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Patterns of Foot-Floor Contact and Electromyography Activity during Termination of Human Gait

Prachuab VANITCHATCHAVAN

Advanced Computer Application and Design Research Group
Faculty of Information Technology
King Mongkut's Institute of Technology Ladkrabang
Ladkrabang, Bangkok 10520, THAILAND
Telephone: (66-2) 737-2551-4 Ext. 532 FAX: (66-2) 326-9074
E-Mail: prachuab@it.kmitl.ac.th

Abstract: This paper concerned with the patterns of foot-floor contact and electromyography activities of the lower extremity of the body during the termination of human gait. The termination of human gait is defined as the transition from a steady-state gait to a quiet standing posture. The transition between these two states has not been extensively studied and defined. There appears to be a critical period in the gait cycle that the decision to terminate gait or continue to take an additional step must be made.

1. Introduction

Rhythmic movements could theoretically be controlled either on a continuous volitional basis, or voluntarily initiated and then controlled on a more subconscious level. Many models have been proposed for the neural circuitry that generates rhythmic movements. However, very little work has been done to address the questions of how the termination of rhythmic movements occurred. Human walking is one of several models of rhythmic movements that must be terminated with accurate control to minimize the likelihood of a poorly controlled stop and possibility of a fall. The biomechanical and electromyographic activities during steady-state gait have been well described, and several variations of gait cycle diagrams have become standard in both scientific and clinical applications. Gait initiation and backward walking have also been studied.

The process of human walking is schematized in the state-diagram below. The transition from state 1 to state 2 is the initiation of gait, when a person starts to walk. State 2 is the steady-state gait, when a person is already walking steadily.

In all cases, a self-motivated or volitional movement starts at state 1 and moves to state 2 within approximately three steps [3] [6]. Then, when termination of that movement is desired, at some arbitrary future time, a transition from state 2 back to state 1 will occur (1 → 2 →... → 2 → 1). This transition from state 2 back to state 1 is the focus of this dissertation. The transition can be either volitional (selected by the subject) or requested through the use of a stop command. A stop command is the signal given to the subjects that requests them to stop walking. In the experiments, both types of gait termination were studied, but primary emphasis was on termination in response to a command.

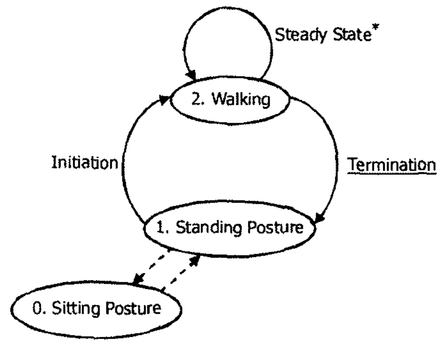

Figure 1. State Diagram for Human Gait

As shown in Figure 1, normal gait has two states and three transitions between them. The first two, initiation of gait [1] [2] [3] [6] and steady-state gait [3] [7] [10] have been thoroughly studied. It appears that termination of human gait has not been extensively studied. To complete the understanding of human gait, all sub processes and transitions between them must be well-defined and thoroughly understood. This dissertation hopes to fill the gap in our knowledge of the process of human walking by obtaining new information on the termination of human gait.

One definition describes human walking as "... a very perturbed and unstable movement. These perturbations result from the large gravitational and forward movement forces that act while the body is supported on one limb for 80 percent of the time. Such a combination is inherently unstable and requires complex control" [10]. For this reason, as stated in the definition, the process of walking requires a high degree of control by the central nervous system. Figure 2 shows a normal steady-state gait. It shows the overall movements, positions, and foot-floor contact of both feet with respect to time. Foot-floor contact is defined by four major events (LHC, LTO, RHC, and RTO). The normal pattern for any steady-state gait is LHC →RTO → RHC → LTO → LHC (observing starts from LHC). Foot movements are defined by the transitions of positions. The duration from a toe-off to a heel contact (either LTO → LHC or RTO →

RHC) is referred to as a swing phase. The duration from a heel contact to a toe-off is referred to as a stance phase. Also, when there is at least one part (either a toe, a heel, or both) of only one foot on the floor, that period will be called a single-support period. If both feet have at least one part on the floor at the same time, that particular instance is called a double-support period. Changes of the mentioned events from the normal values and/or patterns of a steady-state gait cycle are expected when a termination occurs.

