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Factors Contributing to the Walk-to-Run Transition in Human Gait

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Abstract

The study examined factors that contribute to the walk-to-run (WTR) transition occurring in human gait. Specifically, the purposes of the study included: **(A)** confirmation of the hypothesis (Kram et al., 1997; Usherwood, 2005; Usherwood et al., 2012) that the *preferred* WTR for humans occurs at a $Fr = 0.50$; **(B)** determination of a similar estimate for a *maximum* WTR transition velocity (e.g., Fr >0.60); **(C)** testing the following hypothesis: As velocity increases, rather than taking longer steps, subjects (1) take shorter steps, and (2) increase step frequency. The Froude ratio (*Fr*) is calculated as $Fr = v^2 / gL$, where v = velocity, g = acceleration due to gravity (9.81 m/s^2), and L = leg length. Twenty volunteers (10 male, 10 female) participated. Leg length for each subject was measured using a published protocol. To determine **(A)** *preferred* WTR, subjects walked on a level treadmill at a comfortable velocity. Every 15 seconds, velocity was increased 0.045 m/sec until the subject made an observable gait transition and velocity was slowed until the subject walked again. The procedure was repeated for a total of three trials. Procedure for **(B)** was the same as the (A) except that the subjects were instructed to hold their walking gait as long as possible to determine *maximum* WTR velocity. Procedure for **(C)** involved filming each subject during condition (B) to determine step length and step frequency. Frame-by-frame analysis was used to determine changes in step length/frequency in response to changes in velocity. Preliminary results for each part of the study were as follows: (A) mean $Fr = 0.47$ for the *preferred* WTR; (B) mean $Fr = 0.79$ for the *maximum* WTR; (C) subjects did not shorten step length as had been expected; rather subjects maintained step length and increased step frequency prior to *maximum* WTR.

Keywords: Froude ratio, walk-run transition, inverted pendulum, transition velocity

1. Introduction

There are two definitions of a bipedal walking gait. The first, and most common, defines walking as locomotion where one foot is always in contact with the ground.[1] This definition is further explained as involving a double-support phase where both feet are in contact with the ground at the widest point in the stance. Second, the mechanical definition explains that kinetic energy turns to potential energy at mid-stance and returns to kinetic energy after the body falls forward during the second half of the stance.[1, 2] Furthermore, as walking velocity increases, humans and other bipeds make a transition to a running gait.[1, 3]

1.1 Inverted Pendulum Model

The mechanical definition of walking is also known as the inverted pendulum model.[1] During the gait cycle, the body acts as a pendulum that moves over the axis of the ankle.[1, 4] The ankle serves as the weight bearing joint.[1] Muscular force is required to initiate the first portion of the swing, with gravity pulling the body forward after reaching a peak at mid-stance. The inverted pendulum model assumes a rigid stance leg[4] and that the body moves in an arc with a radius equal to leg length (L). The movement of the body during the gait cycle in the inverted pendulum model can be seen below in Figure 1.

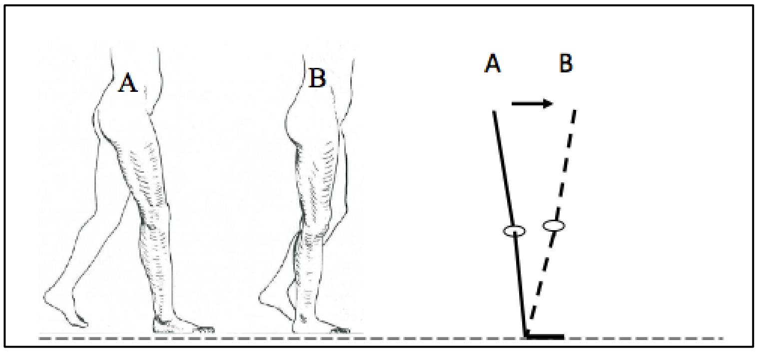

Figure 1. Body movement about the axis of the ankle in the inverted pendulum model of walking gait.[5]

The bipedal walking gait is confined to specific speed constraints. The mechanical definition provides the minimum velocity constraint for walking that sufficient force must be applied to moved the body through mid-stance.[1] Mid-stance must be reached to allow gravity to pull the body forward to complete the stance phase. The upper limit to walking velocity is a result of the leg's inability to oppose tension forces.[1, 6] Since the foot is not attached to the ground, if the force of the push provided by the muscles exceeds the centripetal acceleration of gravity, the body "takes off" into a flight phase, and the walk-to-run (WTR) transition occurs.[1, 4]

1.2 Froude Ratio

The two primary forces involved in the inverted pendulum model are inertial forces and gravitational forces. As previously mentioned, when the inertial force overcomes the force of gravity, a WTR transition occurs. The inertial force acts as a centrifugal force, while the gravity operates as a centripetal force. The relationship between these forces is shown below in Figure 2.

