Virtual Reality-based Robot-Assisted Method for Gait Training Showing Retention of Anticipatory Motor Responses

Bradley Hobbs and Panagiotis Artemiadis*, *IEEE Senior Member*

***Abstract*— The recent increase in attention toward robotic assistance in gait therapy has prompted a clear need for useful paradigms that can interface with such devices. This is especially true for post-stroke rehabilitation, for which impairments in walking are particularly debilitating and notoriously difficult to overcome. Until recently, robot-assisted gait training methods tended to target only a single aspect of the human sensorimotor system, usually proprioception. To address this limitation, a virtual reality (VR) system is united with the unique robotic rehabilitation platform, the Variable Stiffness Treadmill (VST), in order to understand the complex interactions between visual and proprioceptive feedback in gait. This work proposes a new type of intervention that directly results in significant anticipatory responses to stiffness perturbations, even when those anticipated perturbations may not occur, showing that using a VR system can lead to the retention of training provided. The results show relevant and repeatable responses, which can lay the foundation for more effective protocols that can be used for a wider array of robotic systems and sensory modalities.**

I. Introduction

The majority of the human brain is devoted to vision and movement [1]. Following traumatic brain injuries such as stroke, brain lesions can interrupt these neural circuits [2], which is why many rehabilitation protocols target both modalities [3]. Numerous studies have demonstrated the importance of combining visual and proprioceptive feedback in rehabilitation [4] [5], especially for lower limb gait therapy [6]. This highlights a gap for standardized protocols that can effectively interface with these modalities [7].

Early visual systems in rehabilitation included subjects looking at screens with kinematic-based feedback [8]. This led to the use of gaming devices, such as virtual reality (VR) headsets [9], which immerse the wearer in complex environments for therapy goals [10]. VR has shown promise as a valuable tool to interface with the brain's visual system and combine with other physical modalities of treatment [9]. Given that motor learning requires full attention and intent [11], VR systems play a unique role in robotic gait rehabilitation.

In stroke rehabilitation, particularly VR-based approaches, a lack of motivation is a predictor for poor treatment adherence [12]. Since patient success is dose-dependent on protocol intensity, finding protocols that decrease intensity while maintaining outcomes could increase adherence [13]. Overground walking requires both reactive and anticipatory control [14], with anticipatory control being crucial [15] and affected by aging [16] [17]. Training for anticipation of visual perturbations has shown improvements in variables relevant to stroke therapy, such as step length, walking speed, and balance [18] [19], since the brain controls motor functions in anticipation of ground changes, rather than reflexively responding [20].

Previous studies are limited by inconsistent visual feed-

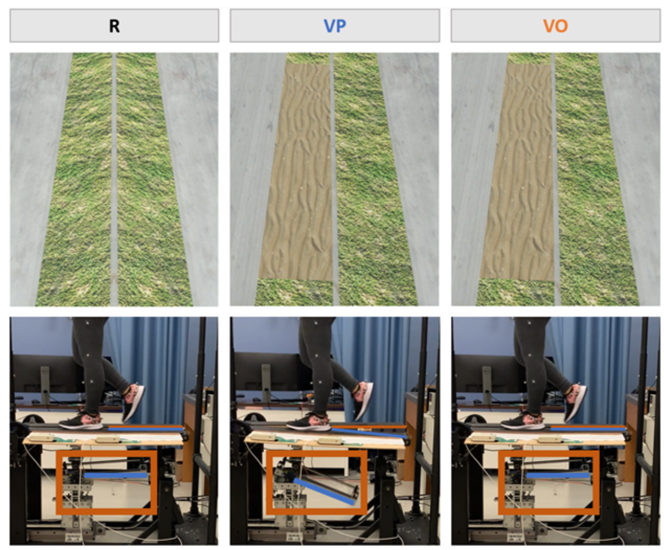

Fig. 1. The three possible conditions experienced by the subjects during the study. The physical perturbation is shown in the lower parts of the figure, with the VP condition section clearly showing a deflection of the VSM and the left treadmill belt, giving proprioceptive feedback to the subject. The physically rigid condition is experienced in the other two lower figures. In the top figures, VP and VO conditions show the sand patch seen by the subject, while all Rigid condition gait cycles show continuous grass when sand patches are not presented as visual feedback.

