The Interlimb Coordination During Movement Initiation From a Quiet Stance: Manipulation of Swing Limb Kinetics and Kinematics. A Preliminary Study

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Abstract

The purpose of the current experiment was to describe interlimb coordination when swing limb conditions are being manipulated by constraining step length or by adding a 5 or 10 pound weight to the swing limb distally. Subjects were asked to begin walking with the right limb to land on the primary target (normal step length) that is 10 ㎝ in diameter. However, if, during movement, the light was illuminated, then the subject had to step on one of the secondary targets (long and short step length). These three step length conditions were repeated while wearing a 5 pound ankle weight and then when wearing a 10 pound ankle weight. Ground reaction force (GRF) data indicated that there were changes in the forces and slopes of the swing and stance Fx GRFs. Long stepping subjects had to increase the propulsive force required to increase step length. Consequently, swing and stance toe-off greatly increased in the long step length condition. Short step length subjects had to adequately adjust step length, which decreased the speed of gait initiation. Loading the swing limb decreased the force and slope of the swing limb. Swing and stance toe-off was longest for the long step length condition, but there was a small difference of temporal events between no weight and weight condition. It appears that subjects modulated GRFs and temporal events differently to achieve the peak acceleration force of the swing and stance limb in response to different tasks. The findings from the current study provide preliminary data, which can be used to further investigate how we modulate forces during voluntary movement from a quiet stance. This information may be important if we are to use this or a similar task to evaluate gait patterns of the elderly and patient populations.

Key Words: Gait initiation; Ground reaction foces; Stepping; Temporal events.

Introduction

Gait initiation (GI) refers to the phase between quiet stance and steady state locomotion. It is also known as the interval between a start signal and toe-off of stance limb. This feature of human locomotion has received greater attention in the last decade. Studying GI provides an opportunity to identify and diagnose many disabilities in the locomotor system including some of those that are not recognized in level walking (Brunt et al, 1999; Breniere and Do, 1991; Nissan and Whittle, 1990). GI has been studied by measuring muscle activity (electromyogram, EMG), ground reaction forces (GRFs), and body motion recordings (Elble et al, 1994; Nissan and Whittle, 1990). The results indicate a stereotyped sequence of muscle activities and postural shifts that culminate in a forward step that begins with a shortening of the stance limb, caused by knee flexion, that is accompanied by a trunk shift to the swing limb. The increased forces on the swing limb acts to move the center of mass (COM) over the stance limb, enabling the swing limb to be lifted from the ground without loosing balance (Elble

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et al, 1994; Breniere and Do, 1991; Nissan and Whittle, 1990). The center of pressure (COP) initially moves posteriorly and laterally toward the swing limb and then laterally toward the stance limb as the swing limb leaves the ground. As a result, the COM invariably moves anteriorly and toward the stance limb. COM and COP move in opposite directions during the rapidly changing events of GI.

EMG data has shown that the muscles of the lower extremities are activated and create movements of force around the ankle and hip that rotate the body like an inverted pendulum. EMG data also has shown that the gastrocnemius-soleus (GS) complex is tonically active during a quiet stance. GI begins with inhibition of activity of the triceps surae and activation of the tibialis anterior (TA) bilaterally. The GS complex of the swing limb increases in activity after the TA activation.

Few studies have attempted to identify the underlying programmed parameters of GI and their timing as well as the function of each limb, and the coordination between them during locomotion. Brunt et al (1991) investigated the timing of selected parameters such as the onset of forces, EMG, toe-off and heel strike of swing and stance limb. They also examined the relationship between the stance limb and the swing limb by varying the speed of GI. The swing limb was found to provide the force for weight transfer during the initial component of GI. The stance limb was found to be primarily responsible for generating momentum to achieve steady-state gait. Weight shift to the stance limb preceded rapid acceleration of the center of gravity. The events before swing toe-off were not directly responsible for progression velocity at the end of the first step. It has been shown that the relative timing of selected parameters did not significantly change when manipulating the speed of GI (Brunt et al, 1991). This was interpreted as proof that GI is centrally programmed. The earlier that swing toe-off occurs, the faster the intended velocity of GI. A 98% correlation was found between time to swing heel strike and stance toe-off indicating there is a precise timing of the double support period to maintain balance at the end of the first step. This showed that there is evidence of a program of interlimb coordination where the relative duration of phases of stance and swing remain invariant (Brunt et al, 1991).

