

Sudden changes in walking surface compliance evoke contralateral EMG in a hemiparetic walker: a case study of inter-leg coordination after neurological injury

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Abstract—Gait impairment due to neurological disorders is a significant problem around the world. Despite the growing interest in using robotic devices for gait rehabilitation, their widespread use remains limited as there is no clear evidence that robot-assisted gait therapy is superior to traditional treadmill-based therapy. This work is a case study that focuses on investigating the existence of mechanisms of inter-leg coordination after neurological injury, and based on that, proposing novel methods for gait rehabilitation. Using a novel robotic device, the Variable Stiffness Treadmill (VST), we apply perturbations to the compliance of the walking surface underneath the non-paretic leg, and analyze the response of the contralateral (paretic) leg. We show that muscle activity is evoked in the gastrocnemius of the paretic leg. From a clinical perspective, the results of this study can be disruptive because our methods provide a safe and targeted way to provide gait rehabilitation in hemiparesis since direct manipulation of the paretic side is not required. This work provides evidence for the first time that muscle activity can be evoked in the paretic leg of a hemiplegic walker in response to unilateral perturbations to the compliance of the walking surface, providing direction for targeted robot-assisted gait rehabilitation.

I. INTRODUCTION

Gait impairment due to neurological disorders has become an important problem of the 21st century. Stroke is a leading cause of long-term disability with approximately 90% of stroke survivors having some functional disability, with mobility being a major impairment. Despite the growing interest in using robotic devices for rehabilitation of sensorimotor function, their widespread use remains somewhat limited by a number of factors, including the assessment of the cost-to-benefit ratio relative to other types of rehabilitation approaches. Moreover, there is no clear evidence that robotic gait training is superior to conventional physiotherapy for either chronic or sub-acute stroke patients [1].

We have proposed an alternative approach to robotic interventions in gait therapy which takes advantage of mechanisms of inter-leg coordination [2]. Considering the neural coupling between limbs in human walking [3], we hypothesize that there is a mechanism of inter-limb coordination that may be utilized to regain functionality of the impaired leg, if this mechanism remains intact after neurological injury. This idea of utilizing the function of the unimpaired leg to provide therapy to the impaired leg provides several advantages over

current rehabilitation protocols. One of the most significant advantages is the safety and comfort of the patient, since there is no direct manipulation of the paretic leg. Moreover, stimulating a mechanism that is still fully functional, such as we suggest in this paper, may elicit greater functional outcome than in stimulating the impaired mechanism.

However, the functionality of sensorimotor control mechanisms of inter-leg coordination after neurological injury are currently not well understood. Investigation of inter-leg coordination usually involves perturbations to the non-paretic leg and the analysis of their effects on the paretic leg. Recent work has shown changes in paretic leg muscle activation due to differential speed split-belt treadmill walking [4] and voluntary increased step length of the non-paretic leg [5].

However, the limitation of previous works is that they have failed to separate the mechanisms of gait from those of body weight support and balance. As a result, perturbations of the non-paretic leg would have likely triggered mechanisms related to body balance and posture. It is not known whether the observed bilateral activation is exclusively caused by the mechanisms required for body stabilization and balance maintenance, or if it is also brought about from inter-limb coordination and mechanisms of gait. This leaves a gap in our understanding of sensorimotor control of gait, and consequently from engineering effective rehabilitation protocols.

In this paper, we present a case study of investigating inter-limb coordination mechanisms after neurological injury by designing and applying unilateral low stiffness perturbations that evoke contralateral leg responses. Moreover, body weight support was given to suppress mechanisms related to balance and posture. We present results of evoked muscle activity in the affected (unperturbed) leg and discuss the potential application to robot-assisted gait therapy.

II. METHODS

A. Experimental Setup

In order to investigate the existence of mechanisms of inter-leg coordination in a hemiparetic walker, unilateral stiffness perturbations were induced using the Variable Stiffness Treadmill (VST) system shown in Fig. 1. The system has been detailed in previous work [6], [7] and will not be described in this paper for brevity.

