Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Termination of Human Gait

Prachuab Vanitchatchavan
Section Information Technology, Graduate School
Dhurakij Pundit University
Bangkok, THAILAND
E-mail: prachuab@it.dpu.ac.th

***Abstract*— This study presents a detailed description of the events that take place during termination of human gait. This study was concerned with the patterns of foot-floor contact, ground reaction forces (Fy and Fz), electromyography (EMG) activities of the four gait related muscle groups, and joint angles of the lower extremity of the body (hip, knee, and ankle angle) 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 been neither extensively studied nor defined. Two mechanisms appear to be involved in termination: reduction of push-off forces in the last push-off and increased braking forces in the first foot to reach terminal foot placement. There appears to be a critical region of the gait cycle where a decision is made to take another step or to stop. Poorly controlled stops were observed in some experiments, and the results could be interpreted to suggest that attempting to terminate gait within this region may result in a higher probability of a fall.**

***Keywords*—Gait Termination, Rhythmic Movement, Human Motor Control**

I. Introduction

Rhythmic movements, such as human gait, 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 electromyography 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.

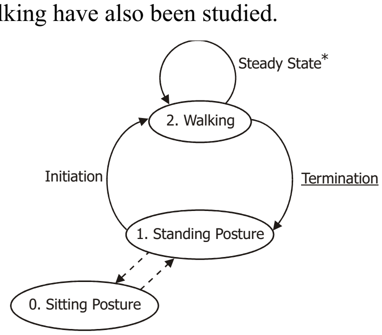

Figure 1. State Diagram for Human Gait

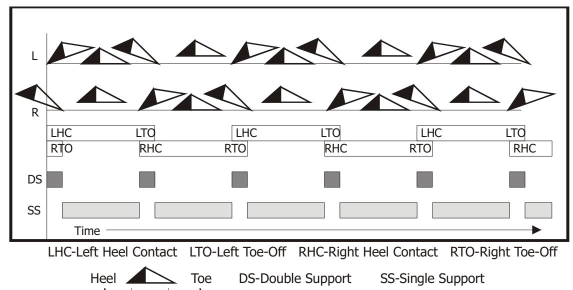

Figure 2. Steady-state gait.

The process of human walking is schematized in the state-diagram shown in Figure 1. 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 (Mann et al., 1979; Hirokawa 1989). 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 study. 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. The purposes of this study are to develop definitions of a quantitative description of the termination of normal gait and to investigate situations that might lead to a poorly controlled stop. When people stop walking (terminating a steady-state, normal gait), they may or may not stop smoothly. Any gait termination with a considerable amount of inconvenience or extra movement is called a poorly controlled stop.

As shown in Figure 1, normal gait has two states and three transitions between them. The first two, initiation of gait (Carlsoo, 1965; Herman et al., 1973; Mann et al., 1979; Hirokawa, 1989) and steady-state gait (Murray et al., 1964; Winter 1979, 1983; Hirokawa, 1989) 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.

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" (Winter, 1983). 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) as shown in Figure 2. Foot movements are defined by the transitions of positions. Changes of the mentioned events from the normal values and/or patterns of a steady-state gait cycle are expected when a termination occurs.

II. METHODS

A subject pool 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 neurological or orthopedic problems. The protocol for these experiments can be described as follows: A subject was asked to walk on a specified walkway. This walkway 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 walkway, there was a video camera to visually record the foot-floor contact. 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 perform 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 constructed from the six normal steady-state walking trials of that particular subject.

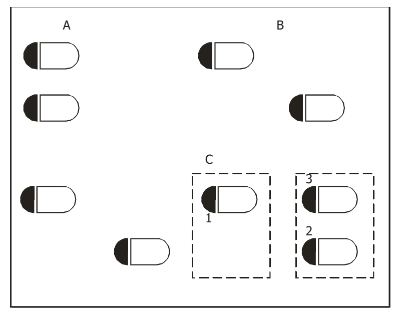

Figure 3. Subject's Foot Position.

