Department of Veterans Affairs

JRRD Volume 42, Number 2, Pages 175–182
March/April 2005
Journal of Rehabilitation Research & Development

Temporal symmetries during gait initiation and termination in nondisabled ambulators and in people with unilateral transtibial limb loss

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Abstract—This study investigated the temporal characteristics of gait initiation and gait termination. Ten nondisabled adult volunteers and ten people with unilateral transtibial limb loss performed starting and stopping for slow, normal, and fast walking speeds. We used kinematic and anthropomorphic data to determine the body center of mass (BCOM) position of each subject. The BCOM acceleration was derived by double-differentiating the position data. An averaged BCOM acceleration was calculated by a filtering of the instantaneous acceleration data at a cutoff frequency set by the cadence for elimination of the step-to-step variation. We used this averaged acceleration to calculate the time the volunteers needed to initiate and terminate gait. The results support the hypothesis that both nondisabled ambulators and the subjects with unilateral transtibial limb loss initiate and terminate gait in approximately two steps, regardless of the steady-state walking speed.

Key words: acceleration, deceleration, disabled persons, gait, human movement, initiation, kinematics, rehabilitation, temporal-spatial, termination.

INTRODUCTION

This study proposes a new method for determining the time a person needs to initiate and terminate gait and for establishing the number of steps needed to complete these processes. The time period during which the body center of mass (BCOM) is accelerating and decelerating, respectively, was analyzed for slow, normal, and fast walking speeds. We performed this analysis in both nondisabled (ND) walkers and in unilateral transtibial (UTT) prosthesis users to assess the effect of limb loss on the temporal-spatial parameters of initiation and termination.

Temporal-spatial gait characteristics are important for understanding walking patterns and asymmetries and for their correlation with kinetic parameters. For steady-state walking, the gait cycle can be divided into distinct, repeatable swing and stance phases for a single limb. During this walking cycle, medial-lateral and sagittal plane variations, and/or temporal asymmetries, are observed in pathological gait. Also, step and stride length variations

Abbreviations: APA = anticipatory postural adjustment, BCOM = body center of mass, ND = nondisabled, SD = standard deviation, UTT = unilateral transtibial, UTTA = UTT amputee subjects initiating with anatomical limb, UTTP = UTT amputee subjects initiating with prosthetic limb, VA = Department of Veterans Affairs.

This material was based on work supported by the National Institute on Disability and Rehabilitation Research (NIDRR), Department of Education, under grants H133E980023 and H133E030030.

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DOI: 10.1682/JRRD.2004.03.0038

during steady-state walking have been shown to influence the magnitudes of the vertical displacement of the BCOM, the peak-to-peak walking velocities, and various other kinematic and kinetic gait parameters [1–3]. Similarly, the temporal-spatial parameters can be used during starting and stopping to help define specific initiation and termination cycles and events, and to help assess the implementation of the acceleration and deceleration periods. Several authors have examined the timing patterns of gait initiation [4–6]. However, the number of steps and the time necessary to reach steady-state velocity from a quiet standing position have been a controversial topic in the literature. A few authors have examined walking patterns during gait termination [7–8], but the time and number of steps necessary to stop have not been addressed to our knowledge.

From earlier trials, we hypothesized that gait initiation and gait termination display symmetric temporal-spatial characteristics. Specifically, we hypothesized that initiation and rapid termination occur in an invariant time interval, requiring approximately two steps. This study quantifies the duration and the number of steps needed to initiate and terminate gait. We performed the analyses on both ND subjects and people with a UTT amputation to assess whether the lack of an anatomical ankle-foot system affects these parameters. The results from this study could be applied to gait laboratory design to ensure appropriate definitions of data capture volumes.

