On the Effects of Visual Anticipation of Floor Compliance Changes on Human Gait: Towards Model-based Robot-Assisted Rehabilitation

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***Abstract*— The role of various types of robot assistance in post-stroke gait rehabilitation has gained much attention in recent years. Furthermore, there is increased popularity to use more than one rehabilitation method in order to utilize the different advantages of each. Naturally, this results in the need to study how the different robot-assisted interventions affect the various underlying sensorimotor mechanisms involved in rehabilitation. To answer this important question, this paper combines a virtual reality experience with a unique robotic rehabilitation device, the Variable Stiffness Treadmill (VST), as a way of understanding interactions across different sensorimotor mechanisms involved in gait. The VST changes the walking surface stiffness in order to simulate real-world compliant surfaces while seamlessly interacting with a virtual environment. Through the manipulated visual and proprioceptive feedback, this paper focuses on the muscle activation patterns before, during, and after surface changes that are both visually informed and uninformed. The results show that there are predictable and repeatable muscle activation patterns both before and after surface stiffness changes, and these patterns are affected by the perceived visual and proprioceptive feedback. The interaction of feedback mechanisms and their effect on evoked muscular activation can be used in future robot-assisted gait therapies, where the intended muscle responses are informed by deterministic models and are tailored to a specific patient's needs.**

I. Introduction

A human's ability to walk is a crucial component of life that is shown throughout almost all daily activities. After brain damage such as stroke, an otherwise healthy individual can become paralyzed in the leg, hindering his or her critical ability to walk. Physical therapy is used to help individuals regain lost function, however the cost associated with rehabilitation is enormous. In fact, the total cost of stroke incidents to the United States is projected to nearly double by the year 2035 [1]. In order to decrease the cost and increase the effectiveness of post-stroke therapy, it is necessary to find and utilize the methods that work.

In recent years, robotic and autonomous systems have gained popularity for their ability to automate the tedious and time intensive therapy needed for rehabilitation [2], [3]. These systems also allow for novel methods to evoke certain neural pathways in the brain that can lead to increased muscle synergy activation [4]. Because locomotion is the result of complex dynamic interactions between a central controller in the brain and feedback mechanisms, the rehabilitation methods that work the best utilize a fundamental understanding of this coordination of human gait [5] in both healthy and impaired individuals. The central controller requires both locomotion patterns from spinal circuits, as well as neural drive through a multitude of descending pathways that trigger desired gait corrections from various sensory modalities [6]. These sensory modalities have been shown to affect the muscle responses to perturbations during walking [7], displaying the importance of sensory modalities in rehabilitation.

Within these gait control mechanisms, proprioception is key for a healthy gait; this modality has been investigated through different methods, including mechanical perturbations [8]–[10]. In addition, visual feedback is also important for normal gait patterns. This has been shown through virtual reality (VR) systems [11] that allow for the manipulation of the visual feedback to the brain, and can lead to improved outcomes when coupled with robotic therapy [12], [13]. In fact, there is a crucial relationship between proprioceptive and visual feedback [6] that has yet to be deeply explored and exploited for rehabilitation. One of the ways this relationship can be elicited for rehabilitation is through perturbation training in a controlled virtual environment. While previous studies have separately investigated proprioceptive and visual feedback in gait, they have not shown the evoked muscle responses from visual feedback alterations. One way to efficiently study the interplay between proprioception and visual feedback is by interactively varying the compliance of the walking surface [14], [15]. Understanding and modeling this relationship could lead to patient-specific interventions for rehabilitation.

In this paper, we focus on the sensorimotor mechanisms involved in human locomotion during the transition from rigid to compliant surfaces using a robotic device. We hypothesize that quantifiable changes in muscle activation will be present both before and after an individual encounters a perturbation. The Variable Stiffness Treadmill (VST) is utilized as the platform for human locomotion, allowing for rigid to compliant surface transitions [16]. The ability to simulate transitions from rigid to non-rigid surfaces while measuring lower-limb muscle responses allows for understanding of interactions among sensorimotor control strategies that have not been investigated before [17].

This study is crucial for understanding the quantifiable characteristics in human sensorimotor control strategies. Our results can be directly applied to improved robot-assisted

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Fig. 1. Subject Walking on the Variable Stiffness Treadmill (VST) while wearing the virtual reality headset (Oculus Rift).

lower-limb rehabilitation that can potentially be more effective than current strategies. The rest of the paper is organized as follows: Section II describes the experimental protocol used for this study and discusses the data collection and processing methods; Section III discusses the results of our study; Section IV concludes the paper with a summary of the main contributions.