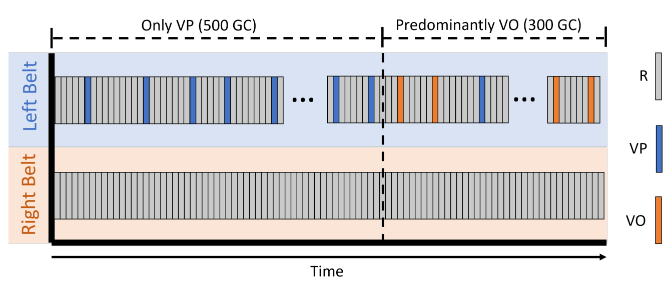

Fig. 2. Experiment design showing a sample of Rigid, VO, and VP gait cycle sections where gait cycle is denoted as GC. The number of VO, VP, and PO patches in this figure is not to scale. The left side of the VST experiences physical perturbations, while the right side remains rigid for this study. The first phase, lasting for 500 gait cycles, contains VP conditioned gait cycles every 7 $\pm$ 2 steps. The second phase lasting 300 GC contains VO conditioned gait cycles every 7 $\pm$ 2 steps.

*This material is based upon work supported by the National Science Foundation under Grants No. #2020009, #2015786, #2025797, and #2018905, and the National Institutes of Health Grant No. 1R01HD111071-01.

Bradley Hobbs and Panagiotis Artemiadis are with the Mechanical Engineering Department, at the University of Delaware, Newark, DE 19716, USA. bwh@udel.edu, partem@udel.edu

*Corrresponding author: partem@udel.edu

back [21] or walking speed [18], disturbances to proprioceptive feedback [19] [22] and exclusion of physical perturbations [19] or virtual environment [23]. To our knowledge, no study has investigated anticipatory accommodation strategies with consistent gait speed and ground contact while controlling for visual and physical perturbations. Observing the ability to anticipate walking surface changes can improve VR-based protocols.

Repetition drives rehabilitation [24], and current robotic methods in proprioceptive-based therapy allow for multiple ways of interfacing with the brain's control of movement. Instrumented robotic treadmill systems provide a way to implement gait training in a controlled environment [25]. Error-inducing methods that force adaptation to force changes, such as perturbations, have advantages in requiring user focus and adaptation [26]. Stiffness changes are useful because they mimic real-world ground changes. Previous studies have demonstrated this with stroke-affected subjects [27–29], but more research is needed to implement such modalities broadly, especially in robotic treadmill systems.

There is a need for visual feedback in motor learning and usefulness for proprioception-based protocols in robot-assisted treadmill training. Preliminary research on combining the two modalities in perturbation-based training has shown promise in increasing muscle activity and gait parameters related to anticipation [30] [31,32], because it is well known that reduced muscle activity on the affected side of the body is associated with motor learning deficiencies, and anticipatory responses are an avenue for targeting these deficiencies [33]. We aim to improve this by understanding how adaptations made during training can be retained, potentially reducing the need for constant physical perturbations, expanding the amount of eligible participants. We hypothesize that these anticipatory responses can be retained without the physical stimulus. In this study, subjects were convinced the next step would be on a compliant surface based on visual feedback alone after training with both visual and physical stimuli. These findings support and build upon previous research and allow for a new type of protocol that can increase retention, decrease training intensity, and be as effective as previous training modalities, offering the next natural step towards robot-assisted gait rehabilitation to a broader patient population.

II. Methods

A. Experimental Setup

An instrumented robotic split-belt variable-stiffness treadmill (VST) was used for the unique capabilities (shown in Fig. 3). This device allows finely controlled changes in walking surface stiffness, influencing the subject's proprioception, through a lever-attached spring underneath the walking surface that is connected to a controlled fulcrum, achieves stiffness resolutions of less than 0.0001 kN/m [34]. The effective stiffness can change from 0.1 kN/m to over 1,000 kN/m within an average human swing phase time [34].

Visual feedback was controlled using an Oculus Rift (Oculus Inc.) headset projecting a virtual reality (VR) environment. The custom-made environment in Unreal Engine 4 (UE4) provided a straight-line walking path resembling a hard, grassy surface, with the softer, sandy surface texture resembling a surface of lowered stiffness (see Fig. 3). The wearer sees real-time leg motion through their avatar (see Fig. 3, on the right).

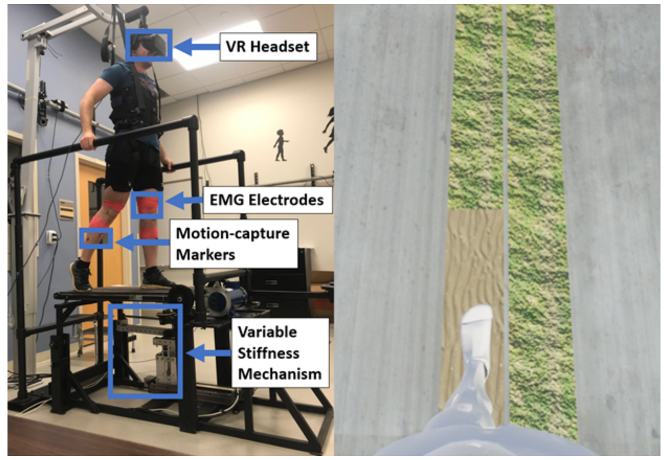

Fig. 3. Left: Real Environment showing experimental setup with subject walking on the VST wearing the safety harness, the VR headset, the EMG electrodes, and the motion capture markers. Right: Virtual Environment showing the left foot placement in the subject's avatar corresponding to the exact foot placement of the subject's real foot.