METHODS

Subjects

The BCOM position was determined in 10 ND subjects (average age 28.0 ± 4.0 yr, average weight 79.8 ± 10.7 kg, average height 175.9 ± 7.0 cm) and in 10 people with UTT amputations (average age 54.1 ± 7.8 yr, average weight 87.3 ± 22.3 kg, average height 177.2 ± 11.7 cm) who signed consent forms approved by the Northwestern University Institutional Review Board. The ND group consisted of nine males and one female, while the group with UTT amputations included eight male and two female subjects. The disabled group included six subjects with an amputation due to trauma, two due to cancer, and two as a result of infections. The duration since the amputation ranged from 4 to 37 years.

Determination of Variables

To address the hypothesis, we analyzed the following variables: (1) total acceleration duration of the BCOM, (2) the period from start of forward acceleration to first toe-off—anticipatory postural adjustment (APA) time, (3) first swing time, (4) peak mean acceleration of the BCOM, (5) deceleration duration of the BCOM, and (6) peak mean BCOM deceleration magnitudes.

In the BCOM calculation, we determined the locations of the segmental centers of mass from the positions of markers that were placed on the body and from the calculated joint centers of rotation. Body mass segment fractions and the segmental lengths were from data extracted from Drillis et al. [9] and are reported in Gard et al [10]. We determined the BCOM vertical position for each subject from kinematic data by calculating the vertical position of the center of mass of each body segment and then using a weighted average based on the segment mass fractions to calculate overall BCOM position [11]. The peak-to-peak amplitudes of the resulting vertical displacement waveforms were averaged for each trial in order to calculate the vertical excursion.

We derived kinematic data from marker position data that we collected at 120 Hz using an 8-camera Motion Analysis™ System (Motion Analysis Corporation, Santa Rosa, CA). Markers were placed according to a modified Helen Hayes marker model [12]. Subsequently, the forward acceleration of the BCOM was calculated by a double differentiation of the forward position data. An averaged acceleration was calculated by a filtering of the data with the use of a fourth-order bidirectional low-pass filter with an effective cutoff frequency set by the cadence. This filtering eliminated the step-to-step variations and provided an averaged acceleration curve, i.e., mean acceleration curve. **Figure 1(a)** shows typical curves of forward instantaneous and mean velocity and acceleration curves during an initiation trial, while **Figure 1(b)** shows the same curves during a rapid termination test. In these figures, the dashed vertical lines represent toe-off events and the solid vertical lines indicate heel-contact events. The lighter vertical lines depict right-side events, while the darker lines are associated with the left side.

We calculated the acceleration and deceleration periods by averaging the filtered acceleration (mean acceleration) during quiet standing and steady-state walking and detecting when the curves exceeded two standard deviations (SDs) from these averages. Specifically, the beginning of forward acceleration (**Figure 1(a)**) was depicted