II. METHODS

A. Experiment Setup

1) Virtual Reality (VR): Subjects wore the Oculus Rift headset (Oculus Inc.) for the duration of the experiment, as shown in Fig. 1. The virtual environment displayed in the headset was developed using Unreal Engine 4 [18]. The virtual reality environment consists of a walkway with two separated tracks; each track has grass material to resemble infinite stiffness, and sand patches are placed randomly (according to our experimental design) along the left track to resemble decreased stiffness. The subject's leg motion is described via joint angles at the sagittal plane (ankle dorsi-plantar flexion, knee flexion-extension, and hip flexion-extension). Those angles are transmitted using TCP/IP from the computer that controls the VST to the computer running Unreal Engine, and they are used to update the virtual avatar's leg motion. This allows subjects to effectively see their leg positions in real time as they are walking on the treadmill. The Unreal Engine outputs 120 frames per second (FPS) to the Oculus Rift headset, allowing a realistic and immersive experience for the subject.

2) Variable Stiffness Treadmill (VST): Briefly, the VST is a split-belt treadmill on which the compliance of the walking surface can be interactively and dynamically controlled. In its most simplified form, the VST is a spring-loaded lever mounted on a translation track that can change the effective stiffness under the foot by moving the linear track. An optical motion capture system monitors the location of the foot in real-time to control the timing of the stiffness perturbations throughout the gait cycle. The effective stiffness of each side/belt of the treadmill can range from its minimum value (61.7N/m) to its maximum, which is theoretically infinite (i.e., rigid walking surface), in 0.13s, which translates to 1/3 the duration of a stance phase for walking at a normal pace of 1.4m/s [19], [20]. Moreover, the resolution of the VST stiffness control is approximately 0.038N/m [17], [21]. These features allow for the introduction of a plethora of dynamic perturbations to the leg that are impossible to implement with current devices. The system has been detailed in previous work [17], [21] and will not be described in this paper further for brevity.

B. Experiment Protocol

Six healthy subjects [age 21.6 ± 2 years, weight 167 ± 9 lbs] walked on the VST at a speed of 0.60 m/s for at least 300 gait cycles. Subjects wore a body harness for safety, but no body weight support was provided. Informed consent from the subjects 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).

Throughout the experiments, there are three different conditions regarding the visual and proprioceptive feedback to the subjects. Visual Only (VO) occurs when a subject sees a sand patch, but no physical perturbation occurs; they are essentially being tricked. Visual Physical (VP) occurs when a subject sees a sand patch and a physical perturbation occurs as expected. Physical Only (PO) occurs when a subject does not see any visual cues (sand patch) but there is a physical perturbation; they are essentially being tricked. Unperturbed (infinite stiffness) occurs throughout most of the duration of the experiment, where there is no indication of a sand patch or any physical perturbation. These conditions are shown in Fig. 2.

The experiment is broken into three phases which appear as just one whole trial to the subjects (see Fig. 3). During the first phase (learning), subjects walked for 10 gait cycles on infinite stiffness, which corresponds to grass material on the tracks in the virtual environment. This phase allows subjects to get familiar with walking with a VR headset on the VST for the first time.

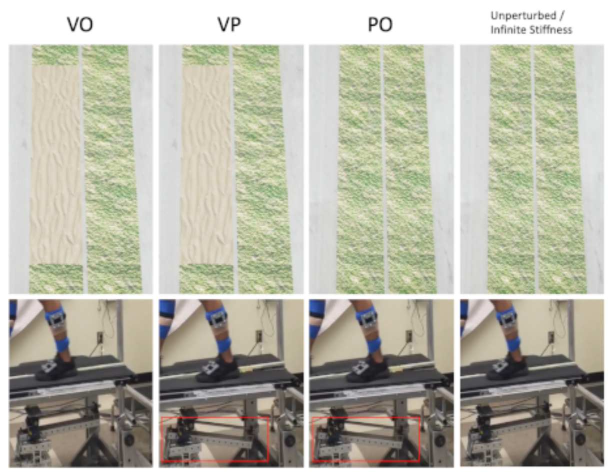

Fig. 2. The four possible conditions experienced during the experiment. Visual feedback (through the Virtual Reality environment) is shown on the top, and the corresponding Physical Feedback (i.e. stiffness perturbation) is shown on the bottom.