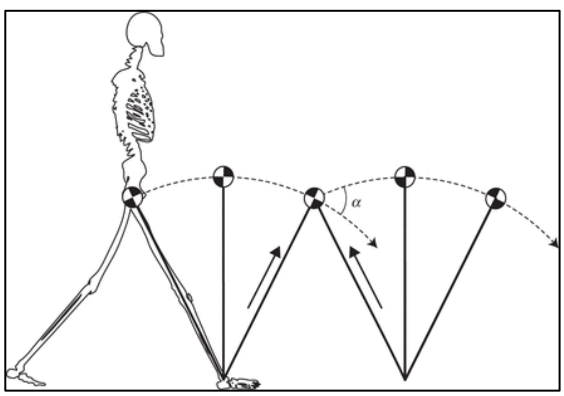

Figure 2. Forces involved in the inverted pendulum model[7]

The Froude ratio (F_r), seen is equation (1) is a dimensionless ratio of inertial (centrifugal) forces and gravitational (centripetal) forces.

$$Fr = \frac{centrifugal\ force}{centripetal\ force} = \frac{mv^2/L}{mg} = \frac{v^2}{gL} \tag{1}$$

Where: m = mass, v = velocity, g = acceleration due to gravity (9.81 m/s^2), and L = leg length.

The inertial force provided until mid-stance is caused by the force of muscle contraction and gravitational force is the result of acceleration due to gravity. The F_r allows the effect of each variable of the WTR transition to be observed and analyzed. An absolute maximum walking speed would be obtained at $F_r = 1$, due to the ratio of centrifugal to centripetal forces and the constraint that "take off" or a flight phase results in a transition to running[1]. However, most bipeds preferred transition is at $Fr \approx 0.50$ [1, 8] and with a preferred transition velocity (PTV) of 2.1 m/s.[4]

1.3 Experiments

1.3.1 experiment 1

The purpose of the first experiment was to confirm the hypothesis [1, 8] that the Preferred Transition Velocity (PTV) among humans occurs at $F_r \approx 0.50$. A PTV is the velocity where a subject would naturally make the WTR transition.

1.3.2 experiment 2

In the second experiment, the goal was to develop an estimated F_r for Maximum Transition Velocity (MTV) for human WTR transitions.[3] While PTV occurs at a natural transition, MTV is the velocity at which the subject is forced to make a WTR transition due to an inability to maintain the walking gait at an increased velocity. Previous research proposed that $F_r \approx 0.6$-0.7.[3] The hypothesis in question was not the result of experimental data, but rather prior mechanical models.[3]

1.3.3 experiment 3

The final experiment endeavored to determine if MTV is a function of stride length (i.e. leg length) or stride frequency. Equation (2) demonstrates how stride length and frequency relate to walking velocity.

$$Walking\ Velocity = stide\ length\ \left(\frac{m}{step}\right) X\ stride\ frequency\ \left(\frac{step}{\text{sec}}\right) \tag{2}$$

Because changes in either stride length or frequency with affect walking velocity, at least one variable must increase to account for walking at MTV. Thus, observation of the changes in both stride length and frequency as velocity increases can provide an explanation of the mechanism behind increased walking velocity.

2. Methods

2.1 Participants

Approval for human subject use was obtained from the Asbury University Institutional Review Board (IRB). Twenty (20) undergraduate students (50% female, ages 18-25 years old) were acquired from the Asbury University student body. All subjects were volunteers and gained no reward for participation.

2.2 Equipment

Equipment used included a True Fitness CS 6.0 treadmill capable of increasing speed by 0.10 mph increments and an incline range of 0-18%. A meter stick was attached to the side of the treadmill to help visualize changes in stride length, and an iPhone was utilized to record video of gait transitions. A 60" (150 cm) flexible tape measure was used in measuring leg length.

2.3 Procedures

2.3.1 experiment 1

Subjects signed an informed consent, and an overview of the experiments was explained. Next, the subjects' leg lengths were measured using a standard protocol.[9] Leg length determined as the distance from the greater trochanter of the femur to the lateral malleolus of the fibula and was measured while standing. Subjects were asked to abduct hip and palpate for the divot in the hip and the bony landmark of the greater trochanter and were then requested to hold one end of a tape measure at greater trochanter while the experimenter measured to the lateral malleolus.

Subjects then stepped onto a treadmill began walking with an initial self-selected velocity at 0% incline. It was then explained to transition from a walk to run whenever a natural transition would occur. Every 15 seconds, the treadmill velocity was increased by 0.045 m/sec (0.10 mph) until an observable WTR transition occurred. The treadmill velocity at the time of the gait transition was recorded as the PTV. This procedure was repeated for a total of three trials. If any two out of the three trials were identical, that transition velocity was used. If all three trials were different, the median was used.