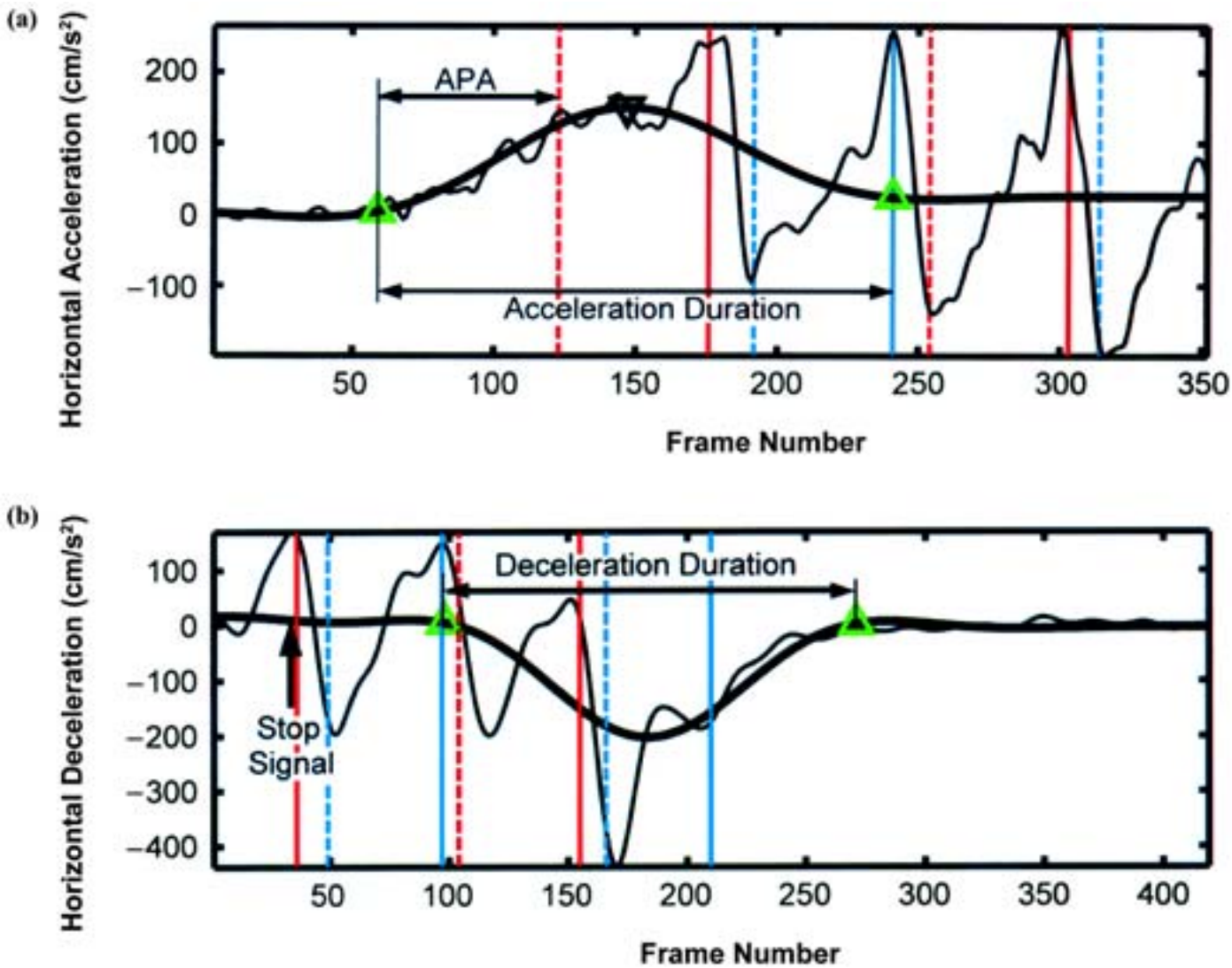

Figure 1.
Forward instantaneous and mean **(a)** acceleration and **(b)** deceleration during typical gait initiation and gait termination trials. Dashed vertical lines represent toe-offs and solid vertical lines indicate heel-contacts. Red vertical lines depict right-side events, while blue lines are associated with left side. Anticipatory postural adjustment (APA) period is defined as time from start of forward acceleration to first toe-off. Triangles define duration of forward acceleration and deceleration.

as the point where the mean forward acceleration exceeded two SDs above the averaged mean acceleration during quiet standing. We used the first 50 frames of each trial to define the quiet-standing acceleration. We calculated the end of the acceleration period by depicting the point where the forward acceleration first returned to the quiet-standing level (approximately zero). For gait termination, we calculated the start of deceleration by determining when the mean deceleration deviated 2 SDs from the steady-state values (steady-state average = average of 50 frames prior to stop signal). The end of the deceleration period was depicted as the point where the mean forward deceleration returned within 2 SDs of the averaged mean acceleration during quiet standing. The last 50 frames of each termination trial were used to define the quiet standing values. Finally, we calculated the acceleration and deceleration durations by dividing the number of frames by the sampling rate of 120 Hz between the start and end of forward acceleration and deceleration, respectively.

Experimental Protocol

In this study all subjects performed walking trials at three different self-selected speeds: slow, normal, and fast. For the initiation trials, the subjects were standing in the measurement volume and were instructed to walk at either a slow, normal, or fast speed. No other instructions were given at this time. Three trials were collected under these conditions at each of the three speeds. Since most subjects had a preferred foot with which they initiated walking, each subject was subsequently instructed to start walking with the opposite foot (same number of trials).

