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Gait Symmetry Can Reduce Dependence on the Intact Limb during Walking with Constraint of Unilateral Metatarsophalangeal Joints

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Abstract

Our previous research showed that healthy subjects exhibited asymmetrical walking gait when their unilateral metatarsophalangeal (MTP) joints were constrained. They relied more on their intact limb for the compensation of missing functions of their constrained limb, which may result in poor balance, increased metabolic cost, and higher risks of falls. We examined how subjects would respond if gait asymmetry in stance time was improved using a split-belt treadmill. Twelve healthy subjects were instructed to walk on a split-belt treadmill at comfortable and fast speeds with their unilateral MTP joints constrained. The walking trials were performed in two conditions, i.e., tied-belt walking (TBW, both belts moved at the same speed), and split-belt walking (SBW, the speed of the belt on the constrained leg was appropriately slower than that of the contralateral leg). The ground reaction forces (GRF) and electromyography (EMG) data during walking were collected. Results showed that the GRF and impulses on the constrained foot at fast speed SBW

significantly increased, compared with TBW, and the activation of medial gastrocnemius and soleus of the intact lower limb decreased significantly, which suggest that improved symmetry in stance time may reduce dependence on the intact limb for humans with the constraint of unilateral MTP joints.

I. INTRODUCTION

Metatarsophalangeal (MTP) joints may play an important role during human walking [1]. For instance, the loss of the MTP joints mobility caused significant impact on gait of patients with rheumatoid arthritis [2]. Similarly, a previous study indicated the restriction of bilateral first MTP joints caused significant decreases in walking speed in healthy controls, although the magnitude was relatively small, i.e., ~3% [3]. The constraint of the MTP joints may impair the function of the foot to effectively generate propulsion force during late stance phase. However, current foot prostheses still have limited range of motion of the MTP joint, which may have negative impact on walking performance of amputees.

The constraint of MTP joints of one leg may force subjects to relay more on the intact leg to compensate this constraint, causing asymmetrical spatial-temporal gait parameters, such as swing and stance times, step length, ground reaction forces (GRF) and joint mechanics [4–8]. Typically, they spend more time in stance on their intact limb and less on their impaired limb [9, 10], and they shift more weight on their intact limb than their impaired limb during walking [11]. On one hand, asymmetrical gait may be due to a compensatory motor strategy of humans since the impaired limb is not suitable for load-bearing because of the missing knee extension or missing ankle push-off [12, 13]. On the other hand, asymmetrical gait may result in poor balance, higher metabolic cost and may increase the risks of back pain, and overuse of the intact leg [14–16]. Thus, the goal of this study was to test whether we could reduce the compensation of the intact leg by artificially increase the symmetry of stance time. We hypothesized that improving stance time symmetry could reduce dependence on the intact limb for humans with the constraint of unilateral MTP joints.

II. METHODS

A. Subjects

Twelve healthy adults (7 males and 5 females) between the ages of 18–46 (mean = 28.7) were recruited from Shirley Ryan AbilityLab and Northwestern University in the study. Subjects had no known musculoskeletal disorders and walking related injuries such as muscle strains, joint sprains, or back injuries at the time of testing. All subjects received written and verbal information about the study procedure and gave written informed consent before the participation in the experiments. The experiments were conducted in the Legs and Walking Lab at Shirley Ryan AbilityLab after the approval was obtained from the Institutional Review Board of Northwestern University.

B. Experimental Apparatus and Procedures

The MTP joints were constrained by attaching a custom fabricated aluminum plate beneath bare foot. The thickness of the plate is 12 mm, and the weight is about 350 g, which is

comparable to the weight of a shoe. The experiment included two sessions. Specifically, in session 1, subjects walked on the overground in two conditions: (1) walking normally (WN), and (2) walking with the MTP joints of the right foot constrained (WMR). Subjects were instructed to walk at their self-selected speed and fast speed (i.e., walking safely as fast as they could without running) for three trials for each condition. A 4.3 m long mat embedded with pressure sensors (GAITRite, CIR Systems Inc., Sparta, NJ, USA) was used to measure walking speed. Walking velocity was obtained using the data collection software of GAITRite, and was further averaged across three trials.