Brunt et al (1999) investigated TA and soleus (Sol) EMG as well as GRFs for the stance limb. They compared normal GI, stepping over a ruler, and stepping over a 10 ㎝ high obstacle and looked at self paced and an 'as fast as possible' speed of gait. Changing the kinematics of the swing limb did not make a difference in EMG (Brunt et al, 1999). This concept was confirmed by Crenna and Frigo (1991).

While EMG patterns have been studied extensively during GI, not a lot of work has been done investigating GRFs during GI. Brunt et al (1999) found the first peak in anterior-posterior (Fx1) GRF for the stance limb to be similar in the different stepping conditions at the self paced speed. However, peak Fx1 increased with the fast speed condition. The second peak in anterior-posterior (Fx2) GRF of the stance limb was less for GI as compared to stepping over a ruler or obstacle. Slope to Fx2 was greater for stepping conditions compared to GI. Stance and swing time decreased with faster speed, but increased when clearing an obstacle. A decrease in stance time was the result of decreased time from stance heel-off to stance toe-off. During the propulsion phase (heel-off of stance limb to toe-off of stance limb) peak Fx2 and the slope to Fx2 were greater for the fast speed condition. The time from stance heel-off to peak Fx2 remained invariant between conditions as compared to the control phase (from start signal to stance heel-off) where the slope stayed the same and the time to peak force varied. Brunt et al (1999) found that to clear an obstacle, more force was required to raise the swing limb. Therefore, the slope had to increase. These findings indicated that there is a precise interlimb coordination.

Breniere and Do (1991) imposed three different step lengths on GI and found that the duration of the movement from the onset of dynamic phenomena to the end of the first step did not vary, regardless of step length differences. They stated that the time taken to reach steady-state walking depended only on the subjects' mass and inertial properties and the position of his or her center of gravity in relation to the ground.

The purpose of the current experiment was to further describe interlimb coordination when swing limb conditions were being manipulated by constraining step length or by adding a 5 or 10 pound weight to the swing limb distally.

Methods

Subjects

This study sample consisted of 2 young adults (mean age: 26 yrs) with no known neurological or orthopedic deficits. Each subject signed an informed consent form approved by the University Institutional Review Board prior to participation.

Instruments

Two force platforms[1)] embedded in a level walkway were used to measure GRFs. Electrical foot switches[2)] were placed in the shoes to measure toe-off of the swing and stance limb. Force platform signals were sampled on-line at a rate of 1000 ㎐ for 5 seconds[3)]. AcqKnowledge software was used to analyze GRF data.

Procedures

The experimental setup is shown in Figure 1. Subjects stood in a predetermined position with each foot on a force platform. Subjects were asked to begin walking at a self-paced speed to a visual cue. Prior to experimental trials the average position of the swing limb heel-strike was determined for each subject through video analysis.

For experimental trials two secondary targets, 10 ㎝ in diameter, were placed on the ground to dictate the position and accuracy of swing limb heel-strike. A small red light emitting diodes was set in the center of each target. These lights dictated when and where to initiate movement. The positions of the two secondary targets were determined through the coordinate system. If, for example, the initial position for each subject is coordinate (0, 0) and the step length is 'radius', the position for long step length condition is coordinate (0, 2 × radius) and (0, 1/2 × radius) for short step length condition. Subjects were asked to begin walking with the right limb landing on the primary target. However, if, during movement, the light was illuminated, then the subject had to step on one of the secondary targets. Subjects completed practice trials and 10 successful experimental trials in each of the following conditions:

1) Step on the primary target (normal step length).
2) Step on the secondary target upon the redirection by the visual cue (short step length).
3) Step on the secondary target upon the redirection by the visual cue (long step length).