For gait termination, data were collected by an instruction to the subject to walk at a slow, normal, or fast speed across the laboratory walkway. During randomly selected trials, the subjects were given an auditory stop signal. We conducted the randomization process by combining walking and stopping trials together. Each trial was assigned a randomly generated number. Subsequently, all trials were sorted in ascending order according to their number and data collection trials were implemented in this order. During termination trials, the stop signal was given at approximately heel contact. Each subject was instructed to comfortably stop as soon as possible after the signal was given. Also, for stability reasons, the subjects were instructed to have both feet together (parallel) when completely stopped.

The length of the measurement volume was 3.66 m. This distance was sufficient for gait initiation or gait termination trials, but not large enough to measure both initiation and termination during a single walking trial. As a result, gait initiation and gait termination trials were conducted during separate independent trials.

Statistical Analysis

Data for the peak acceleration and deceleration magnitudes and the acceleration and deceleration durations were analyzed for the ND subjects and for subjects with UTT amputations when they were performing the given task with either their prostheses or their anatomical limbs. We analyzed the acceleration/deceleration times in the UTT subject groups using a repeated measures analysis of variance ($\alpha = 0.05$) at each of the three speeds to determine if any significant changes were associated with speed. Mean effects within groups were examined with paired *t*-tests with Bonferroni corrections when significant differences were observed. We normalized peak acceleration/deceleration parameters to the steady-state walking speed to eliminate the differences due to the variation in speed from trial to trial. We compared the ND and the UTT groups using *t*-tests. Our statistical analyses were completed with SPSS software (SPSS, Inc., Chicago, IL).

RESULTS

The acceleration durations during gait initiation for all trials for the ND subjects are shown in **Figure 2**. The averaged acceleration durations for all trials performed by the 10 ND subjects at the different initiation speeds were 1.58 ± 0.09 s for slow, 1.61 ± 0.13 s for normal, and 1.6 ± 0.1 s for fast speeds. The results indicate that the time needed to reach a steady-state walking speed is approximately 1.6 s, regardless of the final walking speed ($p = 0.73$). **Figure 2** also shows the APA duration, i.e., the time from where forward acceleration begins to first toe-off, and the first swing duration versus the steady-state walking speed achieved during each initiation. The beginning of acceleration appears to occur consistently at approximately 0.59 s before first toe-off.

The acceleration duration was also calculated for the UTT prosthesis users when they initiated gait with either their prostheses or with their healthy feet (**Figure 3**). The

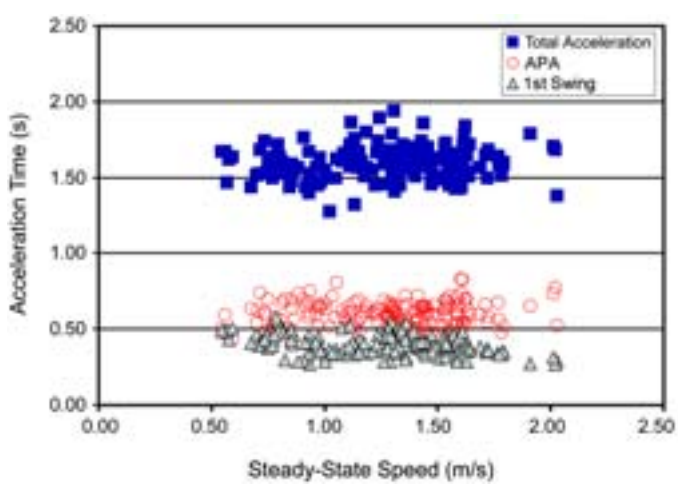

Figure 2.
Total acceleration duration (squares), anticipatory postural adjustment (APA) time (circles), and first swing time (triangles) as function of steady-state speed achieved during gait initiation by nondisabled ambulators. Acceleration duration remains constant regardless of steady-state walking speed. APA period and first swing time are constant over range of initiation speeds and make up approximately 55% of total initiation time.

