Effects of changing protocol, grade, and direction on the preferred gait transition speed during human locomotion

Alan Hreljac a,*, Rodney Imamura a, Rafael F. Escamilla b, W. Brent Edwards c

a Department of Kinesiology and Health Science, California State University, 6000 J Street, Sacramento, CA 95819-6073, United States
b Department of Physical Therapy, California State University, Sacramento, United States
c Department of Health and Human Performance, Iowa State University, United States

Received 30 January 2006; received in revised form 30 April 2006; accepted 14 May 2006

Abstract

Although the preferred transition speed (PTS) reported by various researchers is relatively consistent, the amount of observed hysteresis (difference between the walk–run and the run–walk transition speed) varies considerably. Variations in reported hysteresis appear to be related to the protocol used to determine the transition speeds. This investigation compared the PTS, and the amount of hysteresis observed between the incremental and continuous protocols at various inclination conditions. The PTS was significantly greater in the continuous than the incremental protocol within both the 10% and 15% inclination conditions. The amount of hysteresis, however, did not vary significantly between protocols nor between inclination conditions. In the incremental protocol, the amount of hysteresis appears to be related to the size of the speed increment used. In the continuous protocol, the amount of hysteresis could be related to the rate of treadmill acceleration.

Keywords: Gait transitions; Walking; Running; Treadmill

1. Introduction

Walking and running are the two primary gaits utilized by humans during terrestrial locomotion. Over level ground, the speed of locomotion generally determines the gait of choice, with walking being the gait most commonly chosen at lower speeds. As the speed of locomotion increases during walking or decreases during running, a speed is reached at which a gait transition naturally occurs. The speed of the gait transition has been shown to be fairly consistent both within and between subjects, as demonstrated in a number of studies [1–9] that have reported the preferred transition speed (PTS) to be approximately 2.0 m s⁻¹.

The PTS has generally been defined as the average between the walk–run (WR) and run–walk (RW) transition speeds [4,5,7]. Although the PTS determined during these various studies is relatively consistent, the amount of hysteresis (difference between WR and RW) varies considerably, ranging from −0.12 [10] to 0.41 m s⁻¹ [11], with the negative sign indicating that RW was greater than WR. One possible explanation for the discrepancy in the amount of hysteresis observed is the methodological differences between studies in determining WR and RW [3].

The two primary methods that have been used to determine gait transition speeds are the incremental protocol and the continuous protocol. In the incremental protocol, the treadmill speed is increased (or decreased) incrementally, with a decision period (usually about 30 s) given to subjects to determine whether walking or running is the preferred gait at the selected constant speed. No true gait transition occurs during this protocol, but the PTS is able to be accurately accessed. In seven studies in which an incremental protocol was utilized to find both WR and RW, an average hysteresis of 0.02 m s⁻¹ was reported [6,7,10,12–15]. In the continuous protocol, a constantly accelerating treadmill is used to determine the transition speed. Using this protocol, an actual gait transition does occur, but the determination of the transition speed is more difficult than with the incremental protocol since the treadmill speed is constantly changing.
and the instant of the transition is not always obvious. In eight studies in which WR and RW were both reported using a continuous protocol, an average hysteresis of 0.13 m s\(^{-1}\) was found [1–3,8,9,11,16,17].

It has been clearly demonstrated [3,5] that the PTS decreases with increasing treadmill inclination. Although it has been suggested that treadmill inclination may also have an effect on the difference between WR and RW, the evidence is inconclusive. In one of the two studies which measured both WR and RW in level and inclined conditions [5], no difference was found in the amount of hysteresis between the three different inclination conditions tested. The results of the other study [3], however, appear to suggest that increasing inclination may decrease the amount of hysteresis.

There have been no published studies conducted in which both an incremental and a continuous protocol were used to determine PTS, WR and RW, but clearly these variables, as well as the amount of hysteresis may be affected by the protocol used during a study. If there are systematic differences due to protocol, it would be important for researchers to be aware of this, so that valid comparisons between studies could be made. The primary purpose of this investigation was to compare the preferred transition speed, and the amount of hysteresis observed between the incremental and continuous protocols at various inclination conditions within a single group of subjects. It was hypothesized that the preferred transition speed would not be affected by protocol, but a greater amount of hysteresis would occur when using the continuous protocol, and the amount of hysteresis observed would decrease with increasing inclination within both protocols.