2. Methods

A subject pool of 15 individuals participated in the experiments. A number of preliminary experiments were performed that are not included in this study. The range of ages for the research subjects was from 20 to 42 years with an average age of 29 years. All subjects were male in order to avoid sex related differences in gait. Also, to avoid complications, all subjects were in good health with no known neurologic or orthopedic problems. The subset of human subjects from the subject pool performed walking trials along a walkway. The protocol for these experiments can be described as follows: A subject was asked to walk on a specified walk way. This walk way was a straight path with the approximate length of 8.5 meters, in a well-lighted and unobstructed path on the laboratory floor. At the end of the walk way, there was a video camera to visually record the foot-floor contact. Also, an ultrasonic range measurement device was pointed toward the subject to keep track of the distance. This distance was later used during the data analysis to determine the subject's gait velocity. In each trial, a subject was given a signal to indicate that the data collection had begun. After being given a signal, the subject started walking at his own convenience. There were three types of trials in one experiment: normal walking, volitional stop, and a requested stop. The normal walk trials served as the normative values to construct the patterns of normal gait for that subject which was transformed into a template (of normal values). The requested stop trial was similar to a normal walk except at some point during the walking, an audible tone (which is referred to as a stop command) was given. The first protocol required the subject to stop walking with his feet symmetrical. The second protocol required the subject to stop walking as fast as possible regardless of the terminal foot position. The given stop command was synchronized with the left heel contact (which is referred to as the triggering LHC) with various delays. These delays were varied from 0 to approximately 640 ms. Normally, each trial (for requested stop trials) for each delay value was performed twice. The subject had four foot switches attached underneath heels and toes of both feet. The data collected in this part were four foot switches (to indicate the foot-floor contact), distance (to indicate the distance and to further calculate the gait velocity), and the stop command (to indicate when the stop command was given). The requested stop trials were performed twice. In the first part, the subject was instructed to stop walking with his feet symmetrical. This part is referred to as stop with feet symmetrical trials with the subject's terminal feet position as shown in Figure 3 (A). In the second part, the subject was to stop as soon as possible regardless of the position of his feet upon the stop command. This part is referred to as stop as fast as possible trials with the subject's terminal feet position (one possibility) as shown in Figure 3 (B). These two protocols were randomly selected at different trials and at different values of the delay of stop command to avoid subject's anticipation. In each set of experiments, each subject was instructed to performed 30 walking trials; six trials were normal 'steady-state' trials without any stop command, the remaining 24 were 'stop trials'. These 24 stop trials were equally divided into two stop protocols as described. The normal walking template for each subject was contructed from the six normal steady-state walking trials of that particular subject.

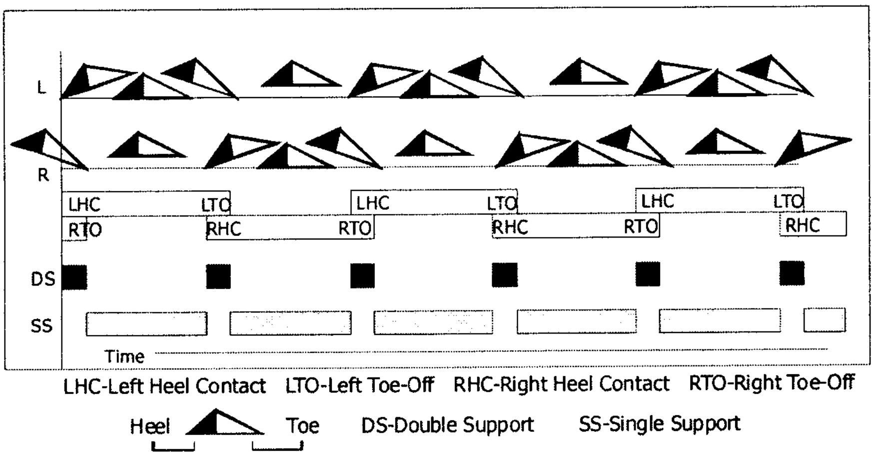

Figure 2. Steady-state gait.