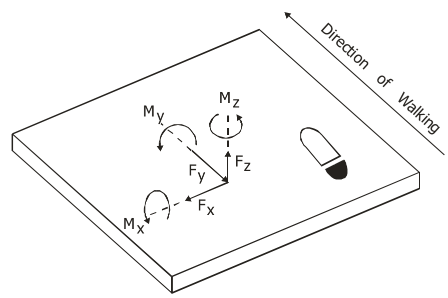

Figure 4. Biomechanics Platform.

There are four sets of experiments performed on the subjects to monitor the various activities of the lower extremity of the subjects' body. These experiments are:

- Foot-switch experiment which collects the foot-floor contact patterns,
- Ground reaction forces experiment which collects F_y (antero-posterior shear forces) and F_z (vertical forces),
- Joint-angle experiment which measures the joint angles on each of the subject's leg at hip, knee, and ankle, and

Electromyography experiment which measures the EMG activities on the following muscles: tibialis anterior (TA), gastrocnemius & soleus (GS), quadriceps (Q), and hamstrings (HS) as illustrated in Figure 13.

III. 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. Table 1 summarizes the gait termination time from all subjects. 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 (Vanitchatchavan, 2000). The hypothesis for gait termination time is shown in Figure 6. These 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.

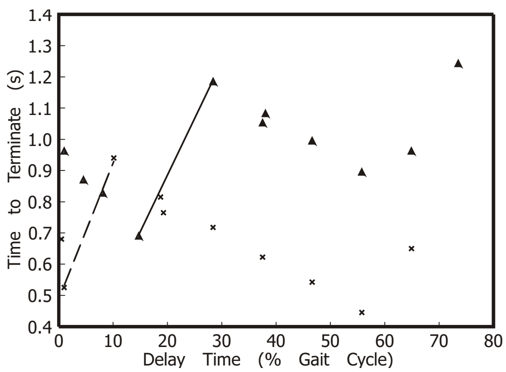

Figure 5. Gait termination time from one subject.

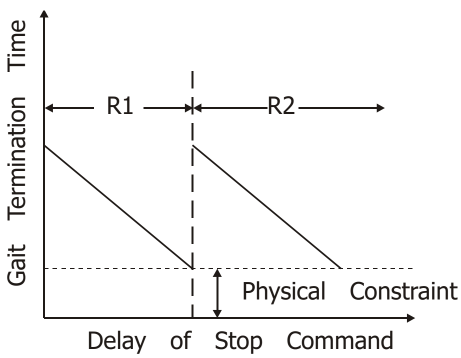

Figure 6. Gait termination time hypothesis.

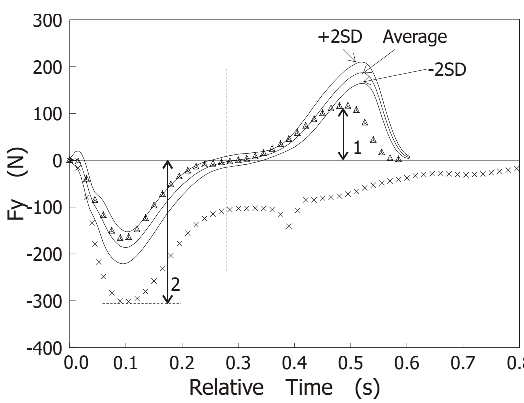

Figure 7. Patterns of F_y ground reaction force components.

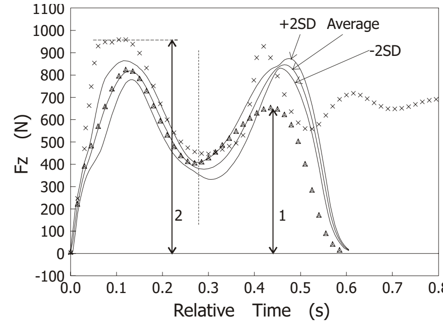

Figure 8. Patterns of F_z ground reaction force components.

