Unilateral Compliant Surfaces in Post-Stroke Gait Retraining: Enhancing Symmetry and Stability

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***Abstract*— Stroke is a leading cause of disability worldwide, frequently resulting in gait dysfunction characterized by asymmetries in kinematics and kinetics, reduced push-off force, and diminished muscle activity. These impairments contribute to slow, unstable, and energy-intensive walking, significantly lowering the quality of life and increasing fall risk. Current rehabilitation strategies often fail to deliver a lasting and comprehensive recovery. This study investigates the use of unilaterally compliant terrain as a novel intervention for post-stroke gait rehabilitation. A brief 3 to 4-minute exposure to unilateral low-stiffness terrain was tested on six stroke survivors, yielding statistically significant aftereffects that persisted for up to 5 to 6 minutes post-intervention. Improvements included increased vertical push-off force, reductions in asymmetry in vertical push-off force, and improved center of pressure symmetry, which is related to balance during walking. These promising results suggest that unilaterally compliant terrain may enhance the effectiveness of gait retraining and contribute to more lasting functional recovery for stroke survivors.**

I. Introduction

A stroke, caused by a blocked or ruptured blood vessel in the brain, is a leading cause of disability, particularly affecting gait. Up to 85% of stroke survivors experience hemiplegia, or partial paralysis on one side of the body, which disrupts interlimb coordination – long thought to be controlled at the spine but now attributed to the brain as well [1–4]. Post-stroke gait is marked by slower speeds, instability, and a higher risk of falls [5]. At the timing level, impairments include increased stance and swing times and altered support phases [6–8]. Kinematic deficits involve reduced dorsiflexion, hip and knee flexion, and hip extension [9]. Decreased propulsion [6] and overall lower-limb muscle activity [6, 8] are also evident, though muscle activity patterns are highly variable among individuals. The resulting asymmetry is the hallmark of post-stroke gait, leading to inefficient and unstable walking [10].

Post-stroke gait rehabilitation has long focused on strategies such as body-weight-supported treadmill walking, which enables patients to practice walking in a safer environment with reduced fear of falling and, in some cases, with partial weight offloading to ease movement [11]. Split-belt treadmills, where belts move at different speeds, have shown promise, producing aftereffects lasting up to 10 minutes in both healthy individuals and stroke patients [12–14]. One study demonstrated significant improvements in step length asymmetry and walking speed after a stroke survivor underwent a month-long split-belt treadmill intervention – 30-minute sessions, three times per week – with these gains persisting even one month post-training [15]. While these approaches show varying degrees of success, post-stroke gait rehabilitation remains far from addressing the full spectrum of challenges [16,17]. Expanding rehabilitation strategies by integrating novel physical approaches, targeting diverse neurological pathways, and interacting with patients in innovative ways is likely to enhance outcomes [18].

Integrating robotics into post-stroke gait rehabilitation represents a promising avenue for innovation. Although robots have been extensively explored for upper-limb rehabilitation over the past 25 years [19, 20], their application to gait retraining is still developing. Robots provide unmatched precision and repeatability, making them particularly suited for complex and repetitive tasks like walking [21]. Exoskeletons, orthoses, and other robotic assistive technologies have been investigated for post-stroke gait rehabilitation [22, 23]. However, these technologies often demonstrate limited effectiveness [18], suggesting that further innovation is needed to fully realize their potential.

Efforts to advance robot-assisted post-stroke gait rehabilitation have increasingly focused on low-stiffness environments, particularly unilaterally compliant environments. These terrains theoretically drive neural plasticity by targeting multiple neural pathways. Proprioception is challenged as one foot deflects below the typical ground level, requiring novel postural adjustments [24, 25]. Force feedback is perturbed as the ground reaction force profile is altered during key phases of gait [26, 27]. Additionally, asymmetric balance and interlimb coordination are disrupted, creating a unique stimulus to address gait asymmetry [4,28]. Traditionally, compliant environments have been explored through single or multiple steps on varied surfaces during overground walking [29]. Recently, the Variable Stiffness Treadmill (VST) was developed to provide repeated and precise, compliant surface conditions [30,31]. This split-belt treadmill adjusts stiffness via a linear actuator altering the moment arm of applied forces [30]. Using the VST, experiments with healthy individuals have demonstrated significant brain activity and contralateral muscle responses to unilateral perturbations [3, 4]. Notably, a study found that repeated unilateral stiffness perturbations in healthy subjects produced significant aftereffects, highlighting their potential for post-stroke rehabilitation [32].

