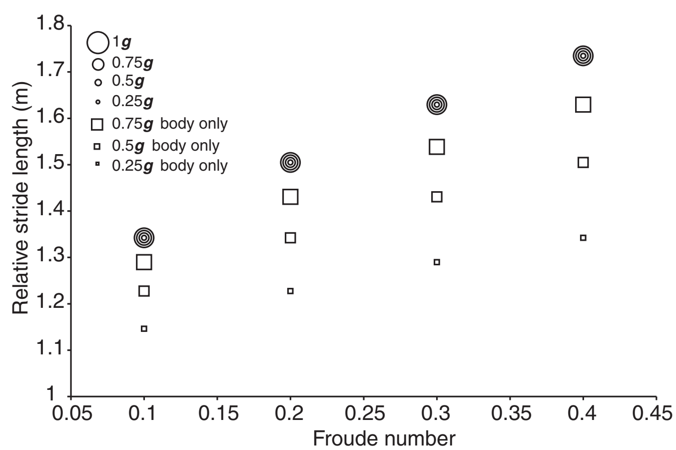

Fig. 2. Effects of gravity on stride length. Circles are model predictions when gravitational acceleration is altered for both the limbs and the body. Squares are model predictions when gravitational acceleration is altered for the body only. Smaller symbols denote reduced gravity. Gravitational forces are presented as a fraction of earth's gravity (9.81 m s^{-2}). Note that data for a single subject are presented here for clarity. Results for all subjects' models are identical.

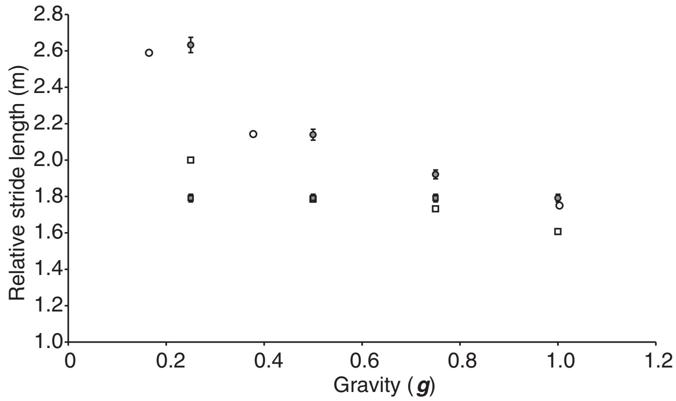

Fig. 3. Comparison of model predictions with parabolic flight data. Stride lengths calculated at a constant velocity ($2\,m\,s^{-1}$) for gravity acting on the body and limbs (gray circles) and for gravity acting on the body only (gray squares). Model values are means ±1 s.d. for all subjects. Data from treadmill experiments [open squares (Donelan and Kram, 2001)] and parabolic flights [open circles (Newman, 1996)] are presented for comparison. Gravitational forces are presented as a fraction of earth's gravity ($9.81\,m\,s^{-2}$).

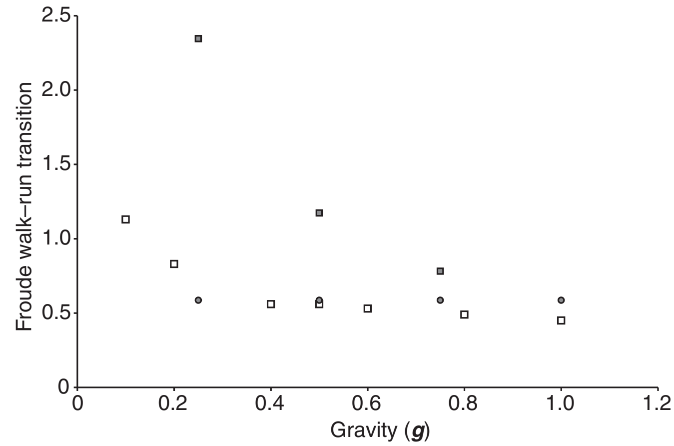

Fig. 4. The Froude number at the predicted walk–run transition speed as a function of gravity. Walk–run transition Froude numbers predicted for two conditions: gravity altered for the limbs and the body (gray circles), and gravity altered for the body only (gray squares). Model values are means for all subjects. Data from treadmill experiments [open circles (Kram et al., 1997)] presented for comparison. Gravitational forces are presented as a fraction of earth's gravity ($9.81\,m\,s^{-2}$).