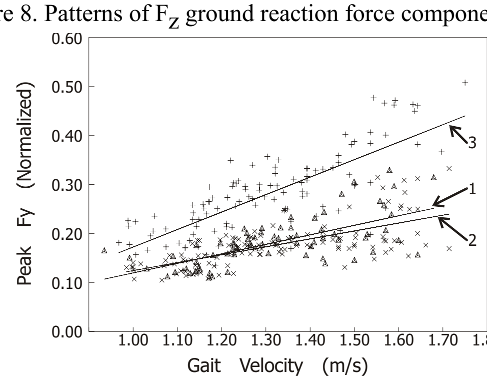

Figure 9. Results of peak F_y from all subjects during the first part of stance phase vs. gait velocity; (Δ) steady-state gait (line 1), (×) gait termination measured at position 1 in Fig. 3C (line 2), and (+) measured at position (2 and 3) in Fig. 3C (line 3). Note that no significant difference on regression line 1 and 2. The regression line 3 denotes the increased braking force component of the ground reaction vector along the direction of walking.

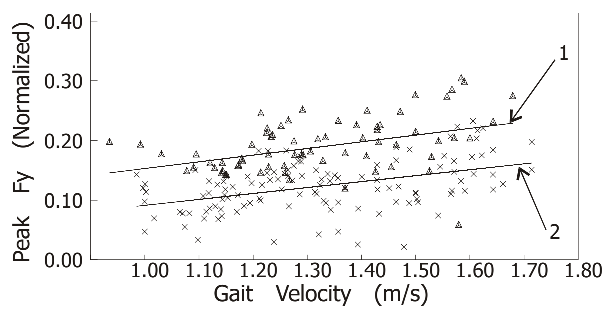

Figure 10. Results of peak F_y from all subjects during the second part of stance phase vs. gait velocity; (Δ) steady-state gait (line 1), (×) gait termination measured at position 1 in Fig. 3C (line 2). The regression line 2 denotes the reduced push-off component of the ground reaction vector.

The ground reaction forces during steady-state gait have been well described. Figures 7 and 8 show peak antero-posterior shear and vertical forces for three cases (typical, single stop trial data, and averaged template from five steady-state trials).These data are consistent with previous studies (Inman et al., 1981; Andriacchi et al., 1977). The most important observation from the gait termination data is the reduced push-off measured at position 1 in Figure 3C (Jaeger, 1992). Figures 9 and 10 illustrate the peak components of F_y, which were normalized to the subject's body weight, for the first and second part of the stance phase. F_z also exhibits the same behavior. Figure 14 illustrates the findings from the EMG experiments.

The results from the joint-angle experiment can be summarized in the Figures 15 and 16. The departure time that marked the deviation from the normal template of the left ankle of one subject as the delay in stop command was increased. The ranking departure times from the normal template, the joint angles at hip and ankle exhibited the departure time from the normal template before the joint angle at knee. This similarity in abrupt increase of the departure times of the joint angles supports the hypothesis set up from the finding of the foot-floor contact patterns described earlier.

The data represented in Figure 17 are the combination of the results from each experiment. The following events are observed in Figure 17:

- a reduction in the push-off of the plantaflexors (GS), denoted by ❶, leads to a lower F_y and F_z at push-off, denoted by ①.
- an increase activity in quadriceps, denoted by ❷, and an increase in F_y and F_z, denoted by ②, are needed for body stabilization at the last heel contact.
- an increase activity in hamstrings, denoted by ③, may function as hip extensors to prevent the trunk from an excessive swaying and falling forward.
- an increase activity in TA, denoted by ❹, is not clear in why it happens. Although there are no dorsiflexion of the ankle (at ④), this increase activity exists.

IV. Discussion

The results from foot-floor contact pattern experiments showed that the stop time decreased as the delay of the stop command increased. This phenomenon continued until the delay of the stop command reached its lowest value for a given subject. At that point, the stop time increased abruptly (refer to Figure 5). Then, the stop time continued to decrease again until the delay of the stop command entered the next gait cycle. This tendency appears to be cyclic.

This phenomenon suggests that there is a critical region (or segment) in the gait cycle in which the decision either to continue walking or terminate each gait cycle must be made. If the time passes beyond this critical region, that gait cycle may not or cannot be safely or normally terminated. The instructions (protocols) on how to terminate gait also have the impact on both the time to terminate gait and where the critical region will be in the gait cycle (refer to Figure 5 and Table 1).

