

Intentional Increases in Push-off Force Coupled With Visual Feedback: Towards New Strategies in Robot-Assisted Gait Rehabilitation

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Abstract—In recent years, robot-assisted gait rehabilitation has increased the use of visual feedback as a tool for therapy. In addition, specific training related to ground reaction forces, such as push-off force (POF), is associated with positive motor recovery outcomes after brain injuries such as stroke. This study investigated explicitly the effects of visual force feedback on intentional increases in POF. Findings include significant increases in POF for subjects who received visual feedback compared to the control. Further, significant increases in the activations of ankle and knee muscles are observed before, during, and after push-off when compared to baseline, along with strategic changes in all lower limb joint angles relating to POF-increasing strategies. This work sheds light on the interplay between visual feedback and intentional ground reaction force control, with direct implications for current robot-assisted gait training aspects. Targeted therapy focused on these strategies can be useful in the context of certain rehabilitation protocols based on the present results.

I. INTRODUCTION

The human eye contains up to 100 million photoreceptor cells for VF to make informed, dynamic decisions [1]. Walking, a complex task involving dynamic decision-making, can be challenging, especially on unfamiliar terrain or with obstacles that the body is less capable of handling, and even more so for individuals with lower limb pathologies [2].

Brain lesions can disrupt visual systems [3], making navigation difficult [4]. These lesions often lead to muscle control loss [5], complicating retraining needs. Therefore, many therapy techniques incorporate live VF. For example, upper limb rehabilitation with VF devices has shown better outcomes compared to conventional therapy [6]. However, feedback is used in somewhat limited forms in gait therapy, with kinematic-only feedback most frequently used. For example, kinematic feedback such as toe trajectory, helps subjects understand foot clearance [7], reducing drop-foot incidents in stroke survivors with hemiplegia [8]. Direct joint feedback has guided patients towards optimal training trajectories [9], while force feedback has had limited use to increase anterior-directed push-off forces [10–13], with direct force feedback remains largely unexplored, particularly for vertical push-off forces [14].

Gait therapy goals vary widely depending on individual pathology and recovery time. Increasing muscle activation

is often primary [15], with step length symmetry showing importance for progress and outcomes [16], and monitoring joint angle trajectories are crucial for ensuring proper gait training patterns [17]. Toe-off force is a primary concern [18] since it can encompass the above-mentioned goals into a single target [19]. The 3D push-off force is an adjacent measure of not only ankle muscle performance [20] but also the lower limb kinetic chain [21], with the anterior-posterior component responsible for forward propulsion [22], and the vertical component having the largest magnitude [23].

Previous studies have often focused on within-subject designs, investigating only anterior-posterior forces at push-off without measurement of the muscle activity surrounding the hip and knee, or analysis of joint kinematics during push-off [10–12]. These are critical to measure to fully assess the effectiveness of visual force feedback in increasing push-off force before combining it with complex robot-assisted therapy interventions.

Thus, there is a need for VF in gait training, and robotic devices can fulfill this need [9, 24]. This work evaluates live, sustained visual vertical force feedback in gait training aimed at increasing push-off force. We propose a unique framework and hypothesize that visual force feedback during gait training can outperform training that does not use VF, and that even those trained to increase push-off force can still benefit from VF. These experiments show that VF successfully trained subjects to increase push-off force, and those who continued using VF significantly increased the desired push-off force level. This study also provides the resulting joint kinematics and muscle activity associated, with analysis and comparison to a control group. These findings support using visual force feedback in rehabilitation protocols, advancing robot-assisted gait therapy techniques.

This paper is organized as follows: Section II introduces the unique experiment setup, protocol, and data processing techniques. Section III presents experimental results, and comments on the interventional outcomes. Section IV concludes by highlighting the novel contributions and discussing future implications of this work in robot-assisted rehabilitation.