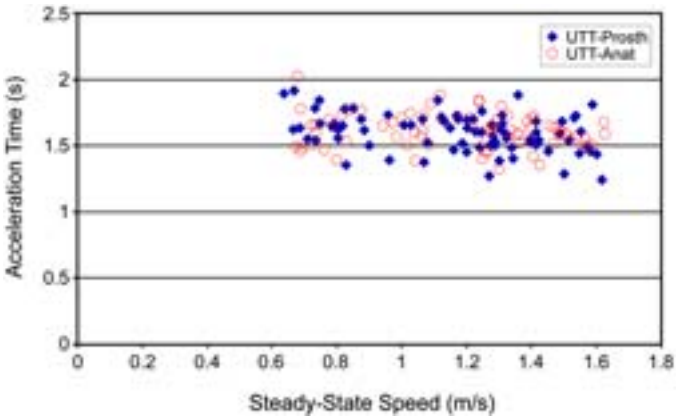

Figure 3.
Acceleration duration for gait initiation during slow, normal, and fast walking for subjects with unilateral transtibial (UTT) amputations. Diamonds indicate initiation with transtibial prosthetic leg (UTT-Prosth), while circles show initiation with transtibial healthy anatomical leg (UTT-Anat). No difference exists in acceleration duration when subjects with UTT amputations initiate gait with anatomical or prosthetic limbs.

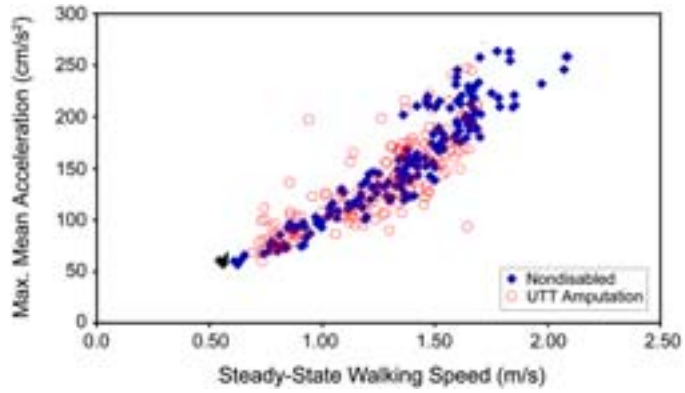

Figure 4.
Maximum mean acceleration for gait initiation versus steady-state walking speed for subjects with unilateral transtibial (UTT) amputation (circles) and for nondisabled (ND) subjects (diamonds). Maximum mean acceleration increases nonlinearly with increasing walking speed. No difference exists in maximum mean acceleration between ND subjects and subjects with UTT limb loss.

averaged acceleration durations for all trials performed by the ten subjects with a UTT amputation when they initiated gait with their anatomical limbs at the different initiation speeds were 1.61 ± 0.14 s for slow, 1.59 ± 0.15 s for normal, and 1.58 ± 0.09 s for fast speeds. When these subjects initiated gait with their prosthetic limbs, the averaged acceleration durations were 1.63 ± 0.13 s for slow, 1.62 ± 0.10 s for normal, and 1.57 ± 0.11 s for fast speeds. Statistical analysis indicates that regardless of the foot used to initiate gait, the acceleration duration remains constant over the range of initiation speeds ($p = 0.401$).

In addition to the acceleration duration, we calculated the peak mean acceleration for both groups. The peak mean acceleration is shown as a function of steady-state walking speed in **Figure 4**. The magnitude of the mean acceleration rises as the target steady-state walking speed increases ($p < 0.0001$). The figure suggests that there is no difference between the two population groups, nor is there is a difference between the prosthetic or healthy leg initiation in the amputee subjects. Statistical analysis indicates no difference in the peak acceleration between the ND subjects, the UTT amputee subjects initiating with the prosthetic limb (UTTP), and the UTT amputee subjects initiating with the anatomical limb (UTTA) at slow and normal speeds. *T*-tests indicated no statistical differences in peak acceleration values between ND and UTTA and ND and UTTP, but a difference was evident between UTTA and UTTP at fast walking speeds ($p = 0.001$).