This study utilizes a new device, the VST 2, an advanced robotic split-belt treadmill specifically designed to investigate

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unilaterally reduced ground stiffness as a novel post-stroke gait rehabilitation intervention [33]. The VST 2 builds on its predecessor with significant enhancements, including a larger walking area, improved stiffness accuracy, vertical deflection capabilities, and the ability to independently adjust the stiffness of each belt, enabling precise and targeted perturbations. Using this device, the study evaluates the effects of a single 3-4 minute unilateral low-stiffness intervention on six hemiplegic stroke patients. The intervention produced statistically significant aftereffects lasting up to six minutes, including increased vertical push-off force, reductions in asymmetry in vertical push-off force, and improved center of pressure symmetry, which is related to balance during walking. These results suggest that unilateral low-stiffness walking has strong potential as an effective and innovative rehabilitation tool for restoring more natural and symmetric gait patterns in stroke survivors.

II. METHODS

This study investigated the short-term aftereffects of repeated unilateral stiffness perturbations on the gait of stroke survivors. Participants walked in a unilaterally compliant environment, and the effects on their gait were subsequently evaluated on rigid ground. Six stroke survivors participated in the study, including two males and four females, with an average age of 61.8 $\pm$ 7.8 years. Three had left-side hemiplegia, and three had right-side hemiplegia. All participants were relatively active and could walk without assistive devices, though one subject used a sling for arm support while walking. The treadmill's handrails were the only other form of assistance provided. A physical therapist, familiar with each subject's physical capabilities, supervised the experiments to ensure safety. All participants provided informed consent, and the study was approved by the University of Delaware Institutional Review Board (IRB ID# 2068278-1). The experimental setup is shown in Fig. 1.

A. Experiment Hardware Components

The primary device used in this study was the Variable Stiffness Treadmill (VST) 2, a robotic split-belt treadmill capable of independently adjusting the vertical stiffness of each belt across a range from 17 kN/m to rigid (5 MN/m) [33]. At its lowest stiffness, the treadmill allows for several inches of vertical deflection under an adult subject, with finer adjustments as the stiffness approaches rigid. The device offers precise control with an average stiffness resolution of 0.07 N/m. Adjustable handrails on either side provide support to subjects while maintaining visibility for motion capture markers. The treadmill also includes safety features, such as a body-weight support system (Litegait Inc.), which was used purely as a precaution without offloading any subject's weight.

During trials, each subject's movement was tracked using 22 reflective markers placed on their lower body, with an 8-camera motion capture system (Vicon Motion Systems Ltd.). Marker placement followed a previous study's protocol [32], and VICON Nexus software was used for data collection and

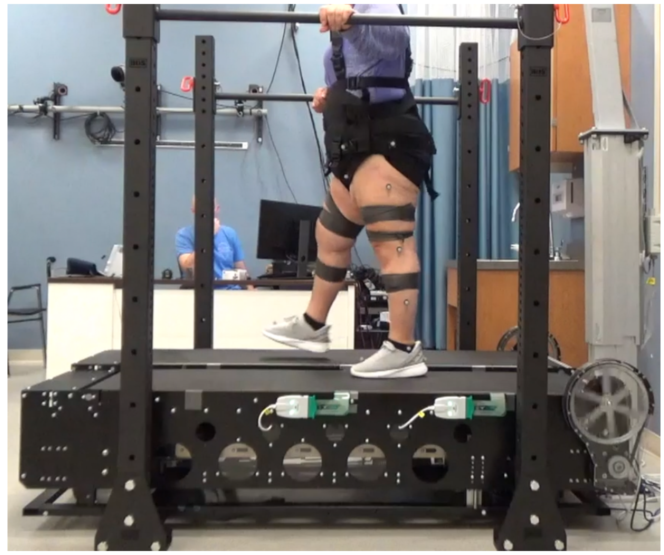

Fig. 1: The Variable Stiffness Treadmill (VST) 2 with the subject wearing motion capture markers, EMGs (under wraps), body-weight-support harness, and heart rate monitor (under harness). The left platform can be seen deflecting as the subject steps on it.

processing. Additionally, force data was captured using Force mats (TekScan 3140 with VersaTek Cuffs, TekScan Inc.) located beneath the treadmill belts. These mats, equipped with 4224 force-sensing cells per belt, measured forces at a spatial resolution of 1 cm and a frequency of 65 Hz, enabling the calculation of total applied force and center of pressure location.