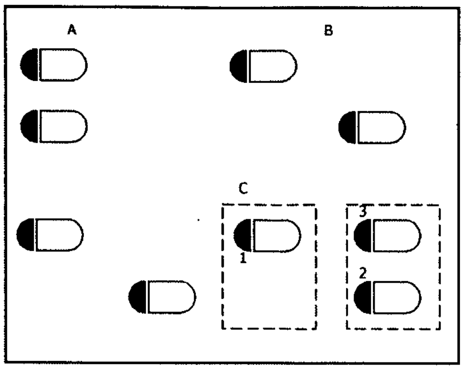

Figure 3. Subject's Foot Position

Another experiments for this study were performed in order to collect the data electromyography activities (EMG) of the muscle groups in the lower extremity of the subject's body during gait termination with the experiment protocols described above. Eight pairs of surface electrodes (four pairs on each leg) are attached on the subject's in order to collect the EMG signal from the following muscles: tibialis anterior (TA), gastrocnemius & soleus (GS), quadriceps (Q), and hamstrings (HS). The raw EMG signal was bandpass filtered (80 – 1,000 Hz), further amplified for a total gain of 2,000, full-wave rectified, and smoothed.

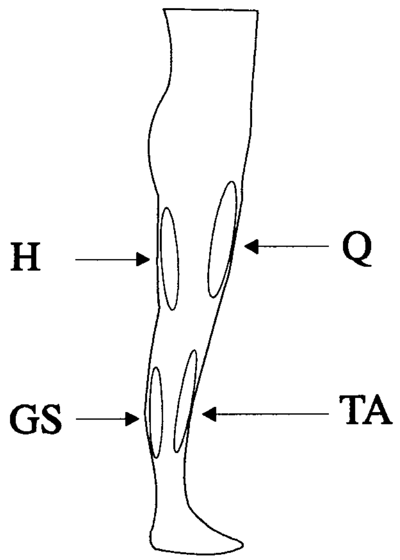

Figure 4. Electrode Placement Locations on Subject's Leg

Three types of experiments were conducted for each subject: normal walking, volitional stop, and requested stop. Normal walk trials were used to construct the subject's normative pattern templates. The requested stop trial was similar to a normal walk except, during the walking, an audible tone (a stop command) was issued at different phases in the gait cycle. The patterns of the collected EMG signal from the requested stop trials were analyzed with respect to the subject's normal templates.

3. Results

The time to terminate gait was defined as the interval between issuance of the stop command and subject's both feet in terminal contact with the floor. The gait termination time vs. delay of the stop command is shown in Figure 5. The data from both sets in Figure 5 shows that the gait termination time decreases as the delay on the issuance of the stop command was increased. However, there is an abrupt increase in gait termination time as the delay in the stop command approaches the threshold; approximately at 18% and 32% into the gait cycle for data set 1 (stop with feet symmetrical) and 2 (stop as soon as possible) respectively [8]. This results suggested that there are critical segments in the gait cycle during which a decision must be made in order to either continue or terminate the steady-state gait. Also, it is only in some segments within the gait cycle that a gait termination can be safely initiated to achieve the result that the gait cycle can be safely terminated.

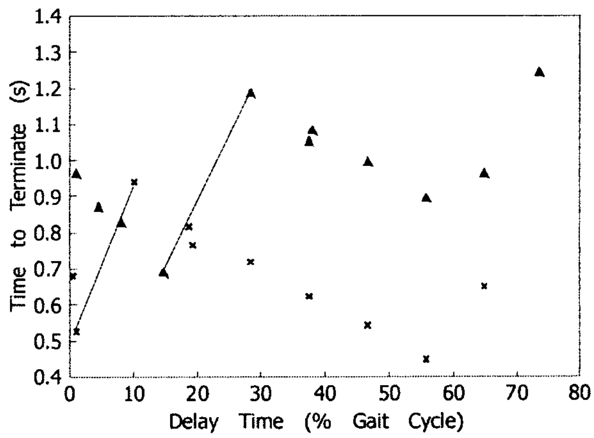

Figure 5. Gait termination time from one subject.