II. METHODS

A. Experimental Setup

A unique instrumented robotic treadmill, the Variable Stiffness Treadmill (VST) [25] was used, as shown in Fig. 1. This device features real-time walking surface stiffness changes by controlling the fulcrum of a spring-attached lever

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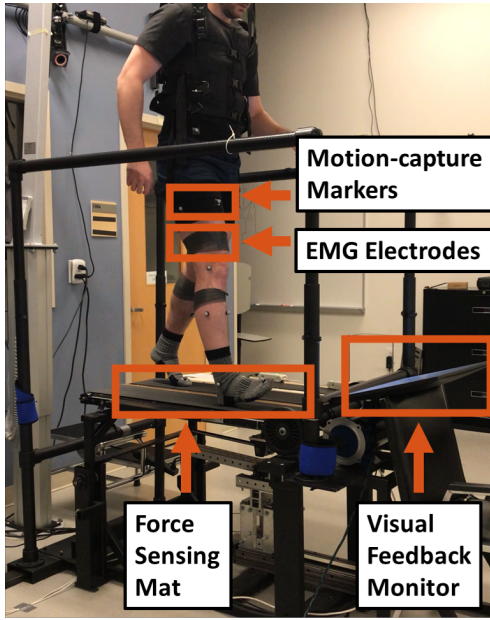


Fig. 1. Experimental setup with a representative subject walking on the force sensing mat, wearing reflective markers and EMG electrodes on the legs, and observing the visual feedback display.

underneath the split-belt platform. VST also includes synchronized motion capture, surface electromyography (EMG), ground reaction force (GRF) recordings, and visual feedback, aligning with the goals of this study. Stiffness changes are not used in this study, but are important for the continuation of this work, detailed in the last section.

Two TekScan Medical Sensors (TekScan Inc.) capture GRFs at 60Hz and shown to the subject with a 27-inch screen (see Fig. 1), placed for a comfortable downward gaze to decrease interference with normal gait mechanics and head position. A safety harness (Litegait Inc.) is used to eliminate safety concerns.

Reflective markers placed on the subject are captured by eight cameras at 100Hz (Vicon Motion Systems Ltd.) and are used for real-time detection of the heel-strike (HS) events [26] and lower-limb joint kinematics. Delsys Trigno wireless surface electromyography (EMG) system (Delsys Inc.) records muscle activity 2000 Hz for the left and right Vastus Medialis (VM), Biceps Femoris (BF), Tibialis Anterior (TA), Gastrocnemius (GA), and the Soleus (SOL). A digital trigger unit temporally synchronizes all data.

B. Experimental Protocol

Participants gave informed consent of the protocol for this study, which was approved by the University of Delaware Institutional Review Board (IRB ID: 1544521-2). A total of ten subjects (6 male, 4 female; age = 26 ± 1.5 years; body mass = 73 ± 13 Kg; height = 171 ± 9.1 cm) free from any injuries affecting the lower limbs, gait abnormalities, and attention difficulties participated in this study. The entire experiment is separated into two halves: the Training half, and the Trial half.

1) *Training Protocol*: All subjects were instructed to walk on VST at 90 cm/s for around 100 gait cycles for

the Acclimation section of Training, aligning with previous works on VST [27,28]. Subjects were informed that the VST monitor displays the force exerted on the left belt surface (see Fig. 2).

A baseline average of the subject's left GRF profile is displayed for the entire training phase as a static background image (see fig. 2) with a dot (BL) representing the peak push-off force (POF), and a target dot representing 150% of the individual's body weight (BW). This target was chosen experimentally beforehand, the subject's baseline was unknown before starting. This produces a meaningful difficulty level, increasing the motivation of the subject. As the subject walks, the real-time GRF is shown as black points moving across the screen, and the subject is able to see the live total force exerted relative to baseline, which has not been done in this application.

Subjects walked for 10 gait cycles normally (BL phase), followed by 30 gait cycles where POF is intentionally increased while watching a monitor (increased POF phase). This feedback gives as much relevant information as possible, allowing real-time adjustment of POF strategy. These 40 gait cycles form one section of training, with subjects given three to twelve sections in total after Acclimation (see Fig. 3) depending on performance. Verbal cues were given to ensure all subjects successfully increased POF equally, with success defined as achieving above-target POF in at least 50% of a training section. External cues have been used extensively in the literature for influencing force output [29, 30]. All subjects reached the same training level before proceeding to the trial portion, with a five-minute rest to prevent fatigue.

2) *Trial Protocol*: Subjects completed one round of three sections using the same strategies as during training (see Fig.

