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SHORT COMMUNICATION

# The preferred walk to run transition speed in actual lunar gravity

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## ABSTRACT

Quantifying the preferred transition speed (PTS) from walking to running has provided insight into the underlying mechanics of locomotion. The dynamic similarity hypothesis suggests that the PTS should occur at the same Froude number across gravitational environments. In normal Earth gravity, the PTS occurs at a Froude number of 0.5 in adult humans, but previous reports found the PTS occurred at Froude numbers greater than 0.5 in simulated lunar gravity. Our purpose was to (1) determine the Froude number at the PTS in actual lunar gravity during parabolic flight and (2) compare it with the Froude number at the PTS in simulated lunar gravity during overhead suspension. We observed that Froude numbers at the PTS in actual lunar gravity (1.39±0.45) and simulated lunar gravity (1.11±0.26) were much greater than 0.5. Froude numbers at the PTS above 1.0 suggest that the use of the inverted pendulum model may not necessarily be valid in actual lunar gravity and that earlier findings in simulated reduced gravity are more accurate than previously thought.

**KEY WORDS: Biomechanics, Locomotion, Preferred transition speed, Microgravity, Froude number**

## INTRODUCTION

In humans and other bipeds, the preferred transition speed (PTS) is the speed at which a subject chooses to change from a walking gait to a running gait. Here, walking is defined as a gait in which at least one foot is in contact with the ground during the stride, and running is defined as a gait containing a flight phase in which both feet are off the ground Although the exact trigger mechanism for the PTS is not known, both energetic and mechanical explanations have been suggested. Walking at speeds above the PTS has been shown to be metabolically more expensive than running (Margaria, 1938), while more recent literature supports the notion of a kinetic PTS trigger related to the overexertion of ankle musculature (Hreljac et al., 2008).

The dynamic similarity hypothesis for locomotion suggests that animals of different sizes will move in similar fashions at equal Froude numbers (Alexander and Jayes, 1983). The Froude number for legged locomotion is a dimensionless quantity that relates the centripetal force to the gravitational force acting upon the body. The Froude number for a given velocity can be found as:

$$\text{Froude} = v^2 / \boldsymbol{g}l\,, \quad (1)$$

where $v$ is the locomotion velocity, $l$ is the leg length and $\boldsymbol{g}$ represents the acceleration due to Earth's gravity (i.e. 9.81 m s$^{-2}$). This Froude number was derived using the inverted pendulum model of Alexander (Alexander, 1977).

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In Earth's gravity, humans select a PTS at a Froude number approximately equal to 0.5 (Alexander, 1977; Hreljac, 1995). If the dynamic similarity hypothesis is correct, when gravity is reduced, the PTS should occur at slower velocities corresponding to a Froude number of 0.5. However, in overhead suspension trials simulating low-levels of reduced gravity (i.e. 0.2 and 0.1 $\boldsymbol{g}$), the PTS occurred at speeds with corresponding Froude numbers greater than 0.5 (Donelan and Kram, 2000; Kram et al., 1997). Differences were postulated to be due to the accelerations induced by the swinging limbs increasing the downward force applied to the body by gravity, and when accounted for, the PTS would occur at a velocity corresponding to a Froude number of ~0.5 (Kram et al., 1997). Their experiments, however, were conducted in normal Earth gravity using an overhead suspension device to reduce the net downward force on the body; it is unknown whether their findings of increased PTS relative to that predicted in lunar gravity were due to their experimental setup. The primary purpose of this study was to determine the PTS in actual lunar gravity (~1/6 $\boldsymbol{g}$). A secondary purpose was to provide a side-by-side evaluation of the PTS in actual lunar gravity with that in simulated lunar gravity.

## RESULTS AND DISCUSSION

For each subject, the PTS values during simulated and actual lunar gravity were greater than predicted using the Froude number equation set equal to 0.5 (Fig. 1). The measured PTS in actual lunar gravity occurred at 1.42±0.24 m s$^{-1}$, corresponding to a Froude number of 1.39±0.45 (Table 1). In contrast, the PTS corresponding to a Froude number of 0.5 was 0.86±0.01 m s$^{-1}$. The predicted PTS was highly similar between subjects owing to their relatively homogeneous leg lengths. For all subjects, the predicted PTS considerably underestimated the measured PTS in actual lunar gravity, ranging from 24% to 105%. The measured PTS in simulated lunar gravity occurred at 1.27±0.16 m s$^{-1}$, corresponding to a Froude number of 1.11±0.26 (Table 2). Similar to the findings in actual lunar gravity, the predicted PTS considerably underestimated the measured PTS in simulated lunar gravity, ranging from 18% to 78%. The difference between the measured PTS in actual and simulated lunar gravity was 13±28%.