If an attempt to terminate gait has been made at or within the vicinity of the critical region, an unsmoothed, or even a poorly controlled, stop may result. The unsmoothed or poorly controlled stop can be described as or the combination of the following: an out-of-sequence pattern of foot-floor contact, heels and/or toes popping up and down, an excessive body sway, unusual arm movements, or even stumbling.

There appears to be no significant changes in the swing and stance phase of the step prior to the last step.

The results from the ground reaction force experiments showed that there were significant reductions in forces (both F_y and F_z) during the push-off. These reductions occurred during the second half of the stance phase in the step prior to the last step (refer to Figures 11 and 12). There were also significant increase in both F_y and F_z during the first half of the stance phase of the last step.

These findings suggest that at least two mechanisms are employed during the gait termination.

1) Reduction of the push-off during the second half of the stance phase of the step before the last step; and
2) Increase of the braking force at the step of the terminal foot placement.

These two events occur very close in time. Inability to employ both of these mechanisms may lead to a poorly controlled stop, or make it imperative that an additional step be taken.

Experiments in which EMG and joint angles were studied are consistent with the findings from the foot-floor contact pattern experiments. The results represent the same trends in the way that the stop time decreases until the delay of the stop command reaches the break value. After the abrupt increase, the stop time continues to decline in the same manner of the results from the foot-floor contact pattern experiments. The instructions to stop given to the subjects prior to the experiments (stop with feet symmetrical or stop as fast as possible) also have the impact on how long it will take to terminate gait.

There are still unanswered questions and gaps in knowledge left for expansion and extensions as future research beyond these findings. Some of these topics are as follows:

- Correlation of all events, foot-floor contact patterns, ground reaction forces, EMG, and joint angles, in more detail and precise sequences chronologically.
- Construction of biomechanical models in order to compute joints moments for comparison the EMG events.
- Exploring in the area of neural circuit oscillators, its engagement and disengagement.

There are many potential clinical applications of more detailed studies of gait termination in patient populations. Falls continue to be a problem in the elderly. While the causes of falls are many, one potential time when falls might be considered likely is at the transition between steady-state gait and standing. Many studies examine the effects of various pharmacological agents have focused on transient reflex behavior. Termination of gait (particularly the EMG patterns) may be a fruitful paradigm for assessing drug effects on a critical time in the operation of neural oscillators or pattern generators. Termination of gait may also have applications in the programming of legged vehicles.

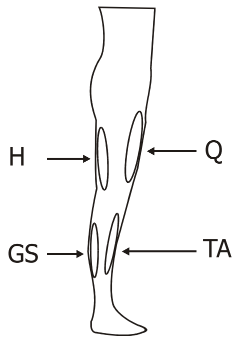

Figure 13. Positions of EMG Electrodes.

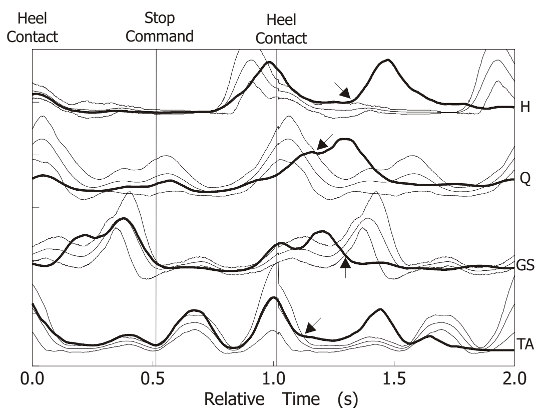

Figure 14. Findings from EMG Experiments.