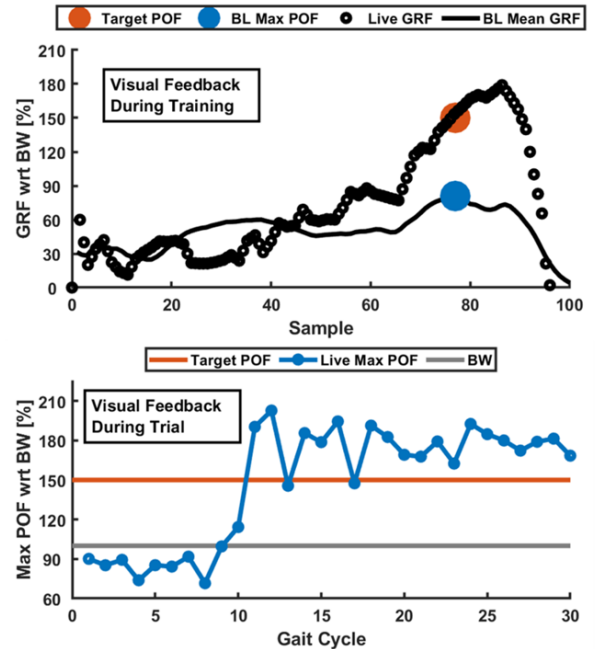


Fig. 2. Snapshot of the actual visual feedback given to the subjects, with training shown on top, and trial shown on the bottom. The axes units, labels, or legends were not shown to the subjects, but they are included in the figure for clarity.

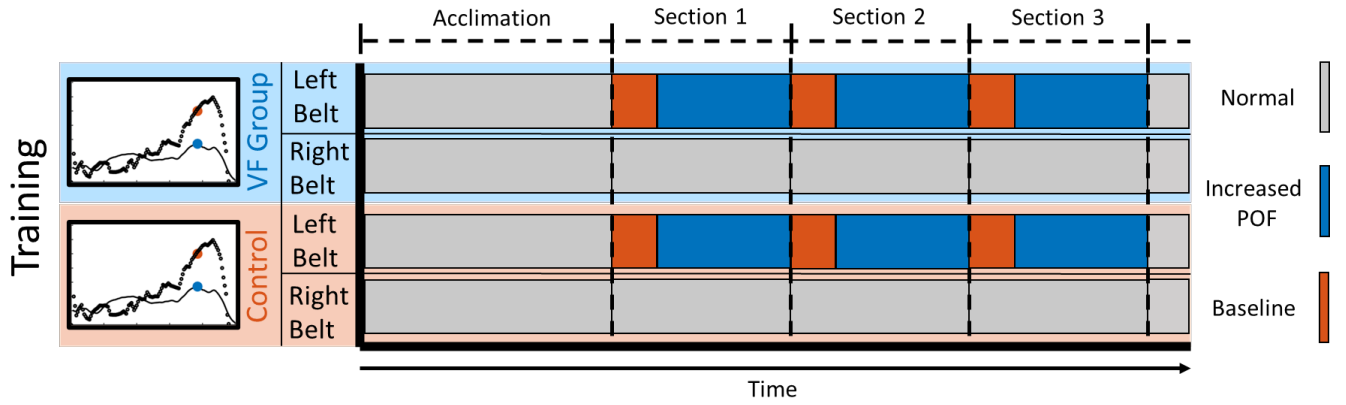


Fig. 3. For each group, the visual feedback used is shown on the left, with the relative number of gait cycles in each trial phase proportioned through time, and for each belt individually. Each group received the same visual feedback, and were trained to increase POF to equal standards.