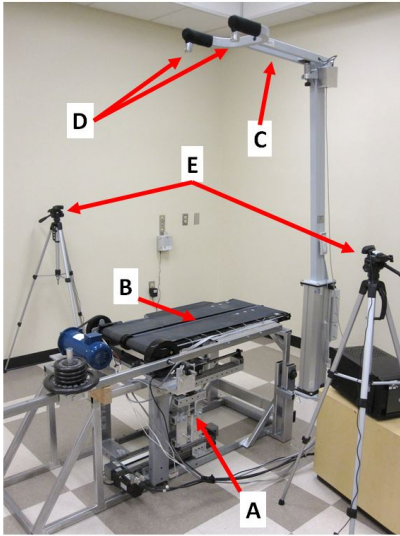


Fig. 1: The Variable Stiffness Treadmill (VST) setup. Sub-systems shown include: A) Variable stiffness mechanism, B) Split-belt treadmill, C) Custom-made harness-based body-weight support, D) BWS Loadcells, E) Motion capture system.

B. Study Participant

The study participant was a 41 year old male (weight 175 lbs) who experienced a traumatic brain injury at the age of 12. A 6-7 hour epidural arterial hematoma in the right hemisphere resulted in hemiplegia. His left leg is the affected limb with gait impairments due to reduced motor control, limited range of motion, and the chronic influence of spasticity.

C. Experimental Protocol

The subject participated in three sequential trials with a brief (approx. 5 minutes) rest break in between trials. For all trials the subject was offloaded by 30% of his body weight using the body weight support system shown in Fig 1. A value of 30% BWS was chosen for comparison with previous studies that have used 30% BWS [2], and because this level of support minimizes vestibular input and mechanisms related to body balance and posture as seen in previous studies [8]. In each trial he walked for approximately 7 minutes on the treadmill at a self selected speed of 0.51 m/s . Since the goal of this experiment is to investigate inter-leg coordination, the left treadmill belt was not allowed to deflect for the duration of the experiment, thus preventing any direct perturbation of the left leg. The surface underneath the right leg was commanded to maintain a stiffness of 1 MN/m , which is very high and considered to be rigid, for 30 gait cycles at the beginning of the experiment. Then, after a random number n of steps, where $n \in [4, 7]$, we immediately dropped the stiffness to a constant value. The stiffness utilized in trials 1, 2, and 3 were 100 , 80 , and 60 kN/m , respectively. The lowest level of stiffness of 60 kN/m was chosen because it resembles that of a gym mat [9] and for comparison with previous work [2]. The low stiffness perturbation began shortly after

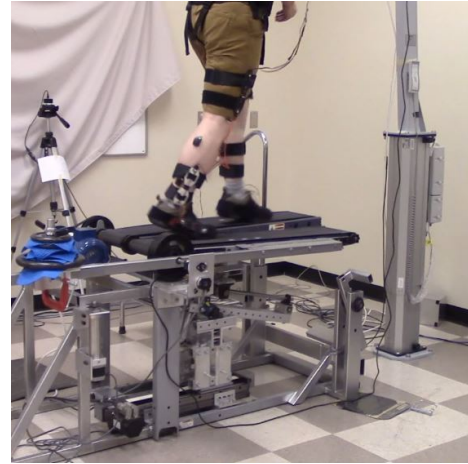


Fig. 2: The subject experiencing a low stiffness perturbation at the right leg.

heel strike (approx. 125 ms) and lasted for the duration of the right leg stance phase (ie. until toe-off) after which the stiffness was commanded back to 1 MN/m for the next n number of steps. The subject experienced 30 perturbations at each level of stiffness which resulted in various levels of unilateral plantarflexion. A picture of the subject experiencing a low stiffness perturbation is shown in Fig. 2. Informed consent from the subject was obtained at the time of the experiment, and the experimental protocol is approved by the Arizona State University Institutional Review Board (IRB ID#: STUDY00001001).

D. Data Collection and Processing

Kinematic data for both legs were obtained at 140 Hz using an infrared camera system that tracked 12 (6 on each leg) infrared LEDs placed as pairs on the thigh, shank, and foot. This data was also utilized in real time for timing of the stiffness perturbation.

The muscle activity of both legs were obtained using surface electromyography (EMG) via a wireless surface EMG system (Delsys, Trigno Wireless EMG) and recorded at 2000 Hz. Electrodes were placed on the tibialis anterior (TA), gastrocnemius (GA) and soleus (SOL) of both legs. Raw EMG signals were processed by finding the moving root mean square envelope of each signal with a 250 ms window. After computing the EMG linear envelope, the data were normalized to the maximum value of that EMG signal.