In session 2, subjects walked on an instrumented split-belt treadmill (Instrumented Treadmill, Bertec Corporation, Columbus, OH, USA) with their right MTP joints constrained. They were instructed to walk at comfortable and fast speeds in two conditions, i.e., tied-belt walking (TBW, both belts moved at the same speed), and split-belt walking (SBW, the speed of the belt on the constrained side was 15% slower than the speed of the contralateral belt so that the two sides could have a comparable stance time). The comfortable speed and fast speed were set as 1.0 m/s and 1.4 m/s respectively. The order of walking trials was randomized across subjects. Subjects walked for 2 minutes for each trial and had a 2-min standing break between two trials. Subjects were allowed to hold onto a forward handrail placed at chest height during walking for the sake of safety. The GRF data were collected at 1,000 Hz using the software provided by the Bertec. Vertical GRF and anterior/posterior (A/P) GRF and their corresponding support impulse and propulsion impulse that incorporate both magnitude and duration were analyzed. Muscle activities from seven muscles including Tibialis Anterior (TA), Medial Gastrocnemius (MG), Soleus (SO), Peroneus Longus (PL), Rectus Femoris (RF), Vastus Medialis (VM), and Medial Hamstring (MH) of both legs were collected using a wireless EMG acquisition system (Delsys Inc., Natick, MA, USA) with the sample frequency at 2,000 Hz.

C. Data Processing and Analysis

Custom programs written in Matlab (The Mathworks, Natick, MA, USA) were used for data process. GRF data were filtered using a low-pass fourth order Butterworth filter with a cutoff frequency of 8 Hz. The EMG data from one subject were excluded because the data were not reliable. EMG data were low-pass filtered at 450 Hz, then high-pass filtered at 10 Hz, and further band-stop filtered at 55–65 Hz using a second order Butterworth filter. All EMG data were also rectified and smoothed using a low-pass second order Butterworth filter with a cutoff frequency at 20 Hz [17]. The GRF and smoothed EMG data were segmented into step cycles from heel strike to the next heel strike of the same foot. Due to the variability in the duration of each step cycle, these data were interpolated and resampled, and then averaged across the last consecutive 20 steps to create a mean pattern [18]. GRF data of each subject were normalized to the corresponding body weight. EMG amplitude was normalized to the peak EMG amplitude of walking at fast speed.

Statistical analyses were conducted in the software SPSS (IBM Co., Armonk, NY, USA). The parameters were analyzed using paired t-test to verify the significant differences between conditions. $P < 0.05$ was set for significant difference in all statistical tests.

III. RESULTS

A. Walking Velocity

Figure 1 shows the group averaged velocity of overground walking in the two conditions. For both self-selected speed and fast speed, the velocity of WMR significantly decreased compared with that of WN ($p = 0.001$). Specifically, self-selected walking speed with WMR decreased 14.15%, while fast walking speed with WMR decreased 15.88%. Based on these results, the speed of the belt on the constrained limb was set as 85% of the speed on the intact limb during SBW in the second session of the experiments.

B. Ground Reaction Forces

Vertical GRF and A/P GRF of the right foot at fast walking speed in two conditions are presented in Figure 2. The peaks of vertical GRF and A/P GRF in the condition of SBW significantly increased during terminal stance phase compared with that of TBW. And the duration of forward propulsion phase (when A/P GRF was positive) in the condition of SBW became longer. As a result, the support impulse and propulsion impulse in the condition of SBW were significantly greater than that in the condition of TBW, see Figure 2. No significant changes in vertical GRF and A/P GRF were observed at comfortable walking speed ($p > 0.05$).