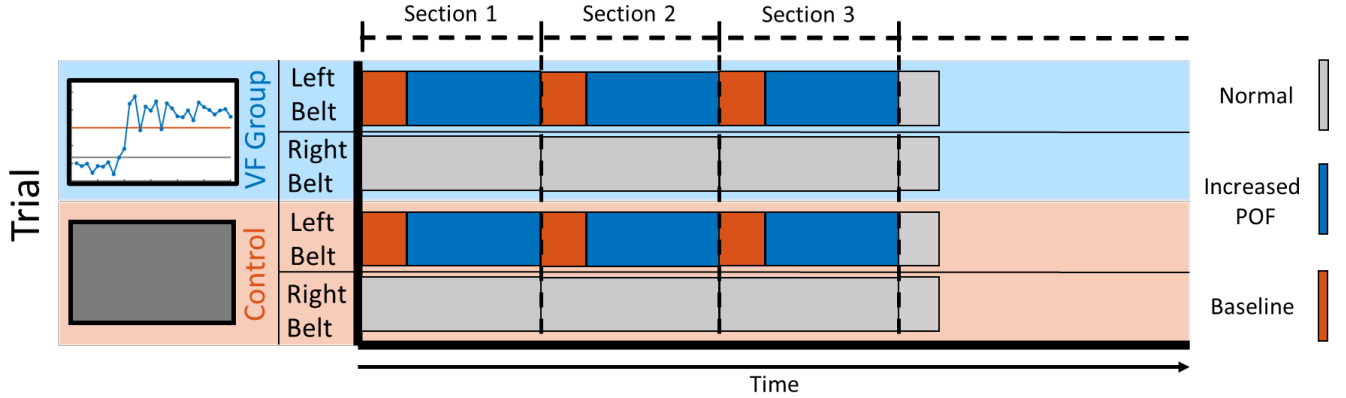


Fig. 4. For each group, the visual feedback used is shown on the left, with the relative number of gait cycles in each trial phase proportioned through time, and for each belt individually.

4), but without additional verbal cues. Subjects were then split into two groups: control and Visual Feedback (VF). The control group had no visual feedback, while the VF group received a simplified version of the visual feedback (see Fig. 2), comprising just a target line and a body weight reference, in addition to the peak push-off force (POF) of the current gait cycle in real-time. Since the subjects were already trained, detailed feedback was not needed. One new point for each gait cycle showed POF performance relative to the target, and remained to show effort relative to previous gait cycles, which is novel for this type of intervention.

C. Data Processing

Only the last section's baseline and increased POF phases were analyzed, with outliers removed using known methods [31]. In order to mitigate the effects of any technique re-learning by the subjects, only the last section's baseline phase and increased POF phase are interpreted below. The POF is normalized to the baseline average, and a single-tailed, two-sample t-test ($\alpha = 0.05$) compared POF between VF and control groups for both the training and trial phases. Force data is further separated within groups to compare the baseline phase and increased POF phase GRF profiles. The 3D joint kinematics are calculated from the Vicon Plug-in-Gait model (Vicon Motion Systems Ltd.), and filtered EMG

data are normalized to the maximum value recorded in the experiment (EM).

III. RESULTS

These findings suggest that subjects were able to significantly increase POF if given visual force feedback when compared to subjects given no feedback at all ($p < 0.0001$), even when training performance between groups did not differ ($p = 0.7$), as shown in Fig. 5. Moreover, results show that subjects in the VF group were able to increase POF even more during the trial phase (+11%) than during the training phase, while the control group was marginally unable to fully maintain the increased level of POF (-1%) and overall struggled to maintain consistency (-15%) more than the VF group. This makes the magnitude of the effect of visual feedback more meaningful since both groups were trained equally well to increase POF. While the retention effects were apparent regardless, only the VF group was able to significantly increase POF, which has significant implications for the future of visual feedback in POF-focused rehabilitation strategies.

Within-group analysis of GRF profiles further indicates that the increase in POF is accompanied by an increase in stance-phase duration by 20% on average (see Fig. 6). Interestingly, even though the control group failed to increase

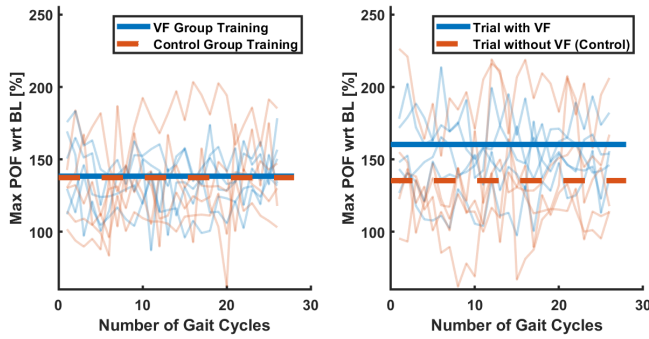


Fig. 5. All subject POF values in the last increased POF phase of training (left) and trial (right), normalized to each subject average POF during the last baseline (BL) phase. Thin lines represent each subject's data, and thick lines are the average across all subjects and gait cycles, per group. The trial phase target was 150% of each subject's bodyweight.