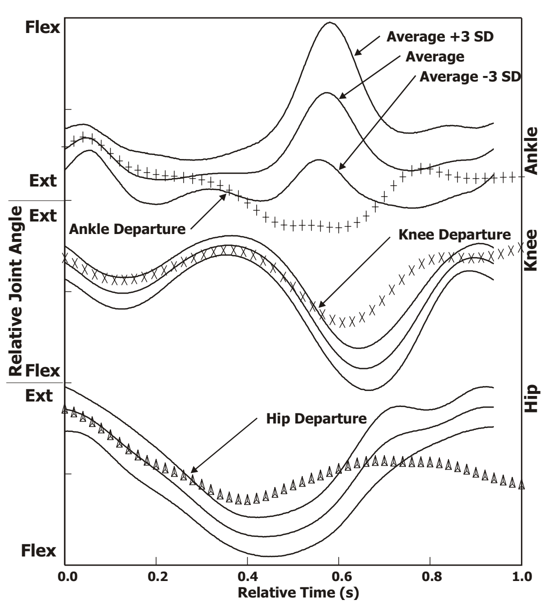

Figure 15. Typical Joint Angle Patterns during Termination of Human Gait.

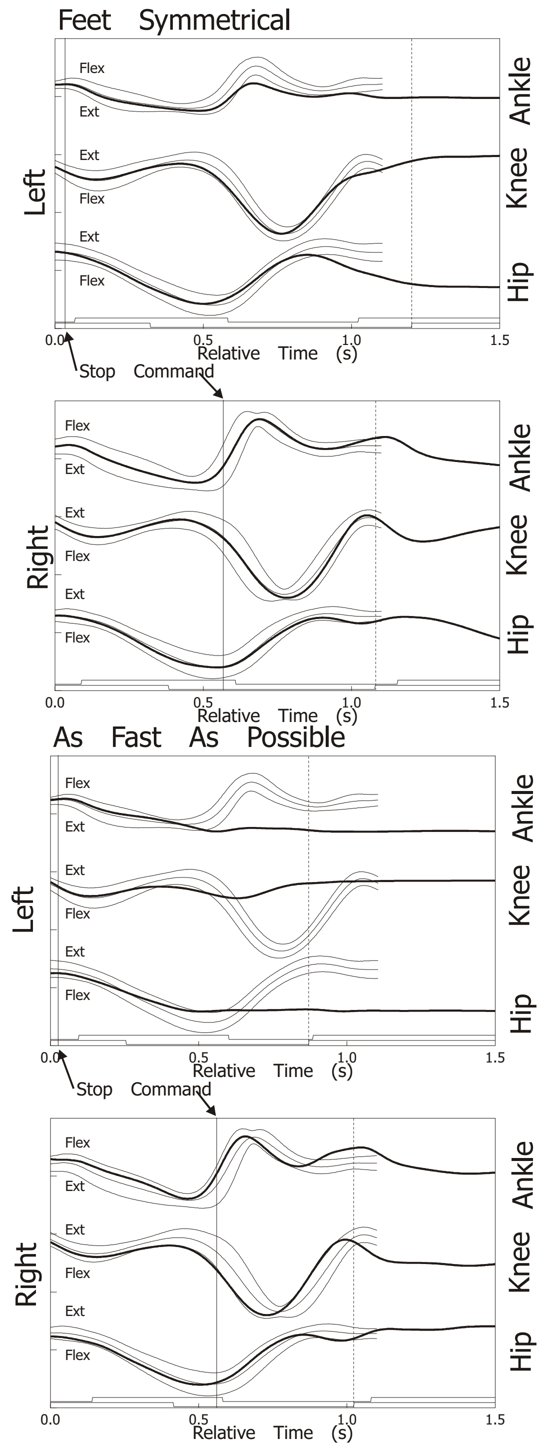

Figure 16. Joint Angle Patterns during Termination of Human Gait from one subject.