Muscle activity was recorded using Trigno electromyographic (EMG) electrodes (Delsys Inc.), placed on ten muscles across both legs following ISEK guidelines [34]. Targeted muscles included the tibialis anterior (TA), medial gastrocnemius (GA), vastus medialis (VA), rectus femoris (RF), and biceps femoris (BF). Heart rate monitoring was performed throughout the experiment using a Polar H10 chest strap, which recorded data at 1 Hz. The physical therapist present used the monitor to oversee subject safety and was prepared to halt the experiment if necessary; however, no interruptions occurred. Since most participants were on beta-blocker medication, the collected heart rate data were not analyzed for exertion levels.

B. Experiment Protocol

In this study, participants walked in an asymmetrically compliant environment where the treadmill's stiffness was adjusted to create an imbalance. The treadmill belt under the nonparetic leg was set to a lower stiffness, while the paretic leg remained on a rigid surface. This configuration was designed to perturb gait in a way that encouraged greater reliance on the paretic limb, aiming to promote rehabilitation through controlled asymmetry. The experiment consisted of three phases in series with no breaks in between: baseline (20%), adaptation (30%), and observation (50%). During the baseline and observation phases, both treadmill belts were rigid, while in the adaptation phase, the nonparetic side experienced reduced stiffness. Subjects were informed of transitions with a one-minute warning and a five-second countdown to ensure preparedness. This setup was intended to challenge neural pathways without causing discomfort or fatigue.

Perturbing the nonparetic limb was chosen for several reasons. First, keeping the paretic limb on rigid ground ensured subject comfort, a priority for both participants and the supervising physical therapist. Second, perturbing the nonparetic side encouraged subjects to engage their paretic limb more actively, contrasting the typical assistive approach of exoskeletons. Most critically, prior research has shown that perturbing one limb activates the corresponding brain hemisphere responsible for the opposite limb [3], making this strategy particularly effective for engaging the brain areas controlling the paretic side.

Subjects selected a comfortable walking speed by incrementally testing speeds between 0.3 and 0.6 m/s, with input from the physical therapist. The stiffness level was similarly calibrated, testing values between 21 and 45 kN/m to achieve approximately 2–3 cm of deflection while maintaining comfort. Depending on the subject's capacity, the experiment duration was set to either 10 or 12 minutes. Finally, throughout the experiment, subjects reported perceived exertion every two minutes using the Borg Rating Scale (6–20) [35], with a threshold of 17 set for immediate termination. No subject reported values above 9, and heart rate monitoring by the physical therapist confirmed safety throughout.

C. Processing and Statistical Analysis of Collected Data

In this study, motion capture, muscle activity, and force data were synchronized using a trigger signal from the VICON Lock Lab system. This ensured the alignment of all data streams for accurate analysis. Heel strikes were identified via the force mats, with a strike detected when force rose from 0 to 5% of the subject's body weight. Toe-offs were determined kinematically by the most posterior position of the toe marker during a gait cycle. Gait cycles were defined based on heel strikes of the nonparetic leg. Force mat data, sampled initially at 65 Hz, was upsampled to 100 Hz using linear interpolation for alignment with motion capture data. The center of pressure (CoP) was calculated by translating force mat measurements to the motion capture frame and normalizing the anterior-posterior CoP relative to the subject's estimated center of mass, determined from the average position of four pelvic markers (left and right anterior and posterior superior iliac spines). Muscle activity data are not discussed in this paper.