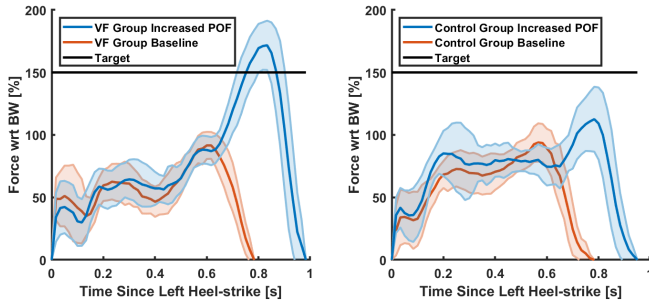


Fig. 6. GRF profile during the final trial phase for a representative subject from the VF group (left) and control group (right). All force values are normalized with respect to body weight (BW) in order to accurately show the target.

POF during the trial, they still maintained an increase in stance-phase duration (18%), implying that the control group subjects were still trying to increase POF intentionally, but through an inadequate strategy. In particular, the effective strategy was lost, and instead of increasing POF, they increased time in the stance phase without any performance benefit.

Delving further into the analysis of the trial phase, it is clear that a number of consistent and coordinated strategies are implemented across subjects in the successful VF group. These strategies can be used to inform future implementations of visual feedback during intentional POF increases in the rehabilitation process and could align with the patient's specific goals. For simplicity, an average subject is used as a representation of the VF group during the trial phase, since averaging the gait cycles across subjects will erase individual patterns, although these results are apparent with generally all subjects of the VF group. In addition, strategies are differentiated by the preparation leading up to the maximum POF, the initiation of POF, and the compensation immediately after the following through.

In the preparation leading up to increasing POF, the subject's left ankle is more plantarflexed during the left single-support phase, with the left knee in a slightly more extended position (see Fig. 7). With this, an increased left TA activation is seen compared to BL, and decreasing at a slower rate compared to BL when leading up to POF (see Fig. 8).

This finding can indicate that subjects are preparing the left leg by lifting the heel pre-emptively and thus are required to stabilize the ankle more with an increase in overall left TA activation. Since left TA activation is nearly double, but with a large standard deviation, this could indicate that there is a lack of efficiency in execution and an increase in preparation strategy variance between gait cycles. More training likely could hone in on the variation, however, this finding is still relevant because it shows that subjects are willing to employ a strategy that adequately prepares for an increased POF, at the expense of an increased need for ankle stability, which is a known target for multiple therapy modalities.

The right leg preparation differences are shown mostly in the time immediately before maximum POF occurs. Specifically, the right hip achieves a higher peak flexion, while at the same time, the knee shows a more sustained flexion for a longer time (see Fig. 7). This means that the subject is allowing the right leg to close the distance between the hip and ankle, thereby staying in a more curled position, to prepare for the right heel strike that directly follows the maximum POF. This corroborates the observation that successful subjects tended to allow the right leg to hang in the air for a slightly longer period of time, just before an increased POF attempt. Even though this results in an overall increase of right swing duration, thus increasing gait asymmetry, this finding is clinically relevant to methods that intentionally target an increase in swing phase duration, for patients with decreased-swing behaviors [32].

During the initiation of maximum POF, there are remarkable changes in the muscle activity involved in both legs. On average, maximum POF occurs between 78-85% of the stance phase, which correlates to 50-55% of the gait cycle, or just before right HS on average for this particular population. Results are most prominent in the left leg, with large increases seen in the left GA and SOL peak activation (see Fig. 8). This is reflected in the markedly larger ankle plantarflexion during the initiation of POF, as well as a more extended knee. This finding alone presents convincing evidence for visual feedback having the potential to play a significant role in rehabilitation protocols that prioritize ankle plantarflexor training, due to the magnitude of effect when compared to baseline. In addition to ankle muscle findings, the substantial appearance of left BF and VM activity is highly notable.