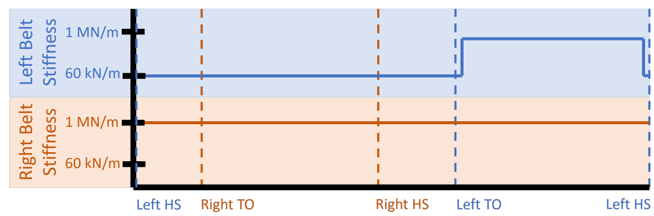

Fig. 4. Timing of the unilateral stiffness perturbation for a single gait cycle, where heel-strike and toe-off are represented by HS and TO, respectively. The left belt stiffness is lowered to 60 kN/m during the left stance phase and is brought back to rigid during the swing phase so that only two stiffness levels are felt for a given gait cycle on the left side of the body. The right side of the body only experiences rigid walking for this study.

Real-time subject motion is captured with a 3D motion capture system using standard reflective markers on the lower body, with eight cameras transmitting data to Vicon Nexus software (Vicon Motion Systems Ltd.). The marker positions are converted to joint angles and sent to UE4, moving the subject's avatar limbs at 200Hz. Delsys Trigno surface electromyography (EMG) electrodes (Delsys Inc.) captured bilateral muscle activity for biceps femoris, vastus medialis, tibialis anterior and gastrocnemius at 2000Hz, representing knee and ankle flexors and extensors, relevant for post-stroke gait analysis and therapy [35].

B. Protocol

All subjects gave informed consent of the protocol approved by the University of Delaware Institutional Review Board (IRB ID: 1544521-2). Nine healthy subjects participated in this study (6 male, 3 female; age = 25 $\pm$ 0.7 years; body mass = 71 $\pm$ 4 kg; height = 169 $\pm$ 7 cm) and were absent of gait abnormalities and regular VR use. Subjects wore a safety harness (Litegait Inc.) and walked on the VST at 0.9m/s for 800 gait cycles (see Fig. 1), divided into two phases (see Fig. 2). The first phase (500 GC's) included Rigid (R) and visually and physically perturbed (VP) gait cycle conditions. Gait cycles during the Rigid condition show the hard, grassy path while walking on 1,000 kN/m surface stiffness, with VP condition showing the soft, sandy texture while walking on 60 kN/m stiffness [36] on the left belt, returning to rigid before the next left heel-strike (see Fig. 4). The VP condition appeared after 5-9 gait cycles with an average R:VP ratio of 7:1, with the aim being to learn association between visual and physical stimuli.

The second phase (300 GC's) included Rigid (R) and *visually only* perturbed (VO) conditions. The condition of *physically only* perturbed has been studied and is outside the scope of this experiment [31, 32].

Gait cycles during Rigid condition match the first phase, with VO condition involving the soft, sandy texture while walking on 1,000 kN/m stiffness. The VO condition appeared after every 5-9 gait cycles with an average R:VO ratio of 7:1, assessing if subjects showed similar anticipatory responses as the first phase, but without physical stimuli. Intermittent VP condition gait cycles ensured subject confidence in the association, appearing after every 3-5 VO condition with an average VO ratio of 4:1, and are omitted from analysis.

C. Data Processing

The Vicon Plug-in-Gait (PiG) model was used for marker placement, real-time heel-strike event detection [37], and extraction of hip, knee, and ankle joint angles and velocities, and hip-ankle span. Each gait cycle was normalized to start at the left heel strike (LHS) for kinematic and EMG data, with EMG data normalized as a percentage of the experiment maximum (EM) to prevent excess fatigue during maximum voluntary isometric contraction. Since this work is focused on anticipatory changes, all gait cycles *for each individual type of data* discussed hereafter are grouped into three classifications based on the condition that will *follow* that gait cycle.

Gait cycles are classified based on the next step's condition, excluding data from that next step. Outlier gait cycles were removed based on criteria from [38], and a 2-sample t-test determined if peak values of VP condition were significantly different from Rigid condition (α = 0.05), with the same test conducted for VO and Rigid conditions. If both tests reached statistical significance, the anticipatory responses for the first phase VP, were not only statistically different from rigid gait cycles, but also sustained even in the VO phase, regardless of physical perturbation.

Figures denote statistical significance of peak values with an asterisk, and discussed significance range with a horizontal line segment. Because statistical significance testing is not useful for data with steep slope, only the peak values within the range were checked statistically, however it is highly probable that the region within the line segment is also significant to the discussion and impact of the results from this work, which are detailed below.