2.3.2 experiment 2

Following the first experiment, subjects received a 2-5 minute break before commencing with the second experiment. The break was included to prevent fatigue from becoming a confounding factor. When the break was completed, subjects stepped back on the treadmill and again began walking at a self-selected velocity. Unlike the first experiment, subjects were asked to hold the walking gait as long as possible while treadmill speed increased. The protocol for increasing speed and determining transition velocity was the same as the previous experiment. However, MTV was determined as the treadmill velocity at which the WTR transition was observed.

2.3.3 experiment 3

Subjects walk-run gait transitions during experiment 2 were simultaneously videotaped to analyze changes in step frequency and length. Video recording began when the subject started walking at the initial self-selected velocity and was stopped after an observed walk-run transition. Recordings were taken from the waist down to maintain privacy and anonymity. The video recordings for five of the twenty subjects were randomly selected for analysis. At the time of this paper, only five of the videos analyses were complete.

3. Results

Means and standard deviations were determined for leg length, Froude ratio, and transition velocity. There was a statistical difference between male and female leg length ($t = 5.17$, $df = 18$), $p < 0.001$. Leg length and F_r were poorly correlated, $p > 0.05$.

3.1 experiment 1

The study resulted in an average $F_r = 0.47$ and showed great similarity to previous studies (Dickens and Kram). Subjects transitioned at an average preferred speed of 1.96 m/s. The recorded standard deviations exist in parentheses. Male and female F_r were compared and a statistical difference was observed ($t = 2.18$, $df = 18$), $p = 0.04$.

Table 1. Means (±SD) values for leg length, W-R Transition Velocity, and F_r.

Study	Leg Length	Transition Velocity	Froude Ratio
Otley/Kulaga (2016)	0.85 m	1.96 m/s	0.47
N = 20	(0.08)	(0.23)	(0.11)
Dickens (2010)	0.97 m	2.07 m/s	0.49
N = 16	(0.06)	(0.19)	(0.07)
Kram (1997)	0.89 m	1.98 m/s	0.45
N = 9	(0.04)	(0.04)	(0.02)

3.2 Experiment 2

The average F_r = 0.47 and MTV = 2.49 m/s. Three of the F_r at MTV exceeded 1.0 and were treated as outliers. The recorded standard deviations exist in parentheses.

Table 2. Means (±SD) values for leg length, PTV and MTV, and F_r

	Leg Length	Transition Velocity	Froude Ratio
Preferred TV (N = 20)	0.85 m (0.08)	1.96 m/s (0.23)	0.47 (0.11)
Maximum TV (N = 17)	0.85 m (0.08)	2.49 m/s (0.23)	0.79 (0.12)

3.3 Experiment 3

Movement analysis software (Kinovea) was used for analysis. The software allowed frame-by-frame analysis of the video recordings. Leg length measurements were scaled using actual known measurements (leg length in meters) for each person. Using the actual leg length, the software allowed for measurement of step length. Figure 3 shows the leg length (0.84 meters) and the step length (0.62 meters). Step lengths were observed during early walking phase and just prior to achieving the maximal transition velocity.

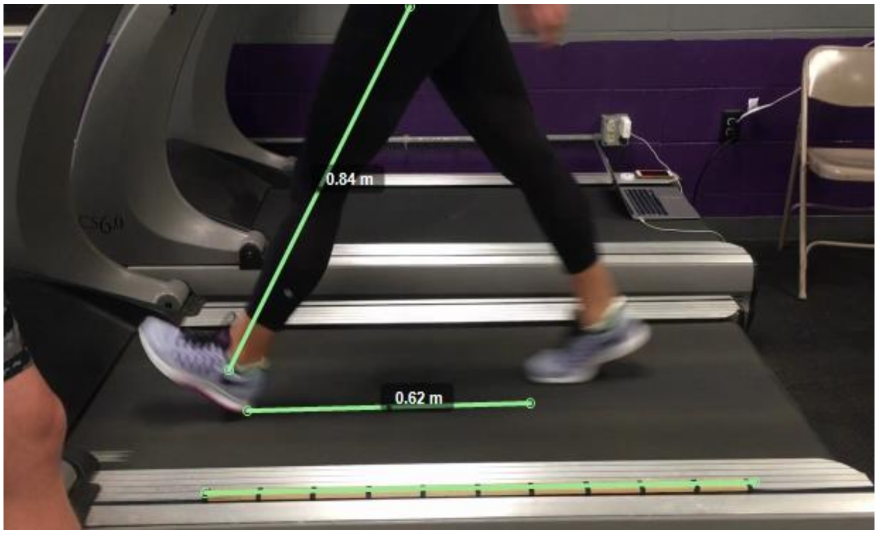

Figure 3. Leg length and step length from movement analysis software (Image by author).