In addition to the data on gait initiation, we determined the time needed to reach a complete stop (deceleration duration) and the peak mean decelerations of the BCOM for gait termination. Statistical analysis shows that the time needed to rapidly terminate gait is invariant with the steady-state walking speed ($p = 0.259$), at approximately 1.6 s. Further statistical analysis indicates that no significant difference exists between the acceleration and deceleration times across the different speeds ($p = 0.73$).

The deceleration duration was also determined for the subjects with UTT amputations when they were stopping with either their prosthetic or anatomical limbs. These deceleration durations were compared with those measured in the ND subjects (**Figure 5**). No statistically significant differences existed between the three groups ($p = 0.257$), nor did any significant difference due to speed ($p = 0.993$).

The acceleration and deceleration peak magnitudes were compared for the ND subjects. Statistical analysis showed no differences between peak acceleration and deceleration magnitudes at slow ($p = 0.081$) and fast ($p = 0.074$) speeds, but the deceleration magnitudes were higher at normal speeds ($p = 0.013$).

The peak deceleration magnitudes were compared between the ND subjects and the UTT amputee patients when they were terminating gait with either their anatomical or prosthetic limbs (**Figure 6**). All three conditions

appear to be similar. A quadratic relationship appears to exist between the peak deceleration magnitude and the steady-state walking speed in all three conditions. Statistical analysis shows no significant difference between the three groups at slow walking speeds (p = 0.666). The analysis did, however, show a difference at normal and fast speeds. At normal walking speeds there was a difference between UTTA and UTTP (p = 0.004). Also, differences at fast walking speeds were found between the ND and UTTA groups (p = 0.006) and the UTTA and UTTP groups (p = 0.021). These differences could be due to the different walking speeds for each group. For example, the mean normal and fast walking speeds for the ND group are significantly different than the normal and fast walking speeds for the amputee group. Since a quadratic relationship exists between walking speed and the peak acceleration magnitude, these differences in speed can affect the statistical outcomes. Although the statistical analysis showed slight differences between a few of the conditions, these differences are probably not clinically significant.

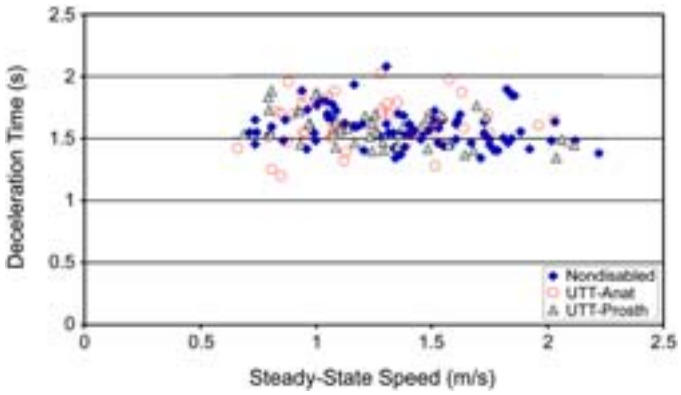

Figure 5.
Deceleration duration for slow, normal, and fast walking for nondisabled ambulators (diamonds) and for unilateral transtibial (UTT) amputee subjects when terminating gait with anatomical legs (UTT-Anat) (circles) or with prostheses (UTT-Prosth) (triangles).