All statistical analyses in this study were conducted using the Wilcoxon rank-sum test, a non-parametric alternative to the t-test that does not rely on assumptions about the data's distribution or shape [36]. An alpha level of 0.05 was used to determine statistical significance. The primary focus of this study was to evaluate aftereffects, so statistical comparisons were made between the observation phase and the baseline phase. Rather than analyzing responses during the intervention, the analysis targeted changes that persisted post-intervention, comparing these to pre-intervention behavior. Specifically, tests were performed between the last 30 gait cycles of the baseline phase and the first 30 gait cycles of the observation phase (early observation), as well as between the last 30 gait cycles of the baseline phase and the last 30 gait cycles of the observation phase (late observation). This approach aimed to identify both immediate and sustained aftereffects of the intervention, which was the main goal of the study.

III. Results

Figures 2 and 3 illustrate findings related to average vertical push-off ground reaction force (GRF) across all six subjects. This force, quantified as a percentage of body weight (PBW), was determined as the second peak of the vertical GRF during the stance phase. Significance lines at the top of the graph indicate the comparisons between data sets, with arrows showing the direction of change – upward for an increase and downward for a decrease. Blue lines represent the nonparetic limb, red lines indicate the paretic limb, and purple lines combine results from both limbs.

All subjects demonstrated a statistically significant aftereffect of increased vertical push-off force in both their paretic and nonparetic legs. On average, the nonparetic leg's push-off force increased from a baseline of 98.20 PBW to 100.20 PBW (a 2.04% increase) in early observation and 99.42 PBW (a 1.24% increase) in late observation. The paretic leg showed more substantial gains, rising from a baseline of 90.63 PBW to 97.42 PBW (a 7.49% increase) in early observation and 94.69 PBW (a 4.48% increase) in late observation. These results, illustrated in Fig. 2, not only indicate significant improvements on both sides but also suggest a shift toward greater symmetry, which is further explored in the subsequent discussion.

Although this study focused on vertical ground reaction forces, these forces are related to horizontal propulsive forces through kinematic interactions. Under consistent kinematics, an increase in vertical force would imply a corresponding increase in horizontal propulsion. In summary, the observed significant average increase of about 8% in vertical push-off force across all six subjects is an encouraging outcome, potentially contributing to improved step length and walking speed during overground locomotion.

A notable aftereffect also observed is the improvement in symmetry of vertical push-off forces between the paretic and nonparetic limbs. As highlighted earlier, while both limbs demonstrate increased push-off forces following the intervention, they also exhibit a shift toward greater symmetry. Before discussing the results, it is essential to clarify that asymmetry is always calculated by subtracting the paretic side's parameter value from the nonparetic side's parameter value. Therefore, a positive asymmetry value indicates that the nonparetic side's parameter is greater than that of the paretic side. On average, the baseline asymmetry in vertical push-off force among the six participants was 17.45 PBW. This asymmetry significantly decreased to 10.10 PBW (a

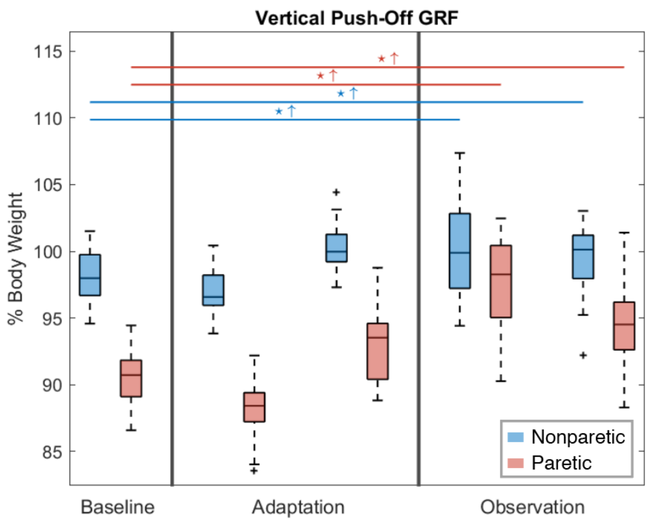

Fig. 2: Average vertical push-off ground reaction force (GRF) for all six subjects. The push-off force was calculated as the second peak of the vertical force during the stance phase. Significance lines are shown connecting the two data sets compared, with an arrow pointing to the direction of change.