4. Discussion

4.1 Findings

The significant difference between male and female leg length is important only in explaining the difference in transition velocity between genders. Leg length did not correlate well with F_r and thus was not a good predictor of MTV.

4.1.1 experiment 1

The results confirmed that subjects did, in fact, make a WTR transition at the expected $F_r \approx 0.5$.[1, 8] The increase in the number of participants led to a larger standard deviation. Although subjects did seem to differ with their confidence in deciding when to "naturally" transition, the results were consistent with the previous hypothesis.

4.1.2 experiment 2

The MTV was higher than expected and therefore resulted in a slightly larger F_r than the 0.6-0.7 that had been hypothesized in a previous study.[3] This was believed to be a response to the nature of the cue for subjects to "hold walk as long as possible". Many of the subjects were collegiate athletes and may have had a competitive response to the prompt.

While the recorded F_r was larger than the predicted value, it still exists within an acceptable and expected range. As stated previously, the maximum F_r is 1.0 due to the nature of the ratio involving opposing centripetal and centrifugal forces. Thus three trials in which $F_r > 1$, were eliminated. This discrepancy was likely due to measurement error.

4.1.3 experiment 3

The final experiment was an attempt to determine if MTV is function of stride length (i.e. leg length) or stride frequency. The hypothesis was that as velocity increased subjects would increase step frequency while actually decreasing step length. That is, they would take shorter but many more frequent steps. However, these were not observed. In the five video recordings analyzed, the subjects all maintained step length while increasing step frequency. This finding has a significant limitation. The investigators allowed subjects to self-select the starting velocity for the treadmill, but did not make a record of the velocity. Only the velocity at the walk-run transition was recorded. Future investigation of changes in step length and step length as velocity increase is warranted in addition to assessing the remaining subjects.

4.2 Limitations

A previously mentioned assumption of the inverted pendulum model mentioned a rigid stance leg. The model employed also involves the simplification of the trunk as a point of mass vaulting in an arc over the massless rigid leg.[1] This is sometimes referred to as the Compass gait model.[1, 10]

Another limitation is the possibility of a difference of gait between walking on a treadmill and a stationary level surface. The treadmill was chosen for this experiment due to its simplicity in measuring transition velocity and its overall static position to allow for un-obscured observations of the occurrence gait transitions.

While subjects were considered to be in normal health do to gait observation, previous injuries that may have affects on gait speed or mechanics were not considered.

4.3 Future Directions

4.3.1 *effect of incline on walk-to-run transition*

Researchers Hubel and Usherwood (2013) described a study in which subjects walked on inclines from 0 to 9.8%, investigating preferred walk-run and maximum walk-to-run transitions.[6] It was reported that preferred walk-to-run F_r

was lower than expected and maximum walk-run F_r was higher than predicted. This suggests that there may be factors other than leg length and velocity in determining when people transition from a walk to a run. A proposed study is to simultaneously measure metabolic cost (using a metabolic analyzer) while subjects are performing Hubel and Usherwood's incline protocol.[6]

4.3.2 *dorsiflexion range of motion*

Does the available dorsiflexion range of motion affect the walk-run transition velocity? In the compass gait or inverted pendulum model, as the center of gravity moves over the weight-bearing foot, the ankle dorsiflexes. Hypothetically, the center of gravity for a person with greater dorsiflexion range of motion should move farther before the foot has to leave the ground and begin the swing phase. This could affect both the bio-energetic efficiency of walking as well as the velocity at which the person transitions to a running gait. One challenge is that dorsiflexion can be difficult to measure accurately. One challenge in measuring dorsiflexion is the effect of the gastrocnemius, which crosses both the knee and the ankle.[11] A recent study employed a lunge technique for measuring dorsiflexion.[12] Future investigation will focus on the correlation between this weight-bearing method of measurement and walk-to-run velocity or the obtained Froude ratio.

4.3.3 leg length and froude number relationship

The dynamic similarity hypothesis, the basis for a single F_r ($F_r \approx 0.50$) that represents the preferred walk-run transition for bipeds has been questioned.[9] The correlation between leg length and the obtained F_r is low and not statistically significant. This suggests that other factors may determine the preferred walk-run transition.[6] Future investigation, using video analysis, should closely examine the step frequency. Coupled with transition velocity and leg length data, it is hypothesized that step frequency will build a clearer picture of the factors contributing to the walk-run transition will emerge.

4.3.3 application

The Froude ratios found for normal gait may differ greatly with the presence of contractures or the addition of orthotics and prosthetics. Future investigation could provide insight into the biomechanical advantages of current devices.

5. Acknowledgements

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