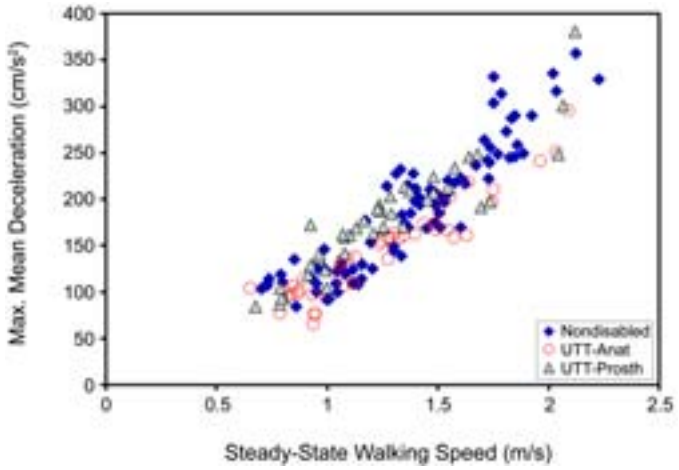

Figure 6.
Maximum mean deceleration for slow, normal, and fast walking for nondisabled ambulators (diamonds) and for unilateral transtibial (UTT) amputee subjects when terminating gait with anatomical legs (UTT-Anat) (circles) and prostheses (UTT-Prosth) (triangles).

DISCUSSION

Although disagreement exists in the literature over the number of steps necessary to achieve steady-state walking, the BCOM acceleration method used in this study indicates that steady-state velocity is achieved in approximately two steps. **Figure 2** indicates that the time needed to reach steady-state velocity is relatively invariant with the target steady-state speed. Specifically, **Figure 2** indicates that the APA period and the first swing time are constant over the range of initiation speeds and constitute approximately 55 percent of the total initiation time. Such invariance can be achieved if the system behaves as a passive, free-falling inverted pendulum with different effective initial angles, depending on the speed. These effective starting angles of the inverted pendulum can be modified by ankle dorsiflexion and forward trunk lean. The ankle dorsiflexion moves the center of pressure posterior, while trunk lean moves the center of mass anterior. These combinations create the initial conditions for the inverted pendulum to start the fall forward process [13]. The periods of oscillation for these systems would still depend only on the moment of inertia and distance to the BCOM. Breniere and Do [5] calculated the half-period of such a pendulum and observed that the time varied between 1.01 and 1.1 s for 11 subjects of varying weights and heights. The results measured in this study are slightly lower than the values presented by Breniere and Do [5]. The time needed to complete the first step of initiation (APA + first swing duration) was measured in this study—approximately 0.88 s (55% of 1.6 s). Breniere and Do used a simple inverted pendulum model to calculate the half-period [5]. The addition of a rocker to such a model could account for the slight discrepancy in the first step duration while still maintaining the time invariance.

The data indicate that the beginning of forward acceleration seems to occur consistently and at approximately 0.59 s before first toe-off. The average acceleration duration seems to be approximately 1.6 s in duration regardless of the final steady-state speed. The beginning of the acceleration process seems to be a result of a forward fall. Previous research has indicated that the second step of initiation is more dynamic, with a significant "push" at the ankle and the hip [13]. Input of energy from the trailing leg during the second step of initiation appears to be necessary, since at first heel contact, the BCOM position is nearing a local minimum in its vertical trajectory. At this stage, the body has achieved approximately 70 percent of the steady-state forward velocity and additional energy is needed to transition the body into steady-state.

We observed invariance of the acceleration duration when measuring the time needed by transtibial amputee subjects to reach steady-state walking speeds. No differences were observed in the acceleration times between people without limb loss and subjects with UTT amputations, nor did a difference exist when the subjects with limb loss initiated gait with their prosthetic or anatomical leg (**Figure 3**). Since the prosthetic ankle in the transtibial amputee subjects is a passive element, invariance in the time needed to reach steady-state suggests that at least during the first step of initiation, the physiological ankle does not provide a significant "push."

Since the data indicate that steady-state velocity is achieved in a relatively invariant time interval, how are different walking velocities achieved? **Figure 4** indicates a nonlinear relationship between the magnitude of the peak mean acceleration and the desired steady-state walking speed. This peak acceleration seems to occur consistently around the time of the first heel-contact. Thus, the results suggest that higher walking velocities are achieved through higher acceleration magnitudes within approximately the same time interval. Higher acceleration magnitudes could be achieved through adjustments in the initial conditions during the APA phase, such as through ankle dorsiflexion and/or trunk lean.