The inverted pendulum model of walking predicts that humans cannot walk at speeds corresponding to Froude numbers greater than 1.0. A Froude number greater than 1.0 indicates that the centripetal force needed to keep the stance limb in contact with the ground is greater than the gravitational force, resulting in a flight phase defining a running style of gait. Six of eight subjects in actual lunar gravity, and five of eight subjects in simulated lunar gravity, selected PTS values corresponding to Froude numbers greater than 1.0, thereby refuting the assumption that humans walk like an inverted pendulum in lunar environments.

During the stance phase of a walking gait, the stance limb rotates about the foot/ankle and the motion of the hip traces a concave down arc. Simultaneously, the swing leg rotates about the hip joint and traces a concave up arc. The mass and motion of the swing leg

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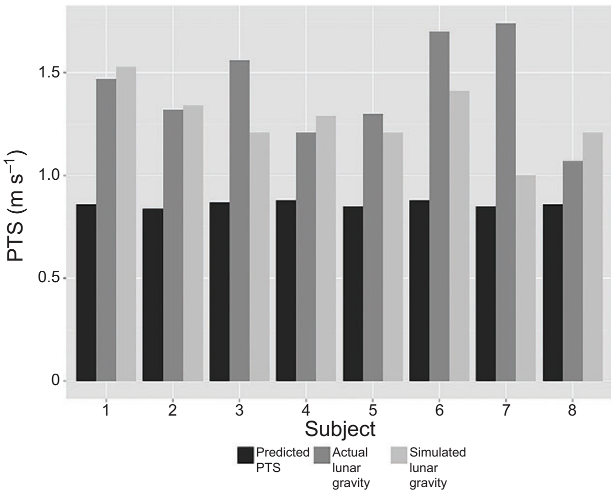


**Fig. 1. Preferred transition speeds in actual and lunar gravity.** Lunar preferred transition speed (PTS) predicted with Froude number equal to 0.5, in actual lunar gravity during parabolic flight and in simulated lunar gravity using overhead suspension for each subject.

exerts a downward acceleration on the hip joint/center of mass that is in addition to the downward acceleration of gravity. This issue was recognized by Kram et al. (Kram et al., 1997), who calculated Froude numbers corresponding with the PTS in simulated reduced gravity. After the authors adjusted for the additional downward acceleration provided by the swinging segments, the 'adjusted' Froude numbers fell closer to 0.5, indicating dynamic similarity across gravitational environments. Our findings from actual lunar gravity suggest that the downward swing-induced accelerations provided by the arms and legs in simulated reduced gravity may be as significant as hypothesized. If this were the case, the triggers for the PTS in lunar gravity may be the same as in normal gravity, but activation may be delayed because of the assistive downward accelerations of the swinging limbs. Future researchers could gain more insight into this speculation by testing subjects in actual lunar gravity while walking with and without arm swing to determine the significance of these segmental accelerations.

Donelan and Kram (Donelan and Kram, 2000) used simulated reduced gravity to compare human locomotion at equal Froude numbers and concluded that the Froude number is necessary but not sufficient to completely define dynamic similarity in human locomotion. More recently, Raichlen and colleagues (Raichlen, 2008; Raichlen et al., 2013) have provided further support for this supposition. They propose that the dynamic similarity hypothesis is supported in reduced gravity when inertial forces attributed to the swinging limbs are taken into account. Taken together, these findings suggest that in lunar gravity the inverted pendulum model and the resulting Froude number computation are not adequate to describe locomotion.

There were some limitations during parabolic flight trials, the first being that the ceiling of the aircraft cabin might have caused alterations in subjects' preferred gait. The cabin height was ~1.94 m from the treadmill surface, and we limited the height of our subject pool to 1.75 m to ensure adequate clearance between the ceiling and subjects' heads during locomotion. Although no subject directly expressed concerns about head clearance, it is possible that subjects may have attempted to limit their vertical excursion by purposely delaying their PTS. Until an aircraft with a larger cabin height is available for testing, there would be no way to examine the sensitivity of this limitation. A second limitation during parabolic flight was that the treadmill belt was shortened to a length of 112 cm because of the support frame. Kram and Powell (Kram and Powell, 1989) showed the relationship between foot contact distance and speed during walking as:

$$\text{Contact distance} = 0.665 + 0.25V, \quad (2)$$

where contact distance is in m and $V$ is walking speed in m s$^{-1}$. The 112 cm long treadmill surface was usable for walking up to speeds of approximately 1.82 m s$^{-1}$, which was larger than our measured or predicted PTS. Therefore, the restricted treadmill length did not influence our results. Although we did not measure stride length, Donelan and Kram (Donelan and Kram, 1997) reported shortened stride lengths in reduced gravity, which further supports the view that treadmill belt size did not influence gait style.