The kinematic and EMG data corresponding to the gait cycles of normal conditions and the cycles pertaining to the perturbations were found and normalized temporally to percent gait cycle in order to eliminate discrepancies due to natural variations in gait patterns (i.e. stride length, cycle duration, etc). The data of each gait cycle was resampled at each 0.01% of the gait cycle (approximately 0.15 ms) during the normalization to percent gait cycle. The first 30 gait cycles and the cycles in between perturbations during the normal conditions are included in the unperturbed data set. One

gait cycle following a perturbation is not included in the unperturbed set in order to eliminate any residual effects from the perturbation. This processing results in normalized EMG signals as a function of percent gait cycle, where 0 and 100% correspond to the heel-strike of the right (perturbed) leg.

In order to evaluate the significance of recorded EMG responses when compared to the normal condition, statistical significance was determined using an unadjusted unpaired t-test at each time instance. The unpaired t-test was selected in this case because it is a comparison of two independent distributions (i.e. gait cycles with and without perturbation) which have similar variances but different sample sizes. Each statistical test was performed at the 95% confidence level and any potential Type I errors from tests being performed at each 0.01% of the gait cycle were eliminated by only concluding significance if at least 400 tests (i.e. 4% of the gait cycle) in a row indicated significance.

III. RESULTS

The results of the experiment show significant changes in evoked contralateral muscle activity of the left leg in response to the low stiffness perturbations on the right leg, showing the existence of mechanisms of inter-leg coordination after neurological injury. Even though the right leg was directly perturbed through the stiffness change of the right walking surface, the analyses for the rest of the paper will be focused on the effects of the perturbation on the response of the contralateral leg.

The muscular response of the affected (unperturbed) leg to unilateral low stiffness perturbations for the impaired walker is shown in Fig. 3. The normalized EMG amplitude for the TA, GA and SOL (mean and standard deviation) for all gait cycles pertaining to each surface stiffness is shown.

The first thing to notice from the figure is that the subject's muscle activations do not match that of what would be expected for normal human gait [10]. Specifically, the GA is only active for a brief period of time. In healthy subjects, the GA is active with increasing amplitude throughout the stance phase, whereas this subject shows only brief activation at the beginning of the stance phase. Moreover, the SOL activity in this subject shows irregular fluctuations in the average muscle activation during the stance phase whereas normal muscle activity for healthy subjects is a smooth curve when averaged over several gait cycles.

The most significant result of this case study is that sudden changes in unilateral stiffness of the walking surface evoke significant changes in contralateral GA activity. As indicated in Fig. 3, the increased GA activity in the affected leg occurred during the early stance phase of the gait cycle when the subject's GA was active during normal walking. Moreover, the significant changes in GA activity are only seen for the 60 and 80 kN/m perturbations, but not for the 100 kN/m perturbation. A significant decrease in TA EMG at the 60 kN/m level was also seen. Since there is less kinematic change created by higher stiffness perturbations, significant changes in EMG are not seen during the highest stiffness perturbations.

IV. DISCUSSION

The results presented in this paper suggest that mechanisms of inter-leg coordination may remain intact after neurological injury and can be stimulated through low stiffness perturbations. This has strong potential for medical application in a novel approach to robotic gait therapy for hemiplegic walkers.

A. Inter-leg Coordination

This paper shows results for the first time that muscle activity in the unperturbed leg of a neurologically impaired subject is changed by unilateral low stiffness perturbations. The increased GA activity in the affected leg occurred during the early stance phase of the gait cycle when the subject's GA was active during normal walking. Therefore, we hypothesize that the stiffness perturbations amplified the existing neural commands. Moreover, the significant changes in GA activity are only seen for the 60 and 80 kN/m perturbations, but not for the 100 kN/m perturbation. As the level of stiffness decreases there is a proportional increase in treadmill deflection (with a constant foot force across gait cycles). Therefore, this suggests that there is a minimum deflection required to stimulate the mechanism of inter-leg coordination.

Our previous work has shown a systematic and scalable contralateral response to the unilateral stiffness perturbations in healthy subjects [2] that are mediated through the brain [11]. Therefore, the results presented in this paper from the case study suggest that mechanisms of inter-leg coordination remain intact after neurological injury. Moreover, the evoked GA activity provides support for the ability to provide therapy to an impaired leg through physical interaction with the healthy leg in hemiplegic gait.

B. Possible Medical Application

From a clinical prospective, the results of this study can be disruptive since they suggest that muscle activity in hemiplegic walkers can be evoked by altering the stiffness of the walking surface. Moreover, low stiffness perturbations to the ipsilateral leg evoke increased GA activation in the contralateral leg. These results suggest a possible novel approach to robot-assisted gait therapy for hemi-paretic patients, that would entail manipulation of the healthy leg through stiffness perturbations in order to provide therapy to the impaired leg.