The invariant time characteristic of gait initiation appears to carry over to the process of rapid gait termination. The time needed to reach a steady-state velocity during gait initiation and the time needed to come to a complete stop during rapid gait termination appear to be invariant to the steady-state walking speed and seem to occur in approximately 1.6 s. Further, the trend of peak deceleration with speed is similar to the trend of peak acceleration with speed. Both acceleration and deceleration peaks increase to reach or stop from higher steady-state walking speeds. In addition, all subjects terminated gait in approximately two steps, requiring approximately 1.6 s. Rapid gait termination appears to be achieved by an increase in the magnitude of the deceleration in an invariant time interval.

During gait initiation and termination, walkers use increasing peak acceleration/deceleration magnitudes to adjust to and from higher steady-state speeds. Also, these acceleration and deceleration durations do not change for subjects with UTT limb loss. Higher acceleration and deceleration magnitudes were associated with higher walking speeds. For gait initiation, the invariant time interval could be explained by the following process: during the first step, the initial conditions set at the ankle and through trunk lean dictate the magnitude and the speed of the passive-like forward fall; during the second step, additional forward momentum is generated by a push from the trailing leg; during rapid gait termination, adjustments in ND subjects appear to be made at the ankle, knee, and hip to control the termination duration. The anatomical and prosthetic feet both appear to absorb energy during this process [13].

The results indicate that gait initiation and rapid termination are achieved in approximately two steps, although the acceleration and deceleration time periods might be a more accurate way to define these transitional phases. The conclusion that steady-state walking speed is achieved in approximately two steps is in agreement with Jian et al. [8], but disagrees with other authors who have suggested that normal walking speed is achieved by the end of the first step [5] or in three steps [4,6]. One explanation for this discrepancy might be that during the second step of initiation, the kinematic and kinetic gait parameters look very similar to those seen during steady-state walking. Thus, if someone were to base his or her conclusion on kinematic or kinetic patterns, he or she could erroneously decide that by the beginning of the second step the body is already in steady state, even though the body is technically still accelerating. Further disagreement between this work and previously published papers can also be attributed to different methods of calculating and assessing the initiation period. Breniere and Do, for example, used ground reaction forces in their analysis to calculate BCOM acceleration [5], while the current work used a differentiation method. Although the force platform method is a more direct way to calculate the forward

acceleration, this method does not allow for the independent analysis of multiple steps because of the availability of only one force platform.

Using a different approach, Miller and Vestraete determined that steady state was attained in three steps using a mechanical energy analysis [6]. In their work, these authors calculated the total mechanical energy of each body segment by adding together the potential energy and the translational and rotational kinetic energies and concluded that steady state is achieved in three steps. They based this conclusion on the fact that the net mechanical work of the body over one stride is equal to zero at steady state. They concluded that in some cases the readjustment of energy in the third step is very small, and the steady state erroneously appeared to be attained only after two steps.

These results are significant, since an improved understanding of the temporal-spatial characteristics of gait initiation and termination can help us better recognize the strategies employed by people while accelerating and decelerating. Such knowledge can help in the design of better training methods for patients with various neurological disorders or patients with limb loss. In addition, since many gait analysis laboratories have limited space, knowing the number of steps needed to initiate and rapidly terminate gait is important for ensuring that the data capture volume is sufficient to record the desired gait events successfully.

CONCLUSIONS

The results of this study suggest that gait initiation and termination occur in a time interval of approximately 1.6 s, more or less invariant with steady-state walking speed. The transition to/from higher walking velocities are achieved by an increase in the magnitude of the acceleration/deceleration. Both processes are completed in approximately two steps.

ACKNOWLEDGMENTS

We would like to acknowledge the use of the Department of Veterans Affairs (VA) Chicago Motion Analysis Research Laboratory of the VA Chicago Health Care System, Lakeside Division, Chicago, Illinois. We would also like to thank Dr. Richard Weir for his help in developing the filtering algorithm for the mean BCOM accelerations. The opinions contained in this publication are those of the grantee and do not necessarily reflect those of the Department of Education.

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Submitted for publication March 29, 2004. Accepted in revised form September 7, 2004.