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Modulating hip stiffness with a robotic exoskeleton immediately changes gait

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Abstract— **Restoring healthy kinematics is a critical component of assisting and rehabilitating impaired locomotion. Here we tested whether spatio-temporal gait patterns can be modulated by applying mechanical impedance to hip joints. Using the Samsung GEMS-H exoskeleton, we emulated a virtual spring (positive and negative) between the user's legs. We found that applying positive stiffness with the exoskeleton decreased stride time and hip range of motion for healthy subjects during treadmill walking. Conversely, the application of negative stiffness increased stride time and hip range of motion. These effects did not vary over long nor short repeated exposures to applied stiffness. In addition, minimal transient behavior was observed in spatio-temporal measures of gait when the stiffness controller transitioned between on and off states. These results suggest that changes in gait behavior induced by applying hip stiffness were purely a mechanical effect. Together, our findings indicate that applying mechanical impedance using lower-limb assistive devices may be an effective, minimally-encumbering intervention to restore healthy gait patterns.**

I. INTRODUCTION

The potential of using lower-limb exoskeletons to augment human performance by reducing metabolic cost and muscle effort during normal walking has been well-demonstrated over the past decade [1]–[8]. However effective methods for modulating gait kinematics, both to assist or retrain individuals with gait impairments, through the use of lower-limb exoskeletons are still needed. Recent studies have examined changes in joint trajectories and joint power (estimated by inverse dynamics) in an effort to explain the reduction in energy consumption resulting from the use of ankle [1]–[3] and hip exoskeletons [4], [5]. Still, changes in joint kinematics were usually a secondary outcome rather than a primary concern.

Conventional lower-extremity robotic rehabilitation has aimed to retrain impaired gait kinematics by imposing pre-

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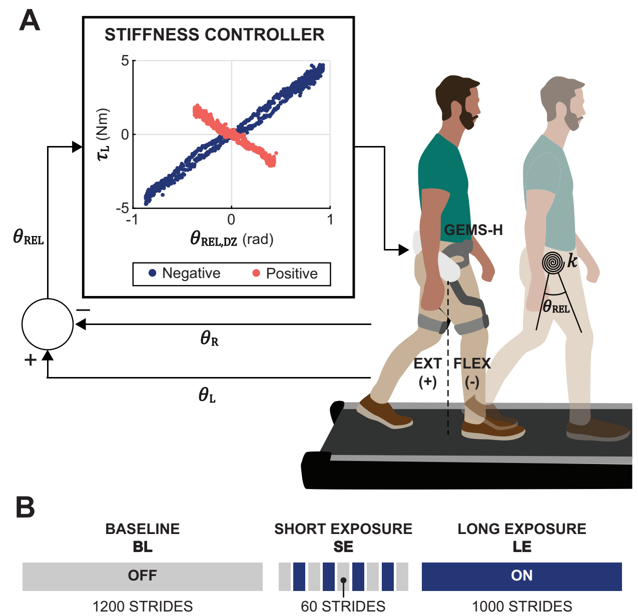

Fig. 1. **A** Experimental Setup. Subjects were instructed to walk comfortably on treadmill while the Samsung GEMS-H exoskeleton emulated mechanical impedance (positive and negative stiffness) between two legs. **B** Experimental protocol consisted of baseline, short-exposure, and long-exposure trials.

planned, repetitive kinematic patterns on patients using high-gain trajectory-tracking controllers. However, these methods do not improve clinical outcome measures more than the current standard of care [9]–[11]. We posit that the limited efficacy of robotic gait rehabilitation stems from the fact that a pre-determined kinematics approach discourages active engagement of patients in making movements [12] and interferes with natural dynamics of walking [13], [14]. We propose that applying mechanical impedance at the leg joints may be a promising alternative method to guide users to change their gait pattern, either through assistance or rehabilitation, without discouraging their active engagement.