These three step length conditions were repeated while wearing a 5 pound ankle weight and then when wearing a 10 pound ankle weight. Second and third conditions were presented in random order.

Data Analysis

Dependent variables included the slope and peak acceleration GRFs of swing and stance limbs and swing and stance toe-off. Changes in the slopes and peak acceleration forces (Fx) were determined following the light signal. Swing and stance toe-off were also determined and were referenced to the first detectable onset of force platform. Means and standard deviations (SD) were used to compare the different conditions.

1) Advanced Mechanical Technology, Inc, Newton, MASS.
2) B & L Engineering, Los Angeles, CA.
3) BIOPAC Systems, Goleta, CA.

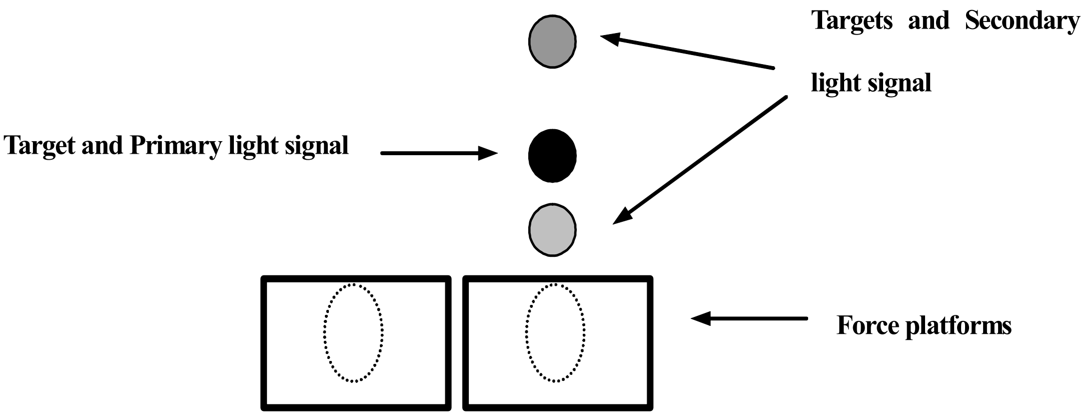

Figure 1. Experimental setup.

Results

Ground reaction forces

Mean data for the ground reaction forces is shown in Table 1. Values were greatest for the long step length condition and smallest for the short step length conditions regardless of weight conditions for both peak swing Fx and slope to peak swing Fx. Less force and slope was recorded for both peak swing Fx and slope to peak swing Fx as weight was added (Figure 2) (Figure 3). As can be seen from Table 1 the stance peak Fx1 and the slope to stance peak Fx1 were greatest for the long step length conditions and smallest for the short step length conditions regardless of weight conditions (Figure 4) (Figure 5). There were no clear changes in the force and the slope with weight except for the short step length condition. The slope to stance peak Fx1 increased as more weight was added to the swing limb in the short step length condition (Figure 5). For the stance peak Fx2 the long step length condition was greatest and the short step length condition was smallest (Figure 6). It appeared that weight didn't make a difference in the stance peak Fx2.

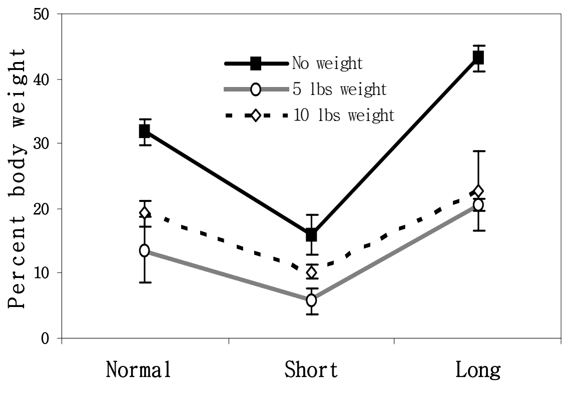

Figure 2. Mean (and standard deviation) peak swing Fx of ground reaction force for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