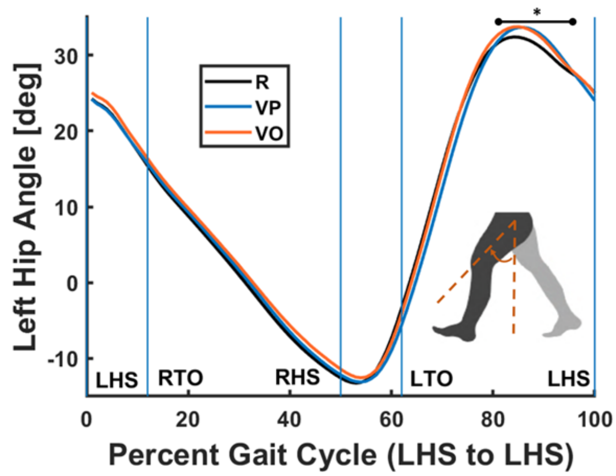

Fig. 5. Left hip flexion mean from 0% to 100% of the gait cycle, beginning at left heel-strike. The profile for VP (blue) and VO (orange) are compared against the rigid (grey) to show unified anticipation response immediately before the perturbation. Peak magnitude reaches statistical significance and is markedly changed after the peak.

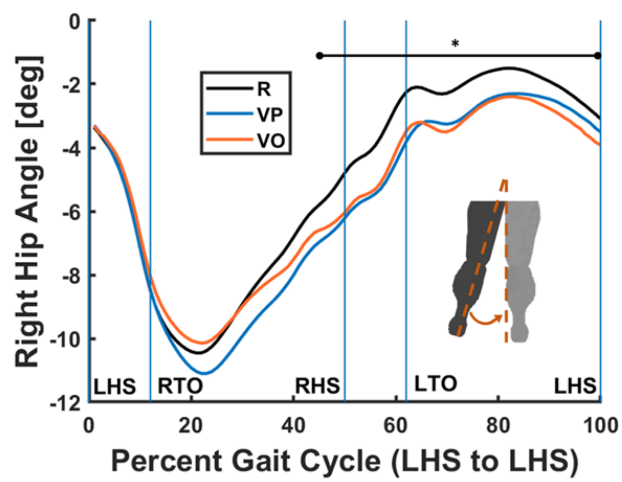

Fig. 6. Right hip adduction mean from 0% to 100% of the gait cycle, beginning at left heel-strike. The profile for VP (blue) and VO (orange) are compared against the rigid (grey) to show unified anticipation response for over half of the gait cycle before the perturbation. Peak magnitude reaches statistical significance during the left swing phase, but is clearly changed throughout the gait cycle as a whole.

III. Results

The results of the current study show that the subjects were convinced they were going to step on a surface of lowered stiffness, and retained those anticipatory responses even when the physical perturbations were removed (VO steps) for the duration of the trial. The subjects did this in a variety of ways that not only corroborate with previous works [32, 35, 39], but also are important to post-stroke robot-assisted gait rehabilitation [29]. To demonstrate the key findings clearly, all figures shown are a snapshot from one subject, representing the majority of changes across subjects, and because all specific patterns of muscle activity and kinematic data are unique to each subject.

Focusing on the kinematics, within the hip joint, the subject shows significant increases in left hip flexion (see Fig.

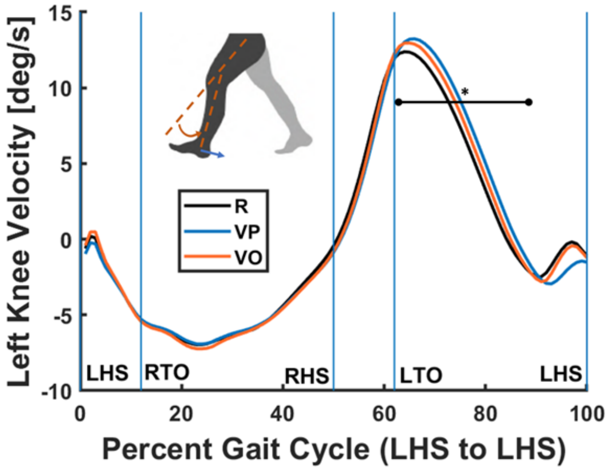

Fig. 7. Left knee velocity mean from 0% to 100% of the gait cycle, beginning and ending at left heel-strike. The VP (blue) and VO (orange) profiles are compared against Rigid (grey) to show unified anticipation response in 60% to 90% of the gait cycle before perturbation, with the peak reaching statistical significance and is markedly changed after the peak.