To summarize, our results indicate that in both actual and simulated lunar gravity, subjects selected PTS values well above velocities corresponding to a Froude number of 0.5 (i.e. the approximate PTS of humans in Earth's gravity) (Alexander, 1977; Hreljac, 1995). In this regard, the dynamic similarity hypothesis was not supported. It is probable, as these findings were consistent with simulated reduced gravity, that the inverted pendulum model of gait is not valid in actual lunar gravity and that earlier findings in simulated lunar gravity are more accurate than previously believed.

## MATERIALS AND METHODS

Eight subjects participated in this study (five males and three females; mean ± s.d. leg length 0.91±0.03 m). The investigation was approved by the Johnson Space Center's Institutional Review Board and each subject provided written informed consent prior to participation. The subjects participating in this study

**Table 1. Parameters in actual lunar gravity**

| Subject | Leg length (m) | Fast walk (m s$^{-1}$) | Slow run (m s$^{-1}$) | Measured PTS (m s$^{-1}$) | Predicted PTS (m s$^{-1}$) | Measured Froude no. | %Difference between measured and predicted PTS |
|---|---|---|---|---|---|---|---|
| 1 | 0.92 | 1.43 | 1.52 | 1.47 | 0.86 | 1.45 | 71 |
| 2 | 0.86 | 1.21 | 1.43 | 1.32 | 0.84 | 1.24 | 57 |
| 3 | 0.93 | 1.52 | 1.61 | 1.56 | 0.87 | 1.61 | 79 |
| 4 | 0.94 | 1.16 | 1.25 | 1.21 | 0.88 | 0.95 | 38 |
| 5 | 0.89 | 1.29 | 1.29 | 1.30 | 0.85 | 1.16 | 53 |
| 6 | 0.95 | 1.61 | 1.79 | 1.70 | 0.88 | 1.85 | 93 |
| 7 | 0.89 | 1.70 | 1.79 | 1.74 | 0.85 | 2.09 | 105 |
| 8 | 0.91 | 0.98 | 1.16 | 1.07 | 0.86 | 0.77 | 24 |
| Mean | 0.91 | 1.36 | 1.48 | 1.42 | 0.86 | 1.39 | 65 |
| s.d. | 0.03 | 0.24 | 0.24 | 0.24 | 0.01 | 0.45 | 27 |

PTS, preferred transition speed.

**Table 2. Parameters in simulated lunar gravity**

| Subject | Measured PTS ($m\,s^{-1}$) | Predicted PTS ($m\,s^{-1}$) | Measured Froude no. | %Difference between measured and predicted PTS | %Difference between measured PTS in actual and simulated lunar gravity |
|---|---|---|---|---|---|
| 1 | 1.53 | 0.86 | 1.56 | 78 | −4 |
| 2 | 1.34 | 0.84 | 1.28 | 60 | −1 |
| 3 | 1.21 | 0.87 | 0.97 | 39 | −29 |
| 4 | 1.29 | 0.88 | 1.09 | 47 | −6 |
| 5 | 1.21 | 0.85 | 1.00 | 42 | 7 |
| 6 | 1.41 | 0.88 | 1.27 | 60 | 21 |
| 7 | 1.00 | 0.85 | 0.69 | 18 | 74 |
| 8 | 1.21 | 0.86 | 0.98 | 41 | −12 |
| Mean | 1.27 | 0.86 | 1.11 | 48 | 13 |
| s.d. | 0.16 | 0.01 | 0.26 | 11 | 28 |

The percentage difference between measured preferred transition speed (PTS) in actual and simulated lunar gravity is also shown.

were recruited as part of an addendum to a larger study (Norcross et al., 2009), three of which had their PTS directly measured in Earth's gravity. The Froude number at the PTS for these three subjects was 0.45, 0.5 and 0.49; PTS values in Earth's gravity were not collected for the other five subjects.

### Actual lunar gravity

Actual lunar gravity was provided during parabolic flight onboard a DC-9 aircraft. The aircraft flew in a series of parabolic trajectories resulting in 20 to 30 s periods of actual lunar gravity during each parabola. All subjects had experience as either a test subject or operator during prior parabolic flight experiments. A total of four parabolic flight missions, flown on consecutive days, were used for data collection. Two subjects were tested during each flight and each subject completed 14 trials during successive parabolas.