C. Electromyography

Individual subject data was visually inspected to see if there were systematic differences in the timing of muscle activity. Since most subjects had similar muscle activation patterns, only changes in amplitude of muscle activity are reported. Muscle activation patterns of each muscle in the two conditions from a representative subject are shown in Figure 3. The durations of muscle activation of MG and SO from the left leg were decreased in the condition of SBW in comparison with that of TBW. The onset timing of PL and VM of the left leg became earlier in the condition of SBW than that of TBW. In addition, the magnitude of MH increased in the condition of SBW in comparison with that of TBW. The integral of the EMG activity was calculated in the interval of a complete gait cycle, and was presented in Figure 4. The integral of muscle activity of MG and SO from the left leg significantly decreased in the condition of SBW compared with that of TBW, although no significant changes in muscle activity of the right leg were observed. In addition, no significant changes in EMG activity were observed when subjects walked at their comfortable speed.

IV. DISCUSSION AND CONCLUSION

The constraint of the unilateral MTP joints induced ~15% decrease in overground walking speed of healthy adults. In addition, subjects may rely more on their intact lower limb for the compensation when walking with their unilateral MTP joints constrained. Results from this study indicated that the compensation from the intact limb could be reduced if the symmetry in stance time of humans with constrained MTP joints was improved.

The constraint of the MTP joints may induce significant impact on walking speed. This is consistent with a previous study, which indicated that the loss of MTP joint mobility of

rheumatoid arthritis patients induced ~11% decrease in walking speed in comparison with healthy controls [2], and partially consistent with a previous study of healthy adults, which indicated that the constraint of the first MTP joint induced ~3% decrease in walking speed [3]. A smaller decrease in walking speed from this study may be due to the first MTP joint was not fully constrained due to the set up or only one MTP joint was constrained. The constraint of the MTP joints may limit the capacity of subjects to generate enough power through foot propulsion to move the body forward during late stance phase of gait. This may be one of reasons why amputee patients wearing prosthetic foot, which has very limited range of MTP joints, walk at a slower speed than healthy controls [19].

A unilateral constraint of the MTP joints may induce compensation from the contralateral leg. For instance, results from our previous study indicated that integrated muscle activities of MG, SO and PL of the intact limb, which mainly provide contribution to body support, forward propulsion and leg swing initiation during the stance phase, significantly increased to compensate the unilateral constraint of the MTP joints. However, repeated use of the compensation from the intact leg may also cause injuries of the intact leg because of overuse, which may be one of reasons why amputee patients have more injuries on the intact leg in comparison with healthy controls. Results from this study indicated that the magnitude of ankle plantar flexors reduced when the stance time of the constrained limb increased, suggesting that the compensation from the intact limb could be reduced if we artificially modulate the stance time of the constrained limb through a split-belt treadmill.

Results from this study may have potential clinical applications. For instance, results from this study suggest that increasing the range of motion of the MTP joints of the prosthetic foot may potentially improve walking speed and reduce the compensation of the intact leg of amputee patients.

However, this study has some limitations to consider when interpreting the results. First, as a pilot study, the sample size of subjects was small. Second, subjects were allowed to hold onto the front handrail during treadmill walking. The use of handrail may cause decreased lower limb loading and reduced proximal muscle activity, which could confound our results. Third, this study only looked at the GRF and EMG data. The kinematics and kinetics of the lower limbs were not studied. In addition, some subjects were right leg dominated and others were left leg dominated, which may potentially impact the results.

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Figure 1.

Group averaged velocity of overground walking in the two conditions, i.e., walking normally (WN), and walking with the MTP joints of right foot constrained (WMR). Asterisk (*) indicates significant difference between conditions.

Figure 2.

Vertical GRF and A/P GRF and corresponding support impulse and propulsion impulse on the right foot when walking at fast speed in the two conditions, i.e., tied-belt walking (TBW), and split-belt walking (SBW). Asterisk (*) indicates significant difference between conditions.

Figure 3.

EMG activity patterns from seven muscles of the left and right legs of a representative subject during treadmill walking at fast speed in the two conditions, i.e., tied-belt walking (TBW), and split-belt walking (SBW).

Figure 4.

Average of integrated EMG area during one gait cycle of treadmill walking at fast speed in the two conditions, i.e., tied-belt walking (TBW), and split-belt walking (SBW). Asterisk (*) indicates significant difference between conditions.