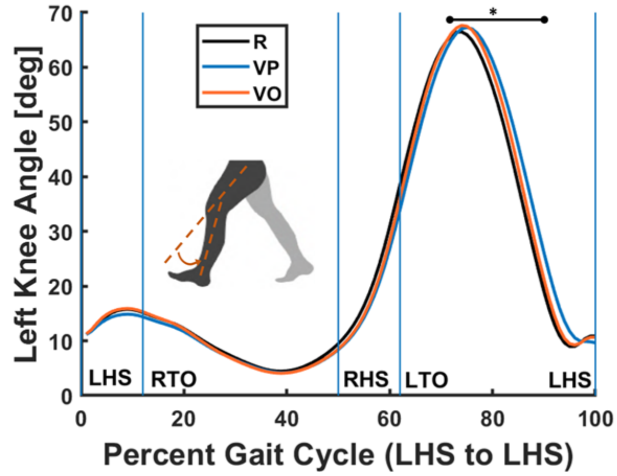

Fig. 8. Left knee angle mean from 0% to 100% of the gait cycle, beginning and ending at left heel-strike. The VP (blue) and VO (orange) profiles are compared against Rigid (grey) to show unified anticipation response in the middle third portion of the left swing phase before perturbation, with the peak reaching statistical significance and is markedly sustained.

5) and right hip adduction (see Fig. 6) during the left swing phase, just before stepping on the compliant surface. This particular finding is important because it shows not only that subjects were preparing to experience the perturbation even at the hip joint level, but also that left hip flexion was seen, as in previous works [32]. It is important to note that the left hip was observed to increase and project more anterior, further increasing the significance of the left hip flexion response; it would be expected that since the left hip joint was higher, further left hip flexion would be more difficult to reach with a higher hip joint. In addition, this increase in left hip position explains the increase in right hip adduction. Since the right leg is in the stance phase at this time, right hip adduction is needed to raise the left side of the hip. Upon further investigation, left hip abduction relative to the pelvis was found to not be statistically different, implying that subjects also increased activity of the left abductors, since the left hip was at a higher position, but the left femur-pelvis angle was unchanged. Since abductor muscle activity was not recorded, more research is needed to further elucidate this finding.

At the knee level, statistically significant findings can be seen in the left swing phase immediately before the perturbation in both the left knee velocity (see Fig. 7) and left knee flexion (see Fig. 8). Further, this increase was also sustained for both occurrences through the majority of the swing phase of the subject, showing a lasting effect of this response. This finding is significant in its own right because it shows that subjects may be anticipating the upcoming stiffness change by recoiling their leg longer to give more time to process the correct foot placement, since the VR is showing a clear finite sandpatch length, that should be fully stepped on, with the foot close to the center, and not partially on the sandpatch. Higher and more sustained knee flexion could be functioning as a way to give just enough time for this decision. Further analysis of the biceps femoris muscle activation showed that it was not consistently higher ($p = 0.4$) during this phase for all subjects, which could be due to other non-recorded hamstring or even the bi-articular gastrocnemius activation. However, this is still a relevant finding that should be explored further.

At the ankle joint level, there is a markedly higher peak left gastrocnemius (LGA) activity during the left stance phase and a decrease in left hip-ankle span during the left swing phase (see Fig. 9). The increase in LGA activity was initiated during the end of the terminal stance phase and was even sustained until the left toe-off occurred. This finding suggests that additional propulsion force was needed by the subject to prepare for the perturbation. It is expected that the placement of the right foot is critical to properly provide stability to the subject immediately before and during the perturbation. Since the right foot can only be planted once, and not shifted again before the perturbation begins, it can be hypothesized that the subject desired the position of the body (supported by the right foot just before the perturbation at the left heel strike) to be closer to the sand patch so that more time and less energy can be put into placing the left foot. This hypothesis is founded on findings of both the hip and the knee. Hip-ankle span is shown to be a marker of particular importance in stroke rehabilitation, as it combines and relates to other key outcome measures [35]. Here, a decrease in left hip-ankle span is seen during the exact period of increased knee flexion (see Fig. 10). Additionally, this hip-ankle span stayed markedly lower until the left heel strike occurred, showing that compared to stepping on a rigid surface, a time delay occurred prior to making the step on the compliant surface, regardless of whether that step was revealed to have a stiffness change or not.