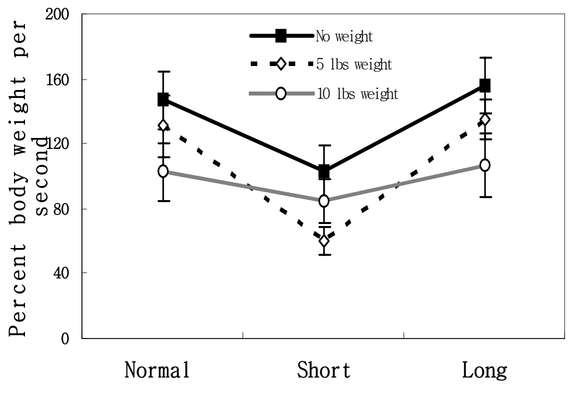

Figure 3. Mean (and standard deviation) slope to peak swing Fx of ground reaction force for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

Table 1. Means (and standard deviations) for peak (%BW) and slope (%BW/S) for force plate. Normal: normal step length, Short: short step length, Long: long step length

	No weight			5 lbs weight			10 lbs weight		
Variables	Normal	Short	Long	Normal	Short	Long	Normal	Short	Long
SW Peak Fx	31.8(3)[a]	15.9(3)	43.2(2)	13.6(2)	5.7(1)	20.5(6)	19.3(5)	10.2(2)	22.7(1)
Slope SW Fx	147(18)	103(16)	156(17)	131(19)	60(8)	135(12)	103(18)	85(13)	107(20)
ST Peak Fx1	61.2(2)	43.2(3)	79.5(5)	63.6(3)	45.5(3)	75(3)	70.5(2)	46.6(2)	71.6(6)
Slope ST Fx1	299(23)	150(27)	361(31)	263(29)	178(22)	325(42)	299(27)	196(16)	310(45)
ST Peak Fx2	90.9(3)	56.8(5)	141(5)	91(5)	51.1(5)	132(2)	83(3)	56.8(3)	134(3)

[a]Mean (SD).

Table 2. Means (and standard deviations) for temporal events (ms). Normal: normal step length, Short: short step length, Long: long step length

	No weight			5 lbs weight			10 lbs weight		
Variables	Normal	Short	Long	Normal	Short	Long	Normal	Short	Long
SW toe-off	447(17)[a]	494(20)	520(30)	477(35)	503(43)	511(17)	494(34)	512(17)	546(48)
ST toe-off	1048(31)	1108(20)	1111(34)	1090(34)	1142(51)	1159(17)	1117(43)	1176(17)	1210(51)

[a]Mean (SD).

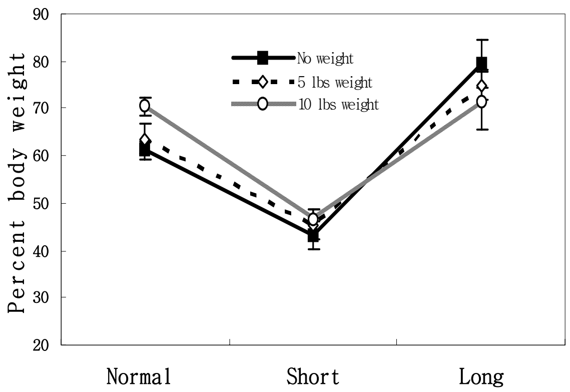

Figure 4. Mean (and standard deviation) peak stance Fx1 of ground reaction force for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

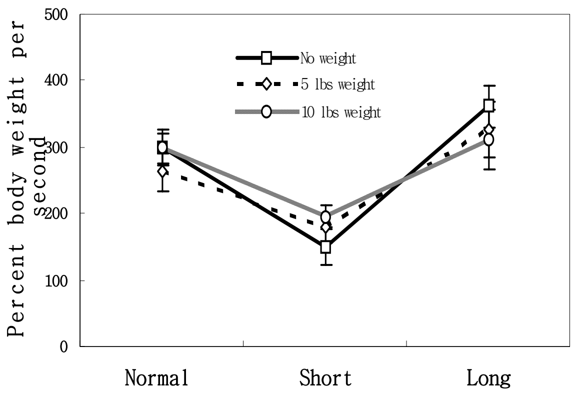

Figure 5. Mean (and standard deviation) slope to peak stance Fx1 of ground reaction force for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