Subjects walked and ran on an instrumented treadmill (Kistler Gaitway, Amherst, NY, USA) containing two force plates placed in a fore–aft configuration beneath the treadmill belt. Each plate contained four piezoelectric load cells that allowed for determination of the vertical ground reaction force (GRF) and center of pressure, which were sampled at 480 Hz. For purposes unrelated to this study, a steel plate was placed over the treadmill belt with a 33 cm wide and 112 cm long cut-out to approximate the size of the treadmill available on the International Space Station at the time of this study.

Treadmill speed was held constant during each parabola. During initial trials, the subjects walked at speeds of ~0.5 $m\,s^{-1}$ to allow for adaptation to lunar gravity. Once the subjects noted that they were comfortable, an incremental protocol to determine the PTS was commenced. Each subject initially completed a walking trial of ~0.67 $m\,s^{-1}$. The subjects then completed a trial at a speed of ~2.0 $m\,s^{-1}$. We chose this speed because it is the approximate PTS during locomotion in Earth's gravity (Kram et al., 1997), and should theoretically be a running speed in lunar gravity – all subjects did run at this speed. During subsequent parabolas, the treadmill speed was varied from trial to trial between faster walking speeds and slower running speeds until a narrow range was identified that contained the PTS. The choice of speeds during each trial was based upon gait during the previous trial, which was subjectively identified by a single treadmill operator (J.K.D.). Therefore no two subjects completed the exact same sequence of speeds. When a subject varied between a walk and a run on a given trial, that speed was repeated during a subsequent trial to allow the subject to settle on a preferred gait. Although the initial distinction between a walking gait and a running gait was determined by the treadmill operator, GRF data were subsequently used to confirm the existence or non-existence of a flight phase. This was done by analyzing the GRF–time series for periods where total force fell to ~0 N for at least 2% of the stride time. The speed at which PTS occurred was estimated as the mean of the fastest walking speed and the slowest running speed.

### Simulated lunar gravity

Simulated lunar gravity was provided using the NASA Johnson Space Center Space Vehicle Mock-up Facility Partial Gravity Simulator (POGO). The POGO is a customized overhead suspension system designed by NASA that uses a pneumatic cylinder to create constant gravitational offloading (Norcross et al., 2009). A waist and leg harness worn by the subject was connected to the POGO by a spreader bar and four straps. Subjects walked and ran on the POGO using a commercially available treadmill (Challenger model 5.0, Reebok Fitness, Logan, UT, USA) with a walking surface 68 cm wide and 183 cm long.

The POGO was similar to the overhead suspension device, or Reduced Gravity Simulator, used by Kram et al. (Kram et al., 1997) in that a near-constant uploading vertical force was applied to the subject via a harness to reduce the subjects' static GRF to lunar body weight. The major difference between the POGO and the Reduced Gravity Simulator was that the POGO provided suspension forces via a pneumatic cylinder and was designed to allow astronauts to perform training activities at varying levels of gravity, including weightlessness; the Reduced Gravity Simulator, in contrast, provided suspension forces via rubber spring elements and was designed specifically for subject ambulation on a treadmill. Whereas the POGO allowed for subject fore–aft translation, the Reduced Gravity Simulator did not.

Unlike parabolic flight, there were no time constraints to determine the PTS on the POGO and, as such, the protocol was more detailed. Subjects first mounted the treadmill and the initial speed was set so the subjects were walking. Treadmill speed was then incrementally increased, stopping at each speed until a steady gait was achieved and a speed was reached where the subjects freely chose to run. Treadmill speed was subsequently adjusted to find the exact speed where: (1) the subject remained walking, but had to exert increased effort to do so; (2) the subject exerted significant effort to avoid drifting rearward on the treadmill; and (3) the subject indicated that they would prefer to slowly jog at that speed if required to do so for an extended length of time. The speed at which all three criteria were met was noted as the PTS.

The predicted PTS in lunar gravity was calculated assuming the PTS corresponded to a Froude number of 0.5. Leg length was the distance between the ground and head of the greater trochanter, measured while the subjects stood barefoot. The percentage difference between actually measured and Froude-predicted PTS was then calculated. The percentage difference between the predicted and measured PTS in actual and simulated lunar gravity was calculated, as well as the percentage difference in measured PTS between actual and simulated lunar gravity.

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#### Competing interests
The authors declare no competing financial interests.

#### Author contributions
All authors contributed to the writing of this paper, the initial draft being prepared by J.K.D. and W.B.E.

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