When using the continuous protocol, walking and running have generally been distinguished by the absence or presence of a flight phase [1–3,9,11,16]. Thus, the event used for determining the exact instant of the walk–run transition by these researchers was the time at which a flight phase first occurred, and the event for determining the run–walk transition time was the instant at which double support was first observed. During slow speed running, at speeds near the PTS, it has been reported [5,18] that subjects often have a short period of double support. If this were the case, the continuous protocol would overestimate WR and underestimate RW since the true transition time may occur one or more steps prior to the instant of a flight phase for WR, and after the emergence of a double support phase during RW. This, of course, would lead to an overestimation of the amount of hysteresis calculated when using this criterion for the continuous protocol.

Walking has often been described by using an inverted pendulum model [19–21] in which the maximum height of the body’s CM during the stance phase occurs at approximately mid-stance. On the other hand, running has often been characterized by a bouncing ball model [19,22], in which the minimum height of the body’s CM during the stance phase occurs at approximately mid-stance. Thus, a more accurate and robust means of estimating the instant of gait transitions may be formulated from an observation of the body’s position at midstance during the transition step. In the current study, the lower extremity segment positions at midstance of the transition step was used as a criterion for determining whether a subject was walking or running, and thus as a means of determining the instant of WR and RW.

2. Methods

2.1. Subjects

Participants in this study were 10 (six males, four females) young, healthy college students (height = 170.0 ± 7.6 cm; mass = 71.9 ± 11.9 kg; lower extremity length = 88.0 ± 5.2 cm), who were free from musculoskeletal injury or disease at the time of the study. Prior to participation, subjects signed informed consent forms, reiterating the basic procedures and intent of the study, as well as warning of any potential risks involved as a result of participation. All subjects were experienced in treadmill locomotion, and wore their own running footwear during each testing session.

2.2. Determination of PTS

The preferred walk–run and run–walk gait transition speeds of all subjects were determined at three different inclination conditions (0%, 10%, and 15% grades), using two different protocols (incremental and continuous). For all trials, an experimenter controlled the speed and inclination of the treadmill. The treadmill controller panel was turned around from its normal position so that the speed indicator was not visible to the subject.

To determine WR with the incremental protocol, the treadmill was initially set to a speed at which subjects would walk comfortably (approximately 1.2 m s\(^{-1}\)). Subjects were instructed to mount the treadmill and utilize the gait which felt most natural. After a decision period of approximately 30 s, the treadmill was stopped and subjects dismounted. If the subject indicated that walking was the preferred gait at that speed (as was the case for all subjects at the initial speed), the treadmill speed was increased by approximately 0.1 m s\(^{-1}\) before the subject remounted. Again, after a 30 s decision period, subjects were instructed to indicate the gait which felt most natural at the new speed. This process continued until a speed was reached at which the subject indicated that running was the most natural gait at that particular speed. That speed was defined as WR. By starting the treadmill at a high enough speed to ensure that subjects ran (>3.0 m s\(^{-1}\)), then decreasing the treadmill speed incrementally (as described earlier), RW was determined. The entire process for each inclination condition was repeated three times in random order. The PTS at each inclination condition was defined as the average of WR and RW.
To find WR using the continuous protocol, the treadmill was initially set to a slow walking speed (approximately 1.0 m s\(^{-1}\)). After subjects were comfortably walking at this speed, the treadmill was continuously accelerated by applying constant pressure to the “increase speed” button of the treadmill controls until the subject began running. During this procedure, subjects were videotaped with a single JVC GR-DVL 9800u digital video camera positioned approximately seven meters from the treadmill. Data were recorded in the sagittal plane (from the right side) at a frequency of 240 Hz. The instant of WR was determined from observation of the digital video recording, and defined to occur at midstance of the step during which the subject switched from an inverted pendulum to a bouncing ball model. The amount of knee flexion at midstance was the criterion used to determine whether a subject was walking or running. When walking, the knee is close to the anatomical position at midstance, while there is approximately 50° of knee flexion at midstance when running [23]. Since these differences are quite large, and easily distinguished by an observer (Fig. 1), no measurements of knee angles were taken. Rather, observations of knee angles at midstance were independently made by two researchers to determine the step during which a transition occurred. For the small number of trials in which a consensus was not reached, a third researcher observed the video of the trial. If there was still no agreement between observers, then the trial would not be accepted. Treadmill speed at WR was determined by averaging the subject’s foot speed while the foot was completely in contact with the treadmill. Foot position was determined from the digitized records of a marker placed on the lateral aspect of the subject’s calcaneus. Digitizing was performed using the Ariel Performance Analysis System (APAS). A three point central difference method was used to calculate the speed of the foot from the smoothed position data. Relevant data were smoothed using a fourth order zero-lag Butterworth filter with a cutoff frequency of 6 Hz. The cut-off frequency was determined using the residual method [24]. To find RW, the process was repeated in reverse, with RW defined to occur at midstance of the first walking step. Inclination and transition direction conditions were randomly ordered, and repeated twice, with rest periods provided between trials to avoid fatigue. For comparison to the incremental protocol, a single value of the PTS for each inclination condition was determined by averaging WR and RW.