The purpose of the present study was to evaluate whether applying hip joint stiffness using the Samsung Gait Enhancing and Motivating Systems for hip (GEMS-H exoskeleton; Fig. 1a) can induce quantifiable changes in the spatio-temporal pattern of gait during treadmill walking, and whether the induced changes varied with extended and repeated exposure. A time-varying effect of applied stiffness on gait behavior would suggest that the changes were induced by a combined mechanical and neural effect, rather than a purely mechanical effect. This would not be surprising given prior evidence that humans adjust or adapt their neural controller of locomotion in response to external perturbations during gait [15]–[18]. Understanding whether any change in overt behavior is induced in part by neural changes has important implications for both gait assistance and rehabilitation.

In the experiment, we controlled the GEMS-H to behave as a virtual spring (either with positive or negative stiffness) between two legs and examined changes in hip joint kinematics and stride time measured by on-board sensors. More specifically, we tested the following predictions:

- Applying stiffness to the hip joints will result in quantifiable changes in kinematics.
- Changes in spatio-temporal gait patterns will be dependent on stiffness parameters (positive or negative).
- The effect of applied stiffness on hip kinematics will vary with extended and repeated exposure, indicating neural adaptation.

II. METHODS

A. Subjects

Four healthy, young adults (gender: one female, three males; age: 24.8 ± 5.5 years) participated in this study. None had previously worn a hip exoskeleton nor partook in a similar experiment. All subjects gave informed written consent before the experiment. The experimental protocol was reviewed and approved by the Institutional Review Board of the Massachusetts Institute of Technology.

B. GEMS-H Exoskeleton

The GEMS-H exoskeleton used in this study was developed by Samsung Advanced Institute of Technology (Suwon-si, Gyeonggi-do, South Korea) (Fig. 1a). This lightweight (2.1kg) robotic exoskeleton is capable of applying torque about hip joints in the sagittal plane. Passive hinges allow for hip abduction and adduction in the frontal plane. Output torque from the actuator is estimated and controlled by sensing electrical current in the motor, and encoders are embedded in the actuator modules. All electronics, actuators, and power sources are located onboard the device, allowing for autonomous operation.

C. Stiffness Controller

The GEMS-H was used to emulate a virtual spring between two legs using the following control law:

$$\begin{bmatrix} \tau_{\mathrm{L}} \\ \tau_{\mathrm{R}} \end{bmatrix} = \begin{bmatrix} -k\theta_{\mathrm{REL,DZ}} \\ k\theta_{\mathrm{REL,DZ}} \end{bmatrix} \tag{1}$$

where $\tau_{\mathrm{L}}, \tau_{\mathrm{R}}$ are joint torques of left and right side, respectively. $\theta_{\mathrm{REL}} = \theta_{\mathrm{L}} - \theta_{\mathrm{R}}$ is relative angle between left (θ_{L}) and right (θ_{R}) hip joints and k is the stiffness of the spring. A deadzone of ±0.035rad (approximately 2°) was applied to relative angle ($\theta_{\mathrm{REL,DZ}}$) to prevent an abrupt sign change in the output torque (Fig. 1a).

When k is positive, the controller acts to push the legs together towards a stable equilibrium point at $\theta_{\mathrm{REL}} = 0\mathrm{rad}$. Conversely when k is negative, the controller acts to pull the legs apart from the unstable equilibrium point ($\theta_{\mathrm{REL}} = 0\mathrm{rad}$). The high-level control loop rate was 200Hz while the low-level current tracking control ran at 10kHz.

In an ideal spring, the net energy flow from the exoskeleton to the human over a single stride cycle should be zero. However, as may be expected, digital emulation of a spring departed from this ideal. In the positive stiffness condition, the estimated total work done by the GEMS-H on the subjects over a gait cycle was positive (positive work: $M = 1.21\mathrm{J}, \mathrm{SD} = 0.26\mathrm{J}$, negative: $M = -0.96\mathrm{J}, \mathrm{SD} = 0.22\mathrm{J}$, net: $M = 0.26\mathrm{J}, \mathrm{SD} = 0.08\mathrm{J}$). With negative stiffness, the exoskeleton absorbed energy (positive work: $M = 5.79\mathrm{J}, \mathrm{SD} = 1.53\mathrm{J}$, negative: $M = -7.26\mathrm{J}, \mathrm{SD} = 1.96\mathrm{J}$, net: $M = -1.48\mathrm{J}, \mathrm{SD} = 0.49\mathrm{J}$). While not perfectly zero, the net work over a stride cycle calculated from the torque and velocity measurements estimated by the onboard sensors was small in each condition.