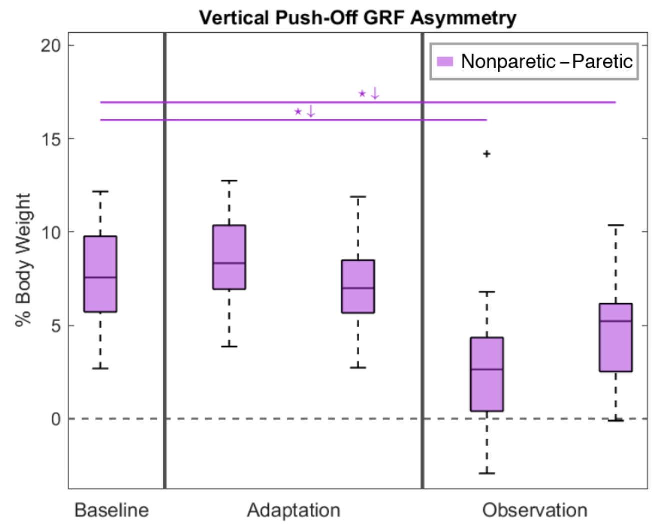

Fig. 3: Average vertical push-off ground reaction force asymmetry across all six subjects is shown. The push-off force was determined as the second peak of the vertical force during the stance phase. Asymmetry was determined by subtracting the paretic side's push-off force from the non-paretic side's push-off force. Significance lines connect the compared data sets, with arrows indicating the direction of change.

42.12% reduction) in early observation and $15.93\ PBW$ (an 8.71% reduction) in late observation, as shown in Fig. 3. These reductions in asymmetry are statistically significant and represent meaningful progress toward more balanced gait mechanics.

Improved symmetry in push-off force may indicate enhanced coordination and a more equal distribution of effort between the paretic and nonparetic limbs. This shift is crucial, as asymmetries in force production are often linked to inefficient and unstable walking patterns, increasing the risk of falls and energy expenditure. The observed improvements suggest that the intervention not only strengthens both limbs but also promotes more natural and efficient gait dynamics, a critical goal in post-stroke rehabilitation.

The total center of pressure (CoP) path also exhibited a more symmetric aftereffect following the intervention. The CoP was measured using force mats positioned beneath the treadmill belts, with normalization applied relative to the subject's center of mass in the anterior/posterior direction to account for drift. In Fig. 4, the orientation depicts the subject as if viewed from above, walking toward the top of the page.

As illustrated in Fig. 4 (top), five key parameters are derived from the CoP path plot. The anterior/posterior length of each lobe, corresponding to the time a limb is in single support, is represented by nonparetic and paretic Y1. The anterior/posterior distance between the front of one lobe and the back of the opposite lobe, referred to as Y2, relates to step length, with each parameter labeled according to the lobe being referenced. Lastly, lateral asymmetry measures the medial/lateral distance between the meeting point of the nonparetic and paretic lobes and the midpoint between their most lateral points. In a healthy, symmetric gait, nonparetic and paretic Y1 values would be equal, nonparetic and paretic Y2 values would match, and lateral asymmetry would measure zero, indicating balanced movement.

Subject 3 was selected as a representative example for discussion (see Fig. 4, bottom), while all subjects had similar results. As a reminder, asymmetry is calculated by subtracting paretic side values from the non-paretic side. During the baseline phase, Subject 3 exhibited a Y1 asymmetry of $-12\ mm$, which improved to a more symmetric $-3\ mm$ in early observation and $2\ mm$ in late observation. Similarly, the Y2 asymmetry decreased from $-88\ mm$ in the baseline phase to $-49\ mm$ in early observation and $-54\ mm$ in late observation, indicating a notable shift toward symmetry after the intervention.

IV. Conclusion

This study highlights the transformative potential of integrating unilateral compliant environments into post-stroke gait rehabilitation. By utilizing the Variable Stiffness Treadmill (VST) 2, designed to create asymmetrical terrain conditions, the research demonstrated statistically significant improvements in key gait metrics among stroke survivors. Notable aftereffects included increased vertical push-off force, reductions in asymmetry in vertical push-off force, and improved center of pressure symmetry, which is related to balance during walking. These improvements, observed after a brief 3-4 minute intervention, underline the immediate efficacy of this novel approach in promoting more symmetric and functional walking patterns.