In general, anticipatory responses were seen relatively quickly after initial VP training. Many subjects confirmed after the trial that they quickly learned to associate visual and physical feedback. From this, it is also likely that the amount of time spent training could even be decreased, and

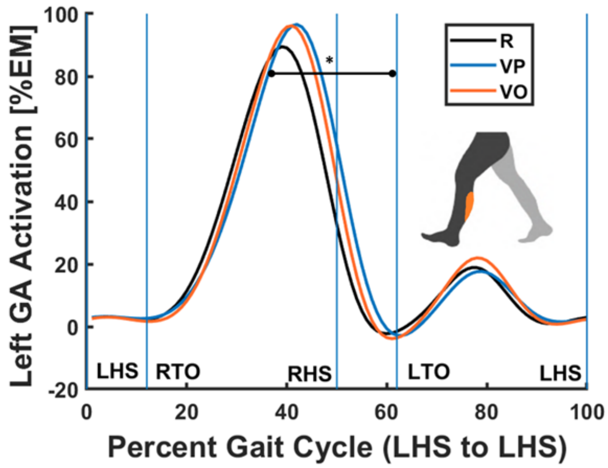

Fig. 9. Left GA activation mean from 0% to 100% of the gait cycle, beginning at left heel-strike. The profile for VP (blue) and VO (orange) are compared against the rigid (grey) to show a unified anticipation response in the middle of the right swing phase of the gait cycle before perturbation. Peak magnitude reaches statistical significance and is markedly sustained after the peak, only noticeably decreasing when left toe-off occurs.

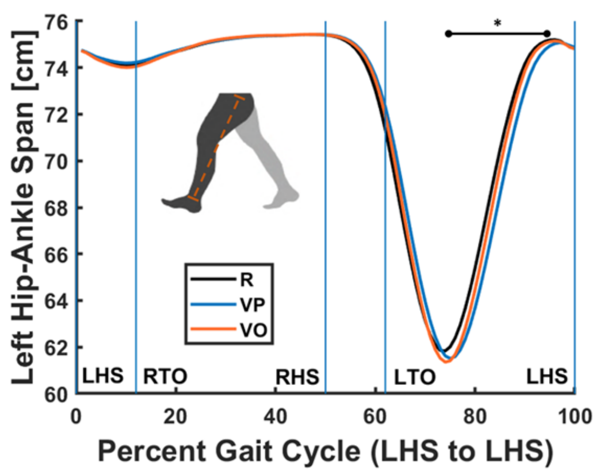

Fig. 10. Left hip-ankle span mean from 0% to 100% of the gait cycle, beginning at left heel-strike. The profile for VP (blue) and VO (orange) are compared against the rigid (grey) to show a unified anticipation response, reaching a peak at around 70% of the gait cycle before perturbation. Peak magnitude reaches statistical significance and is markedly sustained after the peak.

still achieve results. Future studies will investigate further the training dose requirements. Taken to the extreme, a similar protocol could simply include a higher VO:VP2 ratio, or only VO gait cycles in the last phase, but it is likely that subjects may ignore the previous training and walk normally without regard to the virtual environment, since the premise of the current work requires an established association between the sand patches and the compliant surface. Future studies should test for how large this ratio can grow before the participants start to disconnect this association and tailor the protocol accordingly to avoid any negative effects caused by this cognitive conflict. Overall, anticipatory responses were similar after repeated VO inputs, without significant trends of the effects decreasing over time. While every subject expressed being convinced by the majority of VO gait cycles, it could be reasonably hypothesized that eventually subjects may become comfortable with not receiving physical perturbations, and the expectation could wear off, however, this trial was designed to mitigate those effects. It is also possible that some findings were caused by the subjects choosing to exhibit patterns related to stepping on a compliant surface, even though subjects had evidence that the surface might be rigid, because assuming that the surface will be compliant may be more comfortable for the subject due to the reduced joint stiffness and resulting impact forces [40]. Although the scope of this work only includes anticipation changes to answer the primary hypothesis, it is also important to note that all subjects were able to recover from the lack of stiffness changes within the next gait cycle, and without significant gait abnormalities. Another limitation of the current work is the relatively short study duration. Because the current work investigates a novel experimental design, a single-day study duration was chosen. Further studies should investigate how long the responses are retained over a larger timescale, and what changes occur in that timescale in order to have even more applicability to robot-assisted rehabilitation. No motion sickness was reported in this study.

Each finding shows that subjects learned to associate virtual sand patches with stiffness changes in the first phase and were still convinced that the next step would be a compliant surface in both virtual and physical environments. Subjects retained this anticipatory response throughout the experiment, demonstrating coordinated effort to prepare for expected surface changes in VR. These results highlight the crucial role of visual and proprioceptive feedback interplay in the body's responses to environmental changes, influencing long-term expectations, even before those changes occur and even without being presented repeatedly. These anticipatory responses are directly related to targeted therapy goals, providing evidence for coupling visual feedback with expected perturbations to improve recovery in rehabilitation. Such findings support using similar protocols for other robot-assisted gait therapies, improving outcomes through additional modalities.