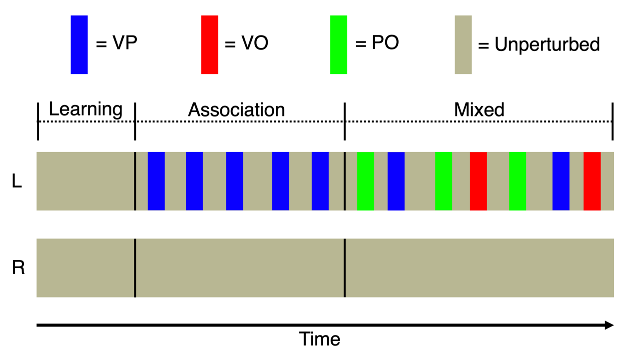

Fig. 3. Experimental design. The number of VO, VP, and PO patches in this figure are not to scale. The left track (L) is the side of the VST where perturbations occur, and the right track (R) is the unperturbed side of the VST. The learning phase consists of 10 unperturbed gait cycles. The association phase consists of 30 VP patches randomly placed every 7 ± 2 gait cycles. The mixed phase consists of 30 VP, 30 VO, and 30 PO patches randomly placed every 7 ± 2 gait cycles.

Next, subjects enter the second phase (association). Just before entering this phase, 30 VP patches are automatically placed every 7 ± 2 gait cycles by using the average gait cycle time collected during the learning phase. The main purpose of the association phase is for subjects to associate stepping on a sand patch with a change in surface compliance. Three gait cycles prior to stepping on a sand patch, the position of the upcoming patch is slightly moved to the predicted step location, based on the average and most recent cycle time data. This slight adjustment ensures that the subject will always be stepping on the center of the sand patch and provides assurance that the perturbed step will be on sand. This adjustment is unnoticeable to the subjects and, in fact, it enhances their immersive experience. After encountering 30 sand patches, the subjects complete the association phase and enter the third phase (mixed).

During the mixed phase, the subjects encounter 30 VP, 30 VO, and 30 PO patches that are randomly selected and placed every 7 ± 2 gait cycles. These 90 patches are placed at the same time that the association phase's patches are placed, so the transition from association to mixed appears seamless to the subjects. The purpose of the mixed phase is to evaluate the visual anticipatory relationships among VP, VO, PO, and unperturbed conditions.

C. Data Collection and Processing

The analysis in this paper focuses only on gait cycles from the association phase and mixed phase; data from the learning phase is omitted for obvious reasons.

1) Kinematics: Kinematic data for both legs were obtained at 100 Hz using a motion capture system (Vicon) that is integrated with the VST. The system tracked 6 marker plates (3 on each leg) placed on the thigh, shank and foot. This system provides the kinematics of both legs at the sagittal plane in real time. This data was utilized for matching the avatar's leg motion with the subject's leg motion, as well as for timing the changes in the surface stiffness.

2) EMG: The muscle activity of both legs was 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) muscles. These muscles were selected as they play a primary role in ankle motion and stability, in which the GA and SOL muscles produce plantar flexion of the foot and the TA produces dorsiflexion of the foot [20], [22]. After computing the EMG linear envelope, the data were normalized to the maximum value of each muscle. The EMG data corresponding to the gait cycles of walking on the rigid surfaces and the cycles pertaining to the different perturbations were found and categorized accordingly. Because muscle activity during walking is highly dependent on the phase of the gait cycle, the data were normalized temporally to the duration of the gait cycle.

3) Data analysis and categorization: The data analysis provides normalized EMG signals as a function of percent gait cycle, where 0%, 100% and 200% correspond to the heel strikes of the left leg at two successive gait cycles; 0-100% corresponds to the cycle before a *possible* perturbation, while 100-200% corresponds to the cycle that the left leg is *possibly* perturbed. For every subject, data was collected during four possible conditions: VP, VO, PO, and Unperturbed walking (see Fig. 2). Let us define one "gait interval" as two consecutive gait cycles. For VP, VO, and PO conditions, one gait interval consists of the gait cycle before the condition occurs (0 - 100%) combined with the gait cycle after the condition occurs (100-200%). For unperturbed conditions, all gait intervals that are in between VP, VO, and PO gait intervals during the association and mixed phases are included. The gait cycles that directly follow VP, VO, and PO gait intervals are excluded in order to avoid collecting residual activity.