D. Experimental Procedure

The experiment took place over two consecutive days. On each day, subjects performed three trials [baseline (BL), short-exposure (SE), and long-exposure (LE)] wearing the GEMS-H exoskeleton while walking on a Sole Fitness F80 treadmill (0.84m × 1.90m deck; 0.045m/s belt speed resolution) (Fig. 1a).

1) Baseline Trial: In the BL trials, subjects walked with the stiffness controller off (i.e., $\tau_{\mathrm{L}} = \tau_{\mathrm{R}} = 0\mathrm{Nm}$) for 1200 strides (Fig. 1b). Subjects were instructed to adjust the treadmill to a comfortable speed within the first 200 strides (Positive stiffness: $M = 1.67\mathrm{m/s}, \mathrm{SD} = 0.17\mathrm{m/s}$; Negative stiffness: $M = 1.65\mathrm{m/s}, \mathrm{SD} = 0.19\mathrm{m/s}$). The treadmill was then fixed at this speed for the remainder of the BL trial and all subsequent trials performed on that day. Only the last 1000 strides were used in the data analysis.

2) Short-exposure Trial: In the SE trials, subjects walked for 540 strides. The stiffness controller started off for the first 60 strides and then toggled between on and off for four blocks. Each block consisted of 60 strides with the controller on, followed by 60 strides with the controller off (Fig. 1b). Stiffness k was positive (5Nm/rad) on one day and negative (-5Nm/rad) on the other, and this order was counterbalanced across subjects. While subjects were informed that the controller would turn on and off during the trial, they were not told how the exoskeleton was controlled. For safety purposes, subjects walked for approximately 10 strides overground with exoskeleton powered before the start of the SE trial. Only the last 480 strides were used in the data analysis.

3) Long-exposure Trial: In the LE trials, subjects walked for 1000 strides with the stiffness controller on (Fig. 1b). The stiffness value was the same as that used in the SE trial of that day.

E. Data Processing

All signals were sampled at 200Hz. The angular position of each hip joint was directly measured by the embedded encoders. Angular velocity was calculated by filtering the position signals offline. An FIR filter of order 50 with 20Hz passband frequency and 30Hz stopband frequency was designed using the `designfilt` function in MATLAB (The Mathworks, Natick, MA, USA) to approximate an ideal low-pass filtered differentiator. The filtered velocity signal was shifted in time by the group delay of the filter to compensate for delay introduced by the filter. Hip extension and flexion were defined as positive and negative, respectively (Fig. 1a).

F. Dependent Measures

The gait cycle (%) was defined using the maxima of the left hip angle profile. 0% of the gait cycle was defined as maximum extension of the left hip joint, which roughly coincides with toe-off [19]. From 0% to 50% of the gait cycle, the left hip was flexing (i.e., negative joint velocity) while the right hip was extending (i.e., positive joint velocity). From 50% to 100% of the gait cycle, the left hip was extending while the right hip was flexing. The angular position and velocity trajectories from each trial were segmented and time-normalized per stride using the `interp1` function in MATLAB to calculate the following dependent measures for each stride. The temporal aspect of each stride was characterized by stride time, and the spatial aspect was quantified by the range of motion (RoM) of the relative angle between the left and right hip joints (θ_{REL}). To further dissect how changes in θ_{REL} RoM arose, the maximum, minimum, and RoM of the individual left (θ_{L}) and right (θ_{R}) hip angles were also calculated.