IV. Conclusions

This paper unifies multiple modalities of sensorimotor learning during robot-assisted therapy for post-stroke gait rehabilitation. The Variable Stiffness Treadmill (VST) combined with a VR system enhances understanding of gait training mechanisms, specifically how the visual system can be used to train responses to visual and proprioceptive feedback. Stiffness changes evoke bilateral anticipatory responses in all three lower limb joints in coordinated ways, particularly when subjects expect the next step to be perturbed based on visual feedback. Increases in left hip flexion, right hip abduction, left swing phase knee flexion and velocity, and gastrocnemius activity are observed. Moreover, the combination of proprioceptive and visual feedback extends the training effect during trials with visual stimuli alone.

These significant findings provide substantial displays of how proper protocol design utilizing connected visual and proprioceptive modalities can drastically improve our understanding of gait training from a motor learning perspective. This study seeks to revolutionize robot-assisted gait rehabilitation, opening possibilities in the integration of neuroscience and robotics toward applications in intent recognition, fall evaluation, and fields outside of rehabilitation, such as dynamic control of robotic prostheses or exoskeletons.

References

[1] J. Stein and M. Glickstein, "Role of the cerebellum in visual guidance of movement," *Physiological reviews*, vol. 72, no. 4, pp. 967–1017, 1992.

[2] C. W. Tsao *et al.*, "Heart disease and stroke statistics—2022 update: a report from the american heart association," *Circulation*, vol. 145, no. 8, pp. e153–e639, 2022.

[3] L. M. Weber and J. Stein, "The use of robots in stroke rehabilitation: A narrative review," *NeuroRehabilitation*, vol. 43, no. 1, pp. 99–110, 2018.

[4] H. I. Krebs *et al.*, "Rehabilitation robotics: pilot trial of a spatial extension for mit-manus," *Journal of neuroengineering and rehabilitation*, vol. 1, no. 1, pp. 1–15, 2004.

[5] C. M. L. Hughes *et al.*, "Upper extremity proprioception in healthy aging and stroke populations, and the effects of therapist-and robot-based rehabilitation therapies on proprioceptive function," *Frontiers in human neuroscience*, vol. 9, p. 120, 2015.

[6] B. Hobbs and P. Artemiadis, "A review of robot-assisted lower-limb stroke therapy: unexplored paths and future directions in gait rehabilitation," *Frontiers in neurorobotics*, vol. 14, p. 19, 2020.

[7] M. C. Moreira *et al.*, "Use of virtual reality in gait recovery among post stroke patients–a systematic literature review," *Disability and Rehabilitation: Assistive Technology*, vol. 8, no. 5, pp. 357–362, 2013.

[8] L. Lunenburger *et al.*, "Biofeedback in gait training with the robotic orthosis lokomat," in *The 26th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, vol. 2. IEEE, 2004, pp. 4888–4891.

[9] E. Wade and C. J. Winstein, "Virtual reality and robotics for stroke rehabilitation: where do we go from here?" *Topics in stroke rehabilitation*, vol. 18, no. 6, pp. 685–700, 2011.

[10] E. De Keersmaecker *et al.*, "Virtual reality during gait training: does it improve gait function in persons with central nervous system movement disorders? a systematic review and meta-analysis," *NeuroRehabilitation*, vol. 44, no. 1, pp. 43–66, 2019.

[11] L. W. Forrester *et al.*, "Exercise-mediated locomotor recovery and lower-limb neuroplasticity after stroke." *Journal of Rehabilitation Research & Development*, vol. 45, no. 2, 2008.

[12] D. Cano Porras *et al.*, "Advantages of virtual reality in the rehabilitation of balance and gait: systematic review," *Neurology*, vol. 90, no. 22, pp. 1017–1025, 2018.

[13] G. Kwakkel, "Impact of intensity of practice after stroke: issues for consideration," *Disability and rehabilitation*, vol. 28, no. 13-14, pp. 823–830, 2006.

[14] J. J. Eng and P.-F. Tang, "Gait training strategies to optimize walking ability in people with stroke: a synthesis of the evidence," *Expert review of neurotherapeutics*, vol. 7, no. 10, pp. 1417–1436, 2007.

[15] C. K. Rhea and S. Rietdyk, "Influence of an unexpected perturbation on adaptive gait behavior," *Gait & Posture*, vol. 34, no. 3, pp. 439–441, 2011.

[16] R. Sakurai *et al.*, "Adaptive locomotion during subtle environmental changes in younger and older adults," *Scientific Reports*, vol. 12, no. 1, p. 12438, 2022.

[17] K. Wilmut and A. L. Barnett, "When an object appears unexpectedly: anticipatory movement and object circumvention in individuals with and without developmental coordination disorder," *Experimental brain research*, vol. 235, pp. 1531–1540, 2017.