Figure 6 shows the typical EMG activities on the left leg. The EMG activities during the steady-state gait have the patterns similar to existing studies [5]. It is obvous that the EMG activities during gait termination depart from the normal patterns. Figure 7 illustrates the pattern composite activities of the foot-floor contact and EMG. During gait termination, the following deviations were observed:

1. A larger than normal hamstring activity burst which extended from the last stance phase into the terminal swing phase,
2. An early and unexpected burst in GS during the swing phase before the terminal stance followed by a reduced burst (in five of the seven subjects). The

3. An extended and reduced burst of TA in the terminal swing phase which may be related to holding the foot in the terminal position.

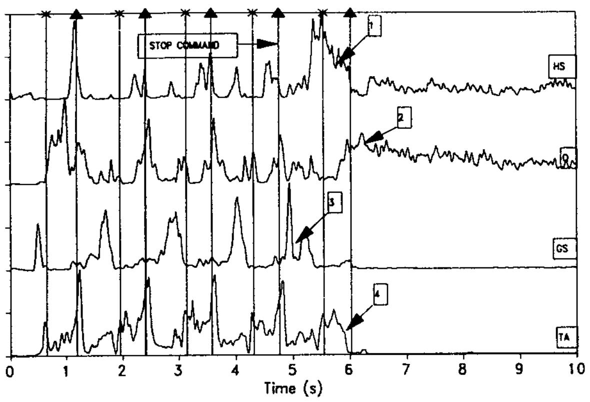

Figure 6. A typical EMG activity from the left leg.

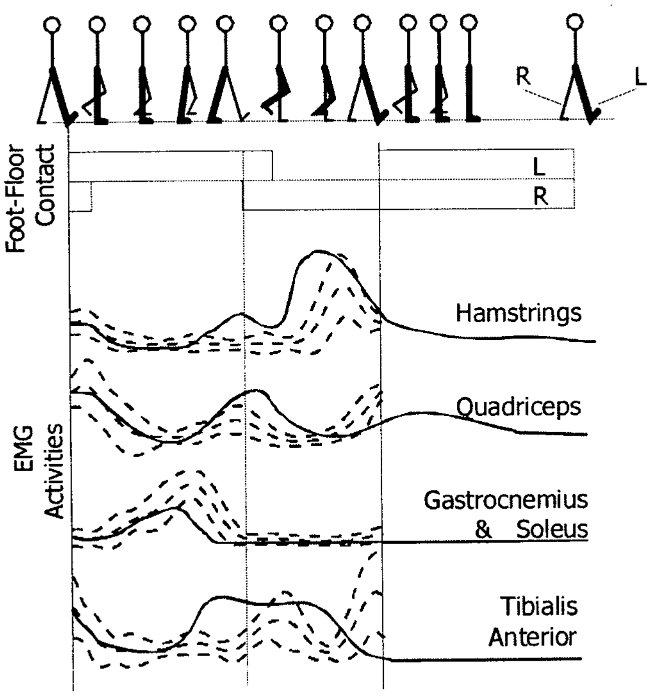

Figure 7. Composite activities during gait termination.

4. Discussion

This paper presents the extension of the previous studies on the foot-floor contact patterns [8] and ground reaction forces [4] [9] during the termination of human gait. The finding on the reduction of the shear force in pusing off in the last step seems to correlate with the activity reduction on the GS muscles. The deviation from the normal pattern continues on other muscles: hamstrings, quadriceps, and finally, tibialis anterior. As the delay in issuing the stop command increased, the same pattern of deviations occurred on the right side instead of the left side due to an additional step has been taken [8].

Understanding human gait termination is necessary in order to understand the whole process of human walking as well as leading to understand the role of hypothesized central pattern generator and afferent feedback in rhythmic movements. The understanding of the process of human walking may be applied to the programming of a human-like, legged robot also.

5. References

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