DISCUSSION

The results of this study suggest that the kinematics of human locomotion are strongly influenced by the dynamics of the limbs swinging as suspended pendula. A very simple model incorporating only anthropometric data predicts stride lengths relatively well and predicts walk–run transition speeds that match experimental data. This model was generated solely to explore the effects of gravity on stride length and the walk–run transition; it is not intended to be an exhaustive depiction of human walking. However, with a few simplifying assumptions, the model does effectively link swing dynamics to whole stride kinematics such that gravity can be altered independently on the limbs and the body. Notably, model predictions matched observed stride lengths and walk–run transition speeds from previous altered-gravity experiments, indicating that the DSH remains valid in altered gravitational environments.

Model

Simplifying assumptions were made to allow for a clear examination of the effects of reduced gravity on human stride lengths. For example, step length is assumed to be constant over all walking speeds, although experimental data show that human step lengths do change slightly with walking speed (e.g. Kuo, 2001). Additionally, while the FDHO model takes individual variation in limb mass distribution into account, it does not account for possible variation in muscle and tendon stiffness. For example, Obusek et al. suggested that there is some individual variation in the stiffness of the muscle–tendon units that will alter the duration of swing period (Obusek et al., 1995). Despite these assumptions, comparisons of the model with experimental data support its use in investigations of the effects of gravity on locomotion. The model predicts stride lengths very well in a sample of humans walking in normal gravity and predicted that changes in stride lengths match those from experimental studies when the effects of gravitational forces are altered for the body only.

It is possible that changes in step length with velocity could impact predicted step lengths in reduced gravity. However, the model results agree with stride length data from parabolic flight experiments of locomotion in reduced gravity. These experiments must be considered the 'gold standard' since alterations in gravity are real and felt by all body parts. The model matches data from these experiments better than treadmill studies. Thus, the close correspondence between model predictions and experimental results from parabolic flights further supports use of this model to examine the effects of gravity on locomotion.

Gravity and the DSH

This model supports the prediction that humans will walk with dynamic similarity in different gravitational environments. As gravity is altered, dimensionless stride lengths are identical at equal Froude numbers. Dynamic similarity should occur only when the ratio of inertial to gravitational forces governing locomotion are equal. When gravity is reduced, equivalent Froude numbers are only possible at lower absolute velocities. If gravity influences stance phase only, then we should expect reduced stride lengths in lower gravitational fields because absolute velocity will be slower at the same Froude number. However, reduced gravity also increases the period of limb swing, which leads to longer stride durations and longer stride lengths. The model suggests that, as gravity is reduced, the increase in swing duration offsets the reduction in velocity at a given Froude number such that stride lengths remain constant.

The model predictions also support previous analyses of locomotion on other planets. The model predicts that the walk–run transition will occur at equal Froude numbers as gravity is altered. Thus, as predicted by Minetti, the walk–run transition velocity will decrease as gravity is reduced (Minetti, 2001). This finding explains why Apollo astronauts reported difficulty walking on the lunar surface and instead preferred running and jumping (Minetti, 2001). Confirmation of these results can improve our understanding of how locomotion will be constrained in future manned missions to the moon or Mars. For example, it may be possible to walk more easily on Mars than on the moon since larger gravitational forces on Mars would allow humans to transition to a run at a higher velocity.

Conclusions

A simple model, based on few assumptions, was able to predict stride lengths in earth's gravity for a sample of individuals and successfully predicted the effects of reduced gravity on human locomotion. The DSH is well supported by the model, and its use remains a valid way to account for the effects of gravity on locomotion. Movement in reduced gravity will clearly affect both swing and stance phase, and analyses of swing-phase or whole-stride kinematics may require either true-reduced gravity experiments (e.g. parabolic flights) or the use of predictive locomotor models. These types of kinematic data may be essential for planning the next generation of space exploration. Models, properly validated by parabolic flight experiments, may be the best way to gather necessary data for how locomotion will change when walking on other planets.

LIST OF SYMBOLS AND ABBREVIATIONS

b	distance of composite spring from hip
d	pendular length of the limb
dSL	dimensionless stride length
f	stride frequency
FDHO	force-driven harmonic oscillator
Fr	Froude number
$\boldsymbol{g}$	gravitational acceleration
h	hip height
I	limb mass moment of inertia
k	Spring constant (composite stiffness of limb muscles and tendons)
L	distance of the limb center of mass from the hip
L_{st}	step length
m	limb mass
SD	stride duration
SL	stride length
T	natural pendular period of the limb
t_{st}	stance duration
t_{sw}	swing duration
$\mathbf{v}$	velocity

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