The co-contraction of these two opposing muscles suggests stability demands are also increased when increasing POF and that joint stiffness is likely increasing during push-off as a result. Because the left hip is similar in both baseline and POF initiation but is more extended immediately afterward, it can be concluded that an increase in hip extension is a secondary means of increased POF. Further, the bi-articular nature of the BF is causing simultaneous hip extension and knee flexion, and since hip extension increase is a known outcome, the knee requires a similar reaction from the knee extensors, namely the VM, in order to counteract this BF. This also likely increases the contribution of the knee in maximum POF, however, it is likely to be less than the

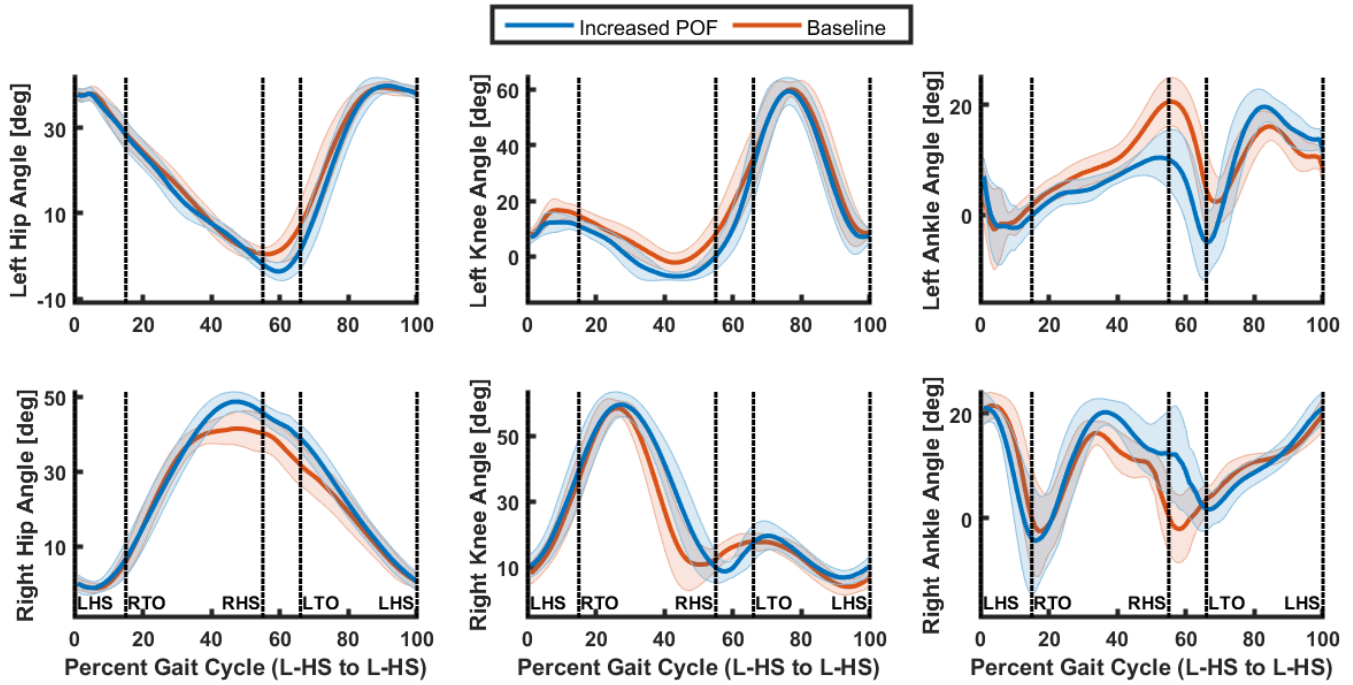


Fig. 7. Results showing all joint angles for both left and right legs of the subject representing the average for the trial in the VF group.