[18] W.-C. Hsu *et al.*, "Anticipatory changes in control of swing foot and lower limb joints when walking onto a moving surface traveling at constant speed," *Gait & Posture*, vol. 41, no. 1, pp. 185–191, 2015.

[19] C. L. Richards *et al.*, "Gait training after stroke on a self-paced treadmill with and without virtual environment scenarios: a proof-of-principle study," *Physiotherapy Canada*, vol. 70, no. 3, pp. 221–230, 2018.

[20] S. Heuninckx *et al.*, "Neural basis of aging: the penetration of cognition into action control," *Journal of Neuroscience*, vol. 25, no. 29, pp. 6787–6796, 2005.

[21] B. J. McFadyen *et al.*, "Substituting anticipatory locomotor adjustments online is time constrained," *Experimental Brain Research*, vol. 236, pp. 1985–1996, 2018.

[22] J. Peng *et al.*, "Anticipatory kinematics and muscle activity preceding transitions from level-ground walking to stair ascent and descent," *Journal of biomechanics*, vol. 49, no. 4, pp. 528–536, 2016.

[23] F. Fiset and B. J. McFadyen, "The switching of trailing limb anticipatory locomotor adjustments is uninfluenced by what the leading limb does, but general time constraints remain," *Applied Sciences*, vol. 10, no. 7, p. 2256, 2020.

[24] P. Poli *et al.*, "Robotic technologies and rehabilitation: new tools for stroke patients' therapy," *BioMed Research International*, 2013.

[25] J. Skidmore and P. Artemiadis, "On the effect of walking surface stiffness on inter-limb coordination in human walking: toward bilaterally informed robotic gait rehabilitation," *Journal of neuroengineering and rehabilitation*, vol. 13, no. 1, pp. 1–11, 2016.

[26] J. T. Choi and A. J. Bastian, "Adaptation reveals independent control networks for human walking," *Nature neuroscience*, vol. 10, no. 8, pp. 1055–1062, 2007.

[27] J. Skidmore and P. Artemiadis, "Sudden changes in walking surface compliance evoke contralateral emg in a hemiparetic walker: a case study of inter-leg coordination after neurological injury," in *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2016, pp. 4682–4685.

[28] J. Skidmore and P. Artemiadis, "Unilateral changes in walking surface compliance evoke dorsiflexion in paretic leg of impaired walkers," *Journal of rehabilitation and assistive technologies engineering*, vol. 4, p. 2055668317738469, 2017.

[29] V. Chambers and P. Artemiadis, "Using robot-assisted stiffness perturbations to evoke aftereffects useful to post-stroke gait rehabilitation," *Frontiers in Robotics and AI*, vol. 9, p. 1073746, 2023.

[30] E. Q. Yumbla *et al.*, "Anticipatory muscle responses in transitions from rigid to compliant surfaces: towards smart ankle-foot prostheses," in *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2019, pp. 880–885.

[31] R. Frost *et al.*, "Sensorimotor control of gait: a novel approach for the study of the interplay of visual and proprioceptive feedback," *Frontiers in human neuroscience*, vol. 9, p. 14, 2015.

[32] M. Drolet *et al.*, "On the effects of visual anticipation of floor compliance changes on human gait: Towards model-based robot-assisted rehabilitation," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2020, pp. 9072–9078.

[33] R. Dickstein *et al.*, "Anticipatory postural adjustment in selected trunk muscles in poststroke hemiparetic patients," *Archives of physical medicine and rehabilitation*, vol. 85, no. 2, pp. 261–267, 2004.

[34] A. Barkan *et al.*, "Variable stiffness treadmill (vst): A novel tool for the investigation of gait," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2014, pp. 2838–2843.

[35] V. Chambers and P. Artemiadis, "Repeated Robot-assisted Unilateral Stiffness Perturbations Result in Significant Aftereffects Relevant to Post-Stroke Gait Rehabilitation," in *IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2022, pp. 5426–5433.

[36] R. S. Barrett *et al.*, "The dynamic loading response of surfaces encountered in beach running," *Journal of Science and Medicine in Sport*, vol. 1, no. 1, pp. 1–11, 1998.

[37] C. Karakasis and P. Artemiadis, "Real-time kinematic-based detection of foot-strike during walking," *Journal of Biomechanics*, vol. 129, 2021.

[38] B. Hobbs and P. Artemiadis, "A systematic method for outlier detection in human gait data," in *IEEE 17th International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2022.

[39] V. Chambers and P. Artemiadis, "A model-based analysis of the effect of repeated unilateral low stiffness perturbations on human gait: Toward robot-assisted rehabilitation," in *2023 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2023, pp. 12 631–12 637.

[40] D. P. Ferris *et al.*, "Runners adjust leg stiffness for their first step on a new running surface," *Journal of biomechanics*, vol. 32, no. 8, pp. 787–794, 1999.