This study introduced a novel use of unilateral low-stiffness terrain as a rehabilitation tool, offering a fresh approach to gait retraining. Unlike traditional methods such as body-weight-supported or split-belt treadmill training,

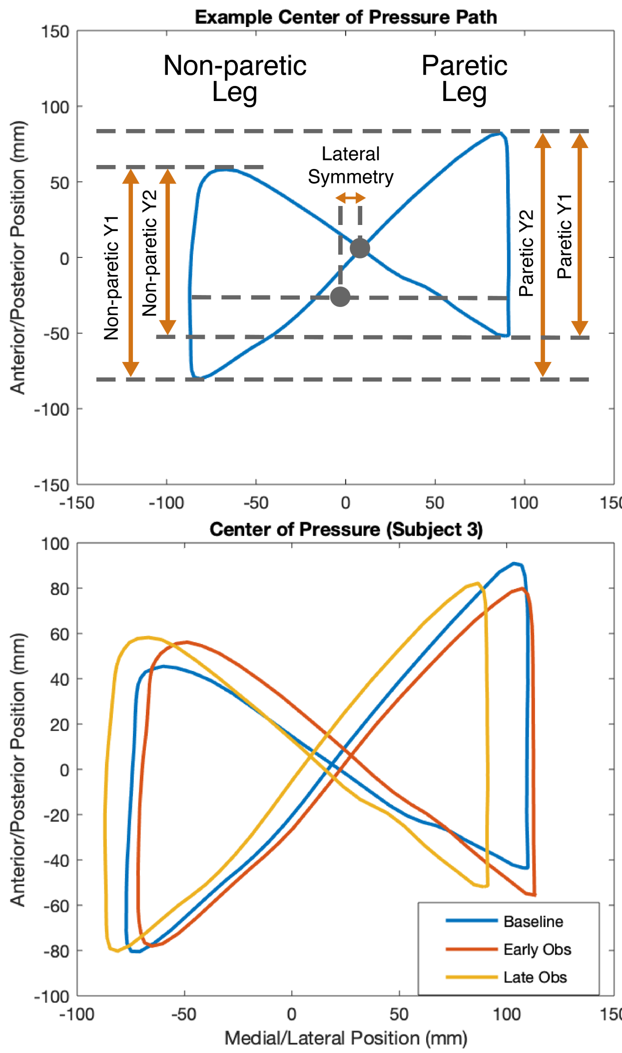

Fig. 4: Illustration of the center of pressure (CoP) path: an example path (top) and the CoP path for Subject 3 (bottom). CoP data was collected using force mats beneath the treadmill belts and normalized relative to the subject's center of mass in the anterior-posterior direction to compensate for drift. The plots are oriented as though viewed from above, with the subject appearing to walk toward the top of the page.

which provide broad benefits, this approach introduces targeted perturbations designed to engage neural plasticity and proprioceptive adaptation more effectively. By employing controlled asymmetry, the methodology aims to stimulate compensatory mechanisms and support neural reorganization, diverging from conventional symmetrical rehabilitation techniques. The integration of advanced robotic systems like the VST 2 ensures precision and consistency in delivering these interventions, enhancing their potential therapeutic impact. A future study that would benchmark this approach against traditional approaches is possible.

This study demonstrated that many after-effects persisted for the full 5-6 minute observation period following just a brief 2-3 minute intervention. This suggests that the induced changes may have had an even longer duration, had the experiment been extended. These findings are both exciting and promising, highlighting the potential for short, targeted interventions to produce lasting after-effects in stroke survivors. However, further research, with a larger sample size, is necessary to explore the longevity and mechanisms of these after-effects, as well as their implications for clinical applications and rehabilitation strategies.

The findings of this study open new avenues for robot-assisted gait rehabilitation. By introducing controlled instability through compliant surfaces, this approach directly addresses gait asymmetry – a hallmark challenge in post-stroke recovery. The results suggest that integrating this technology into clinical practice could foster faster, more robust recovery, reducing reliance on assistive devices and improving long-term mobility. Future research could expand on these findings, exploring the integration of such systems into personalized rehabilitation protocols, potentially transforming the standard of care for stroke survivors.

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