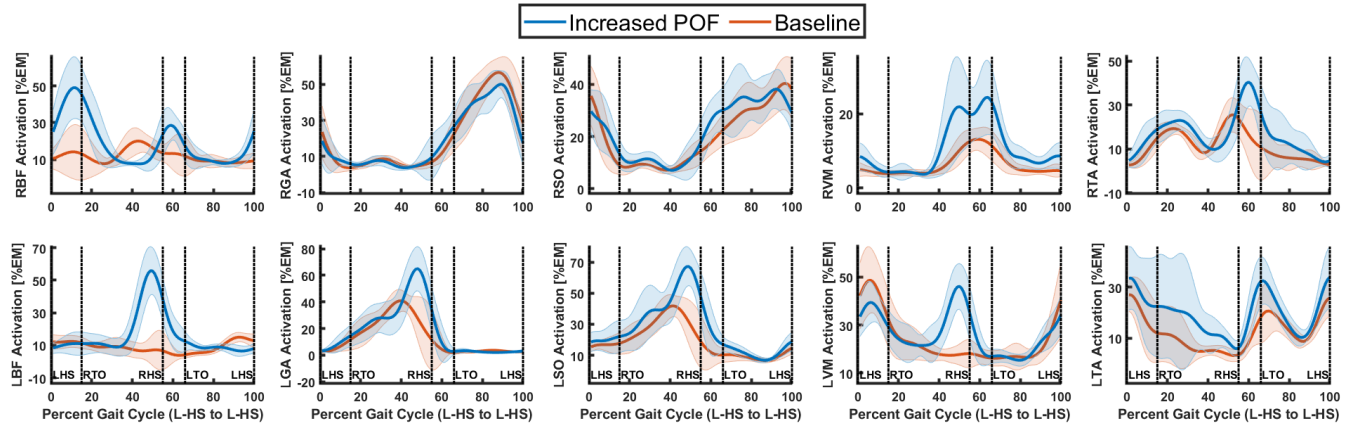


Fig. 8. Resulting muscle activity recorded for both left and right legs of the subject representing the average for the trial in the VF group. The units are normalized to the experiment maximum (EM).

contribution of the ankle. This increase in overall muscle activity and joint stiffness during POF should be explored further extract useful paradigms in gait training based on these findings, as have been done in previous works [33,34].

The immediate compensation following the maximum POF event is seen in two notable ways. The first is an increase in right ankle dorsiflexion after right HS. This effect is coupled with an increase in right TA activation and can be interpreted as a recovery response that potentially minimizes the effect that the left leg has on inducing an imbalance in the individual after increasing POF. This effect is further seen with the increased and sustained activation of the right VM that lasts from POF initiation, through the left toe-off. Since it is not clear what this strategy achieves overall, it is a finding that should be explored further, since the right TA has shown to be a target of interest for stroke rehabilitation [35,36].

A possible limitation of this study could be found in the

fact that the subjects were given a verbal count-down phase transitions. While this likely would not change the overall outcome, there was a trend for some subjects to increase POF during those steps, implying 100% effort may not have been achieved for every gait cycle prior. The use of verbal gait cycle counting, which was chosen to keep the subject's full attention on the screen. There was a noticeable trend in the VF group of decreasing POF during the end of the last session. Since only the last session was included in analysis, results could be even higher for the VF group if fatigue was not a factor. It should be noted that subjects modified gait patterns in general. Abnormal gait cycle characteristics were avoided at the extremes, and overall, the subjects walked mostly normally on average, without any notable jumping, hopping, or skipping to achieve success in either half of the trial. This is significant because the subjects did not have to drastically alter gait mechanics in order to achieve large increases in muscle activation and POF.

IV. CONCLUSIONS

The inclusion of visual feedback as an additional tool in robot-assisted rehabilitation is largely beneficial in many aspects of therapy. This study investigated the effects of visual force feedback on intentional increases in push-off force (POF). Results show that subjects who received visual feedback were able to significantly increase POF when compared to the control. In addition, large increases in GA, SOL, BF, and VM muscle activity are observed at time instances around push-off, alongside coupled strategy changes at the hip, knee, and ankle joint when compared to baseline walking. Based on these results, therapy targeting only one of these strategies could be useful in the context of certain rehabilitation protocols. It is clear that the interplay between visual feedback and voluntary force control could have implications beyond the present work, especially for robot-assisted gait training that would utilize the full capabilities of the VST. Future studies should include more advanced modeling of the joint stiffness changes induced during such a trial, how ground stiffness changes could alter and interact with these strategies, and how visual feedback techniques could be improved for better overall performance.

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