Time slices for every gait interval are found and grouped according to their condition. For kinematics, data collected from the Vicon system during the time slices for a particular condition are plotted, splined, and then the mean of every splined plot for a particular subject is calculated. For example, this process will generate a plot of the mean left ankle kinematics during all PO conditions for a particular subject. This process is done for every joint, condition, and subject in order to create the kinematics figures in this paper. For EMG's, the process is similar, except that data from processed and normalized muscles' activation is plotted instead.

III. Results

The results discussed in the paper are from two representative subjects, who were selected to encompass the main findings of our six subjects. In each figure, the mean EMG or kinematic activity for every gait interval during a particular condition is plotted as a different color. The process of separating and classifying these gait intervals is described in the Data Collection Section above. As a result, we can compare mean EMG or mean kinematics activity across all conditions for any given subject.

The statistical significance tests applied between the perturbed and unperturbed data sets were calculated at the 95% confidence level using an independent t-test. In all figures, a horizontal sequence of colored dots (appearing as horizontal segmented lines) on the top part of the figure corresponds to regions of statistical significance between the two conditions tested. For example, blue horizontal line segments (appearing as VP in the legend of Fig. 4) correspond to regions of statistically significant difference between the VP and unperturbed cycles. Finally, the statistical tests for muscle activation among conditions are only applied when the activation of the corresponding muscles is above 0.1 (10%) of the maximum value, in order to avoid false positives when the muscles are generally inactive.

A. *Effect on leg kinematics*

Figure 4 (top) shows the left ankle kinematics, where the positive vertical axis represents dorsiflexion and the negative vertical axis represents plantarflexion. It shows an accelerated swing phase of the left ankle when the subject is presented with an upcoming sand patch. During this interval of 60-100%, both Visual Only (VO) and Visual Physical (VP) conditions are statistically significant compared to the unperturbed gait cycles; that is, subjects present greater dorsiflexion at each moment of the swing phase. Note that during this interval, the mean for the PO condition is similar to the mean for unperturbed gait cycles (with the exception of statistically significant differences from 87-92%). This is expected since the PO condition does not present a visual cue. Figure 4 (middle) further indicates an accelerated swing phase of the left knee from 79-90% for visual patches. Figure 4 (bottom) displays a similar result, but the evidence of an accelerated swing phase for visual patches is not as strong as that of the left knee and ankle. Both VP and VO conditions

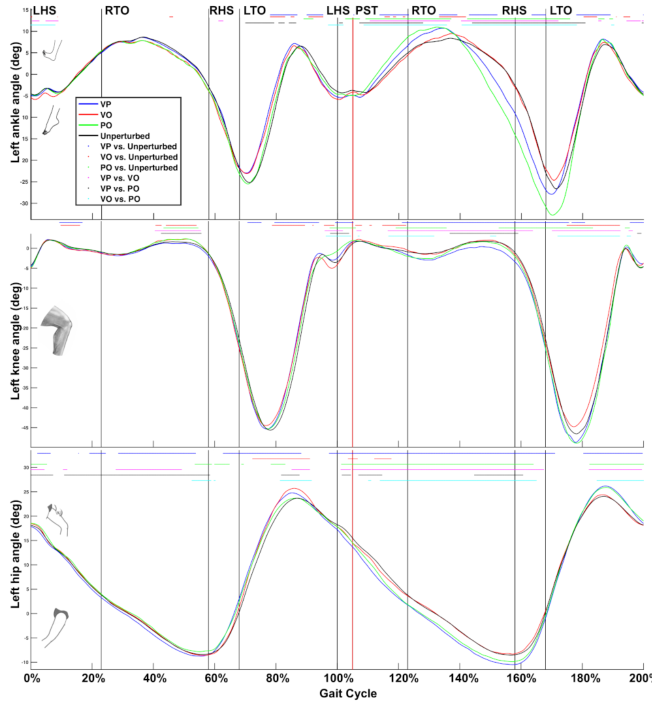

Fig. 4. Mean kinematics of the left (perturbed) leg in the studied conditions. Events of the gait cycle noted on top: Left Heel Strike (LHS), Right Toe Off (RTO), Right Heel Strike (RHS), Left Toe Off (LTO), Perturbation Start (PST). Horizontal sequence of colored dots (appearing as horizontal segmented lines) on the top part of the figure corresponds to regions of statistical significance between the two conditions tested.

are statistically significant (greater hip flexion) together from 72-88%; however, the PO condition also displays statistical significance (greater hip flexion) from 78-83%.