For each subject, the mean of all spatial and temporal measures and the standard deviation (SD) of the temporal measure during the initial 250 and terminal 250 strides in the BL and LE trials were calculated. In the SE trials, the mean of all dependent measures and the standard deviation of stride time for condition (i.e., every 60 strides) were calculated. To detect whether there was transient behavior in stride time and θ_{REL} RoM when the controller transitioned between on and off states in the SE trial, the correlation coefficient (r) of the dependent measures over the initial 15 strides was calculated for each block. An r of a dependent measure would be zero during steady-state and non-zero if there was an approximately linear trend.

G. Statistical Analysis

The first analysis tested whether long application of hip stiffness affected the dependent measures, as well as the stationarity of the effect over the course of 1000 strides. For each stiffness condition (positive and negative), a 2(Trial: BL vs. LE) x 2(Block: initial vs. terminal) analysis of variance (ANOVA) was conducted on each dependent measure. The second analysis tested whether short applications of hip stiffness affected the dependent measures and whether the effect evolved with repeated exposure. For each stiffness condition, a 2(Controller state: ON vs. OFF) x 4(Block) ANOVA was conducted for each measure. If the assumption of sphericity was violated in the effect of block, the Greenhouse-Geisser correction factor was applied to adjust the degrees of freedom accordingly. The statistical analyses were performed using SPSS Statistics for Windows, Version 25.0 (IBM Corporation, Armonk, NY). For all statistical tests, the significance level was set to $p < 0.05$.

III. LONG EXPOSURE RESULTS

The following analysis assessed the effect of applying stiffness between legs on temporal and spatial patterns of gait and tested whether the effects varied over the course of 1000 strides. Fig. 2 exemplifies how the dependent measures changed over strides in the LE and BL trials for a representative subject.

A. Effect of positive stiffness

1) Temporal measures: Mean stride time was significantly lower in the LE trial compared to the BL trial (Fig. 3a). The effect of block and interaction on mean stride time were not statistically significant ($ps > 0.05$). There were also no significant effects nor interactions on the standard deviation of stride time ($ps > 0.05$) (Fig. 3b).

2) Spatial measures: Mean θ_{REL} RoM was significantly lower in the LE trial compared to the BL trial (Fig. 3c). This arose from the fact that the mean θ_{L} and θ_{R} RoM were both significantly lower in the LE trial (Fig. 3d,g). While the effect of block on mean θ_{R} RoM was significant, the interaction was not. In both trials, mean θ_{R} RoM tended to increase from the first 250 strides ($M = 34.85°$) to the last 250 strides ($M = 35.41°$). Though statistically significant, the magnitude of this increase may not be practically meaningful and the result of measurement error.

The decrease in mean θ_{R} and θ_{L} RoM in the LE trial resulted from a reduction in hip extension. The mean maximum values of θ_{L} and θ_{R}, which quantified the extent of hip extension, were significantly reduced in the LE trial (Fig. 3e,h). The extent of hip flexion, as quantified by the mean minimum values of θ_{L} and θ_{R}, was not significantly different in the LE and BL trials (Fig. 3f,i).

Besides mean θ_{R} RoM, the effects of block and interactions on the spatial measures were not significant ($ps > 0.05$).

B. Effect of negative stiffness

1) Temporal measures: Whereas applying positive stiffness decreased mean stride time, applying negative stiffness in the LE trial significantly increased mean stride time compared to the BL trial (Fig. 3a). There was no significant effect of block nor interaction on mean stride time ($ps > 0.05$). Again, there were also no significant effects nor interaction on the standard deviation of stride time ($ps > 0.05$) (Fig. 3b).

2) Spatial measures: Mean θ_{REL}, θ_{L}, and θ_{R} RoM were all significantly higher in the LE trial compared to the BL trial (Fig. 3c,d,g).

The increase in mean θ_{R} and θ_{L} RoM in the LE trial resulted from a increase in both hip extension and flexion. The mean maximum values of θ_{L} and θ_{R} were significantly greater in the LE trial compared to the BL trial (Fig. 3e,h), and the mean minimum values were significantly lower (Fig. 3f,i).