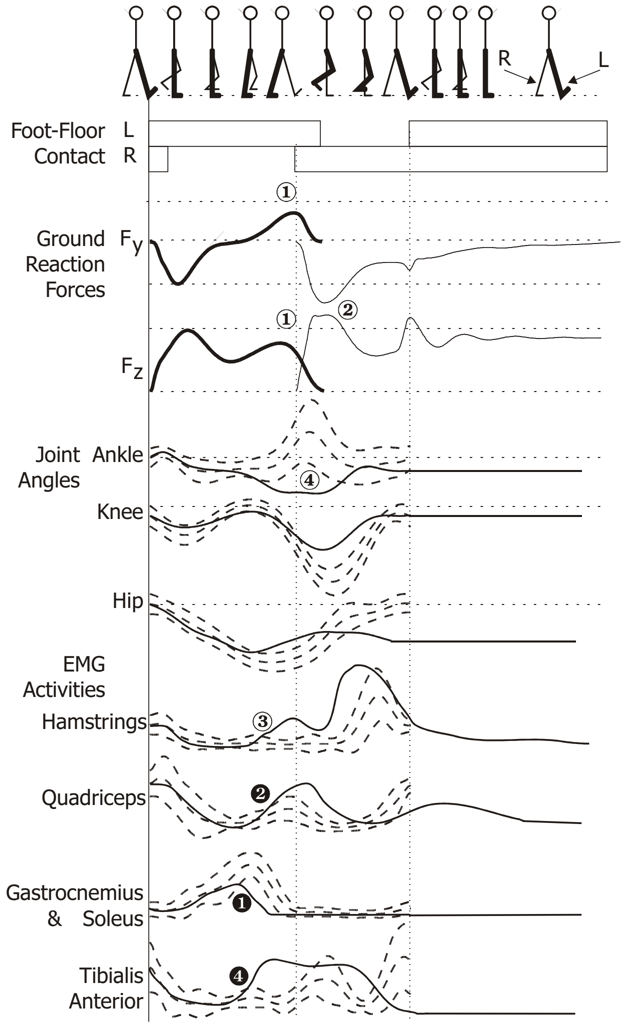

Figure 17. Composite View of the Events during Termination of Human Gait.

Table 1. Summary of Time "Break" Occurred and Time Offset

Subject #	Break Occur at (% Gait Cycle) Stop with Feet Symmetrical	Stop As Fast As Possible	Time Offset (s)
1	24	5	0.401
2	33	25	0.531
3	32	7	0.490
4	40	15	0.191
5	40	22	0.275
6	40	24	0.394
7	30	15	0.663
8	40	15	0.663
9	30	40	0.956
10	15	- -	- -
Average	32.40	18.67	0.507

REFERENCES

[1] Andriacchi, T. P., Ogle, J. A., and Galante, J. O., "Walking Speed as a Basis for Normal and Abnormal Gait Measurements," *Journal of Biomechanics*, 1977,Vol. 10, pp. 261-268.

[2] Carlsoo, S., "The Initiation of Walking," *Acta Anat*, 1965,Vol. 65, pp. 1-9.

[3] Herman, R., Cook, T., Cozzens, B., and Freedman, W., "Control of Postural Reactions in Man: The Initiation of Gait. Stein, R. B., Pearson, K. G., Smith, R. S., and Redford, J. B. (eds) Control of Posture and Locomotion," Plenum, New York, 1973, pp. 363-388.

[4] Hirokawa, S., "Normal Gait Characteristics under Temporal and Distance Constraints," *Journal of Biomedical Engineering*, 1989, Vol. 11, pp. 449-456.

[5] Jaeger, R. J. and Vanitchatchavan, P., "Ground Reaction Forces during Termination of Human Gait," *Journal of Biomechanics*, 1992, Vol. 25, pp. 1233-1236.

[6] Mann, R. A., Hagy, J. L., White, V., and Liddell, D., "The Initiation of Gait," *Journal of Bone and Joint Surgery [American]*, 1979, Vol. 61, pp. 232-239.

[7] Vanitchatchavan, P., "Patterns of Foot-Floor Contact and Electromyography Activity during Termination of Human Gait," Proceedings of 2000 International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC2000), Pusan, Korea, pp. 923-926, 2000.

[8] Vanitchatchavan, P., "Patterns of Joint Angles during Termination of Human Gait," Proceedings, 2000 IEEE International Conference on Systems, Man & Cybernetics, Nashville, Tennessee, pp. 1226-1230, 2000.

[9] Vititayanon, K., Vanitchatchavan, P., Dejhan, K. "Patterns of Ground Reaction Forces and Joint Angles during Termination of Human Gait," Proceedings of 2001 International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC2001), Tokushima, Japan, pp. 1272-1275, 2001.

[10] Winter, D. A., "Biomechanical Motor Patterns in Normal Walking," *Journal of Motor Behavior*, 1983, Vol. 4, pp. 302-310.