A comparison in kinematics between perturbed and unperturbed conditions is not informative during the second gait cycle (100-200%) since the perturbation will obviously affect leg motion and therefore joint angles. For this reason, it is only useful to compare VP vs. PO (blue vs. green solid lines) conditions and VO vs. Unperturbed (red vs. black solid lines) conditions during the second gait cycle. VP and PO can be compared because they both contain a perturbation, while VO and Unperturbed can be compared because neither contain a perturbation. As a result, only red and black statistical significance lines should be interpreted during the second cycle. Comparing VP and PO (blue vs. green solid lines) shows the effect that the anticipation (visual feedback) of the stiffness perturbation has on the kinematics right after the perturbation. Ankle kinematics are mainly different right after the perturbation when there is an anticipation of the perturbation (VP), compared to the case that the perturbation came unexpected (PO). However, this is probably an after-effect of the accelerated swing phase during the previous gait cycle – before the perturbation. Comparing VO vs. Unperturbed (red vs. black) after the perturbation shows no significant consistent changes in the kinematics, as expected, which validates our experiment.

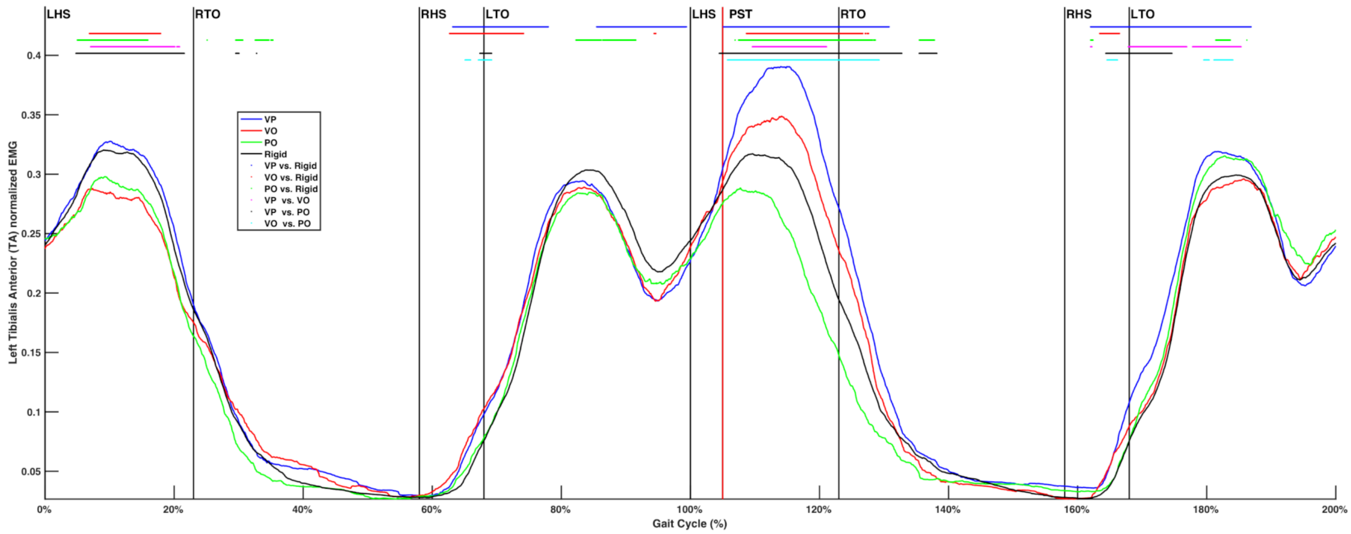

Fig. 5. Mean normalized activation for the left Tibialis Anterior (TA) muscle in the studied conditions. Horizontal sequence of colored dots (appearing as horizontal segmented lines) on the top part of the figure corresponds to regions of statistical significance between the two conditions tested.