2.3. Data analysis

The dependent variables analyzed during this study were the PTS, WR, RW, and the amount of hysteresis (WR–RW). A two (continuous and incremental protocol) by three (0%, 10%, and 15% treadmill inclination) repeated measures analysis of variance (ANOVA) was used to test for differences in the dependent variables between protocols and treadmill inclination conditions (\(p < 0.05\)).

3. Results

The average rate of treadmill acceleration for the WR trials was 0.17 ± 0.02 m s\(^{-2}\), while the average rate of acceleration for the RW trials was −0.19 ± 0.03 m s\(^{-2}\). The rate of treadmill acceleration varied slightly between subjects, but differed by an average of less than 0.02 m s\(^{-2}\) between inclined conditions.

Within each protocol condition, PTS, WR, and RW all decreased significantly as treadmill inclination increased (Figs. 2 and 3). At the level condition, there was no difference between protocols in PTS, WR, and RW, but all of these variables were significantly greater in the continuous than the incremental protocol within both the 10% and 15% inclination conditions. There were no significant interactions found between conditions for any variable.

For both the incremental and continuous protocol conditions, RW was significantly less than WR at all inclination conditions, indicating that there was a hysteresis effect for each protocol at each inclination condition. The amount of hysteresis did not vary significantly between protocols nor between inclination conditions (Table 1). Within each inclination condition, however, the variability in hysteresis was greater during the continuous protocol than the incremental protocol.

Fig. 1. Representation of approximate sagittal plane segment positions at midstance during (a) walking and (b) running.
4. Discussion

The overall PTS (average PTS of the two protocols) of the subjects in the level condition (1.89 m s\(^{-1}\)) was slightly lower than the average PTS reported in several previous studies [1–4,6,7–10,12,14,25], but it was within the range of values (1.83–2.15 m s\(^{-1}\)) reported in these various studies. As expected, the PTS of the inclined conditions for both protocols decreased as treadmill inclination increased. The overall PTS of the inclined conditions, however, was less than the PTS reported in previous studies at comparable inclination conditions, although the PTS was only determined at comparable inclined conditions in two other studies [3,5]. The values of WR and RW followed a similar trend as the PTS. The slightly lower PTS, WR, and RW values found in the current study may be partly due to the fact that the subjects in the current study were of slightly shorter stature than in some of the previous studies. It has been demonstrated [8,12,14] that various body length variables, such as lower extremity length, are positively correlated to the PTS, and may explain up to about 30% of the variance in PTS [14].
None of the transition speed variables, PTS, WR, or RW, differed between protocols at the level condition (Figs. 2 and 3), but all of these variables were significantly greater during the continuous protocol than the incremental protocol for the two inclined conditions. The walk–run transition has been hypothesized [5,6,15,17] to be triggered in response to stress in the dorsiflexor muscles as walking speed approaches the PTS. This stress is likely to be fairly noticeable for subjects when given a reasonably long decision period, as was done during the incremental protocol. The more acute situation of the continuous protocol may not allow subjects to perceive dorsiflexor stress as readily.