Temporal events

Mean data for the temporal events is shown in Table 2. Swing toe-off was longest for the long step length condition and shortest for the normal step length condition (Figure 7). It appeared that time to swing toe-off took longer as more weight was added to the swing limb. For stance toe-off the long step length condition was longest, but normal step length condition was shortest (Figure 8). Stance toe-off increased as more weight was added to the swing limb. A 10 lbs weight condition showed the longest stance toe-off followed by a 5 lbs weight condition.

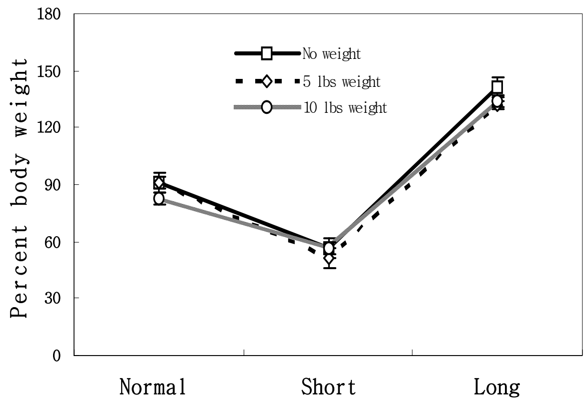

Figure 6. Mean (and standard deviation) peak stance Fx2 of ground reaction force for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

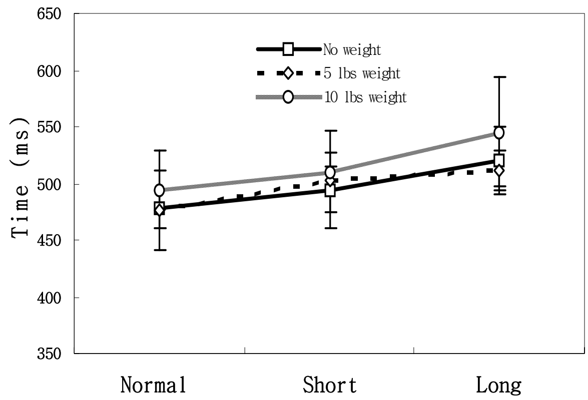

Figure 7. Mean (and standard deviation) swing toe-off for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

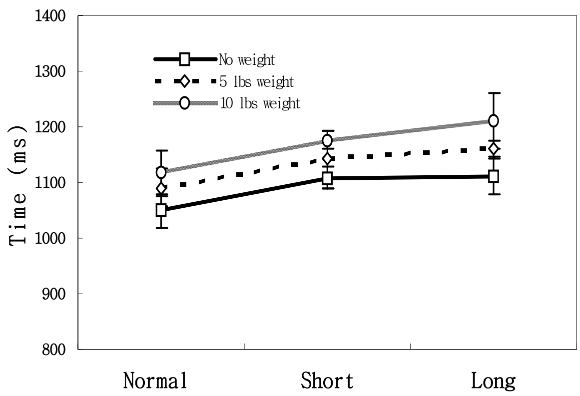

Figure 8. Mean (and standard deviation) stance toe-off for normal, short, and long step length conditions with no weight, 5 lbs weight, and 10 lbs weight.

Discussion

Recent studies have investigated both the programming of GI and stepping over an obstacle, and how the stance limb interacts with swing limb heel-strike (Brunt et al, 1999; Brunt et al, 2000). These recent investigations of movement initiation from a quiet stance have allowed further insight into how such tasks are organized with respect to EMG and force profiles and how the stance and swing limbs are coordinated.