The idea of providing therapy for patients through supraspinal mechanisms of inter-leg coordination has several advantages over current rehabilitation protocols. The most significant advantage is the safety and comfort of the patient since there is no direct manipulation of the paretic leg. Moreover, other studies have stimulated the impaired muscles via functional electric stimulation to improve functional outcome (e.g. [12]), but that technique by-passes the brain which is the location of the root cause of the gait impairment created by a neurological disorder originating in the brain (ie. stroke or traumatic brain injury). On the other hand, the results of this work suggest the feasibility of an alternative approach to create desired contralateral GA activity by exploiting existing

Muscle activity of unperturbed (affected) leg of hemiplegic walker

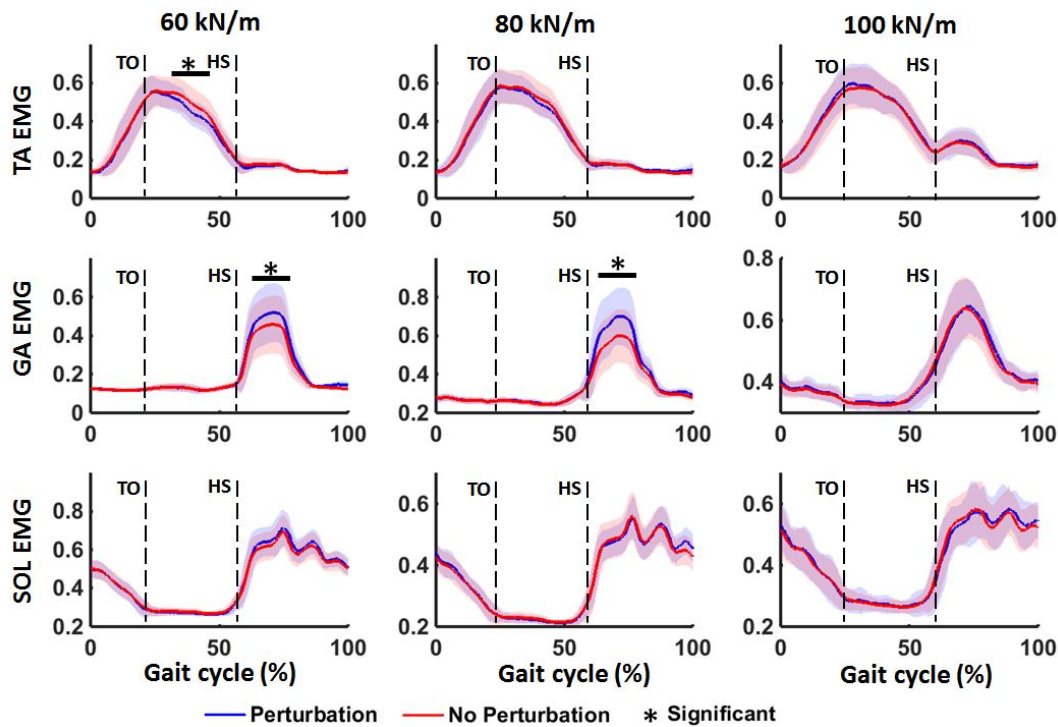


Fig. 3: Averaged muscle activity of the unperturbed (affected) leg for a the participating subject as function of percent gait cycle, where 0% corresponds to heel-strike of the right (perturbed) leg. Plotted in rows from top to bottom are the normalized TA EMG, normalized GA EMG, and normalized SOL EMG for each level of stiffness perturbation (60, 80, and 100 kN/m , from left to right, respectively). Mean (darker lines) and standard deviations (lightly shaded areas) values are shown. Statistically significant changes are indicated by black bars placed beneath a black asterisk. Heel-strike and toe-off of the left leg are indicated by HS and TO, respectively. The duration of the gait cycle is approximately 1.6 s.

supra-spinal neural circuits via regulation of the stiffness of the walking surface.

V. CONCLUSIONS

This paper presented results of evoked muscle activity in the contralateral (affected) leg of a hemiplegic walker in response to unilateral low stiffness perturbations. Statistically significant changes in the activity of the gastrocnemius are seen in the early stance phase of the affected leg. This work provides evidence for the first time that muscle activity can be evoked in the contralateral leg of a hemiplegic walker in response to unilateral perturbations to the compliance of the walking surface. Future work will involve characterizing these mechanisms of inter-leg coordination for stroke patients and other impaired walkers.

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