The amount of hysteresis that should be expected during the incremental protocol is approximately equal to the size of the increments utilized. Assuming that a subject’s true transition speed lies somewhere between two speed conditions, the subject should walk at the lower of the two speed conditions, and run at the higher speed condition regardless of treadmill acceleration direction. This would yield a value of WR which would be greater than the value of RW by the size of the speed increment, and it should be relatively consistent assuming that the speed increments are consistent. The amount of hysteresis observed during the incremental protocol in this study was just slightly less than the speed increment employed for all inclination conditions, and was quite consistent within and between subjects.

It has been suggested [3] that the amount of hysteresis expected during the continuous protocol should be related to a subject’s reaction time. That is, when the subject receives a signal from proprioceptors that a gait transition is desirable, there would be some finite time period before the gait change would actually be effected as the signals are sent. Since the treadmill would be changing speed during this time period, then WR would be greater than RW. It was hypothesized that the hysteresis resulting from this time delay would be greater than the amount of hysteresis observed during the incremental protocol. In the current study, this did not occur, as the amount of hysteresis observed during the two protocols was almost identical at each of the inclination conditions.

When using the incremental protocol, the determination of the run–walk transition speed is really only an affirmation of the walk–run transition speed. Since subjects are given a fairly long decision time period when using the incremental protocol, the reasons for a subject walking or running at a given constant speed are likely to be factors which are determinants of the walk–run transition speed, such as dorsiflexor stress. Thus, when using the incremental protocol, the specific reasons for determining the preferred gait would likely be the same whether the treadmill speed had been increased incrementally upward or downward. This would understandably lead to a consistent amount of hysteresis at all inclination conditions provided that speed increments are consistent.

During the continuous protocol, however, the criteria which determine RW are very likely to be different than the criteria which determine WR. The variables which trigger the walk–run gait transition have been well studied [5–7,13,14,17,26–28] but little research has been conducted concerning the run–walk transition. Although the factors affecting the run–walk transition are not known, it has been shown that running at speeds near the PTS is less metabolically economical than running at higher speeds [18]. It is possible that the increased energy demands of slow running may be a result of increased stress on larger muscles such as the gastrocnemius and quadriceps muscles. To relieve this stress, a transition to a walk could take place. In the only study known to have examined the determinants of the run to walk transition [15], muscle activation of the ankle and knee extensors (primarily the gastrocnemius and quadriceps) was found to be generally lower during walking than running at speeds near the PTS. The results of this study were inconclusive, but the researchers [15] suggested that the run to walk gait transition may be triggered by stress in the ankle and knee extensors as running speed approached the PTS.

Regardless of the exact reasons for the run–walk transition, it is quite certain that the determinants of the run–walk gait transition are different than the determinants of the walk–run transition. Thus, the amount of hysteresis observed when using the continuous protocol should be independent of the amount of hysteresis observed in the incremental protocol. Since the determinants of the run–walk transition should remain consistent for each inclination condition, it should be expected that the amount of hysteresis would also remain relatively constant at all inclination conditions during the continuous protocol. The rate of acceleration used during the current study may have, by chance, yielded a similar amount of hysteresis as observed during the incremental protocol. Previous researchers [3,11,16] have suggested that the rate of acceleration may affect the amount of observed hysteresis. Unfortunately, in the current study, the rate of treadmill acceleration could not be controlled to test this hypothesis. Future studies should be conducted using differing rates of treadmill acceleration with the continuous protocol.

5. Conclusions

The amount of hysteresis appears to be unaffected by the protocol used to determine transition speeds. The amount of hysteresis observed during the incremental protocol is likely affected by the size of the increments used, while the amount of hysteresis observed during the continuous protocol is likely influenced by the rate of treadmill acceleration. Thus, the lack of a difference observed in the amount of hysteresis between protocols may merely be a consequence of the size of the increments used during incremental protocol trials, in conjunction with the treadmill acceleration rate for the continuous protocol trials. In this study, all transition speed variables (PTS, WR, and RW) decreased as treadmill
inclination increased, and were greater in the continuous protocol at the inclined conditions.

References