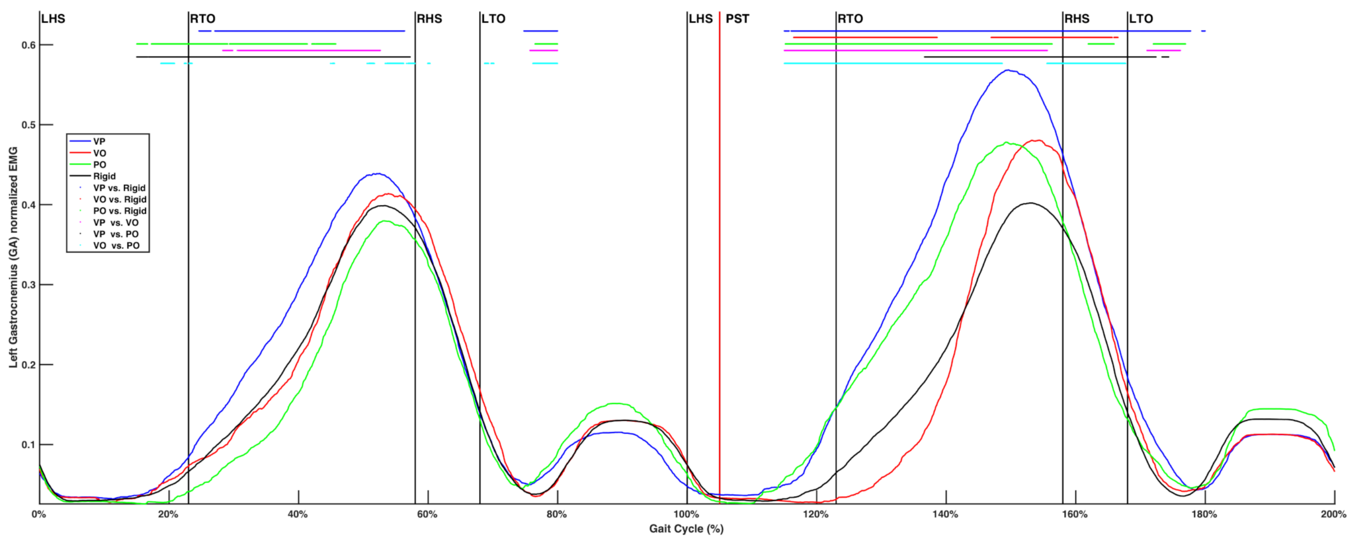

Fig. 6. Mean normalized activation for the left Gastrocnemius (GA) muscle in the studied conditions. Horizontal sequence of colored dots (appearing as horizontal segmented lines) on the top part of the figure corresponds to regions of statistical significance between the two conditions tested.

B. Effect on leg muscle activation

The processed EMG signal from the TA muscle of a representative subject is shown in Fig. 5. Figure 5 shows an increase in left leg TA muscle activity during the initiation of the swing phase when the subject is presented with an upcoming sand patch. Specifically, there is increased TA activity for VO and VP conditions from 63-75%, where both conditions are statistically significantly different to normal rigid surface walking. This increased TA activity at initiation of the swing phase correlates as the cause of the ankle dorsiflexion acceleration presented in Fig. 4 (top). Increased TA activity is also present during the encounter of the visual sand patch from 105-125% for VO and VP conditions when the subject begins foot contact in the VR environment. Moreover, in Fig. 5 there is lower TA activity when the subject encounters an unexpected change in surface stiffness. This lower TA activity is present for the PO condition from 105-130% and has statistical significance when compared to all other conditions. Because this lower TA activity is unique to the PO condition, where there are no visual cues, it implies that unexpected changes in surface stiffness evoke lower TA muscle activation.

The processed EMG signal from the GA and SOL muscles of a representative subject are shown in Fig. 6 and Fig. 7, respectively. Figure 6 and Figure 7 both show a delayed muscle activation for the VO condition compared to normal walking. In Fig. 6, during the second gait cycle for rigid surface normal walking, the GA begins to activate around