In the present study, responses from an unexpected change of step length or adding weight to the swing limb while initiating movement from a quiet stance in healthy young adults were investigated by examining ground reaction forces. GRF data indicated that there were changes in the forces and slopes of the swing and stance Fx. Long stepping subjects had to increase the propulsive force (Fx2) required to increase step length. Consequently, the swing and stance toe-off greatly increased for the long step length condition. In a short step length subjects had to adequately adjust step length, which decreased the speed of GI.

Previous studies (Brunt et al, 1999; Brunt et al, 2000) have shown that the acceleration forces (Fx) of the swing limb determine the intended velocity of GI. This acceleration force increases with faster speed or decreases when subjects are constrained by the accuracy of the swing limb heel-strike. The short step length and adding weight clearly decreased the speed of GI. This decrease was a result of the modulation of both the stance and the swing limb GRFs. This decrease in force and slope was approximately 38% and 35% respectively when compared to a normal step length condition. Swing toe-off marks the first significant event that for the normal step length condition occurred approximately 20.4 ㎳ earlier than the short step length conditions. A subject, therefore, successfully decreased the step length with less acceleration force over a longer period of time. Undoubtedly, the combination of these differences led to a decrease in movement initiation speed in the short step length condition compared to the normal step length condition.

The acceleration force of stance Fx1 is related to the rate of swing limb toe-off. In the present study stance limb peak Fx1 for the short step length condition was 20% BW less than the normal step length condition. This decrease in the stance peak Fx1 paralleled an increase in the time to swing limb toe-off and therefore an increase in time preparation for toe-clearance.

In order to increase step length a subject must generate a response with sufficient force. The lengthening of the step length is mainly achieved by applying a larger acceleration force. The long step length condition showed clear changes in swing and stance Fx GRFs and temporal events. In long stepping this acceleration force increases with faster speed by increasing push-off which facilitates hip flexion. Swing limb acceleration force (Fx) and stance peak Fx1 and Fx2 were greater in the long step length condition compared to the normal step length condition. This increase in force was approximately 37% when compared to normal step length condition. Swing toe-off, however, for the normal step length condition occurred only 75.8 ㎳ earlier than the long step length condition.

Step length is also regulated by controlling the knee extension during foot placement. Swing limb heel-strike coincides with stance Fx2. A previous study (Brunt et al, 1999) has shown that stance peak Fx2 is related to the walking speed. Thus, for fast speed stance peak Fx2 increases and time to stance peak Fx2 is reduced (Brunt et al, 1999). A subject, therefore, successfully increased the step length with relatively faster speed compared to normal step length.

Loading the swing limb decreased the force and slope of the swing limb. The overall mean swing peak Fx for weight conditions was 10.3% BW compared to 30.3% BW for no weight condition. Slope to swing peak Fx also decreased from 135% BW/S for no weight condition to 103.4% BW/S for weight conditions. It is believed that the smaller force and slope is probably related to the smaller loading of the swing limb for weight conditions compared to no weight condition. During the early phase of gait initiation, swing hip abductors created movement of the center of pressure toward the swing limb (Rogers and Pai, 1990). Thus, muscle activity at the ankle and hip tends to propel the center of mass forward and toward the intended stance limb. This transition from unloading to loading occurs slightly before peak Fx of the swing limb.

There was a small difference in temporal events between no weight and a weight condition. In the current study swing and stance toe-off for weight condition only increased 2.0% and 5.5% respectively, compared to the no weight condition.

It appears that subjects modulated GRFs and temporal events differently to achieve the peak acceleration force of the swing and stance limb in response to different tasks. The findings from the current study provide preliminary data, which can be used to further investigate how we modulate forces during voluntary movement from a quiet stance. This information may be important if we use this or a similar task to evaluate gait patterns of the elderly or patient populations. It would be interesting to conduct further investigation of the movement initiation of the 'healthy young' versus 'healthy older' adults, or 'healthy' versus 'frail and balance impaired' older adults, or 'patients with Parkinson's disease' versus 'age matched control group' in order to determine possible differences related to falls.

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This article was received October 12, 2006, and was accepted October 30, 2006.