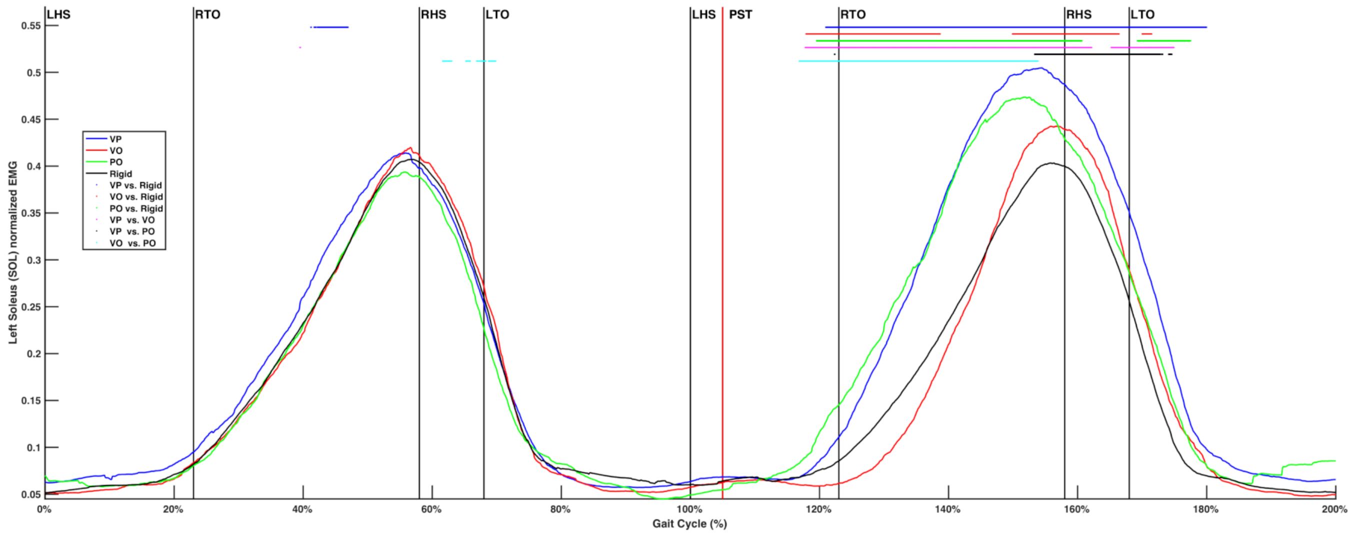

Fig. 7. Mean normalized activation for the left Soleus (SOL) muscle in the studied conditions. Horizontal sequence of colored dots (appearing as horizontal segmented lines) on the top part of the figure corresponds to regions of statistical significance between the two conditions tested.

115%, while for the VO condition the GA begins to activate around 130%. Similarly, in Fig. 7, during the second gait cycle for unperturbed walking, the SOL begins to activate around 118%, while for the VO condition, the SOL begins to activate around 130%. During the second gait cycle, both unperturbed and VO conditions are exerting the same physical effect: rigid surface walking (infinite stiffness). Therefore, the identified delayed muscle activation of the GA and SOL for the VO condition is related to the expectation of the perturbation by the subject and the absence of it.

IV. Conclusion

This paper addresses the interplay between visual and sensorimotor mechanisms of gait, as specifically identified in a unique experimental condition involving sudden changes of the walking surface compliance. A unique tool, the Variable Stiffness Treadmill (VST), is used as the platform for understanding those mechanisms in human locomotion, and in combination with a virtual reality system, they open a window in understanding feedback-driven mechanisms of gait.

The results of this study provide strong evidence that anticipation of walking surface compliance changes affects both muscle activation and kinematics of the leg preparing to land on the surface of different compliance. More specifically, the results show that the swing phase is accelerated when the subjects are convinced that they will be transitioning from a solid to a complaint surface. That accelerated swing phase is also supported by increased activity on the dorsi flexor muscles (Tibialis Anterior) during the swing phase before the landing of the foot. Moreover, the false expectation of transitioning to the new compliant surface, i.e. being prepared to step on a compliant surface but eventually stepping on a rigid one, elicits delayed responses on the plantar flexor muscles (Soleus and Gastrocnemius).

Therefore, this study shows for the first time how simple visual feedback alterations provided during gait can directly affect the dynamic responses of muscle activation and coordination. Going beyond those observations, the evoked responses can lead to significant advances in robot-assisted gait rehabilitation strategies, where simple but targeted visual and proprioceptive feedback disturbances can elicit natural muscles responses. Those have been seen to be linked to supraspinal mechanisms from the authors previous works [23].

In conclusion, this study provides fundamental evidence towards the overall goal of this work, which is to create mathematical models of the sensorimotor mechanisms of gait, and describe the effects of that visual and proprioceptive feedback have on them. Those models can be used in future robot-assisted gait therapies, where the intended muscle responses are informed by them and are tailored to a specific patient's needs, resulting in model-based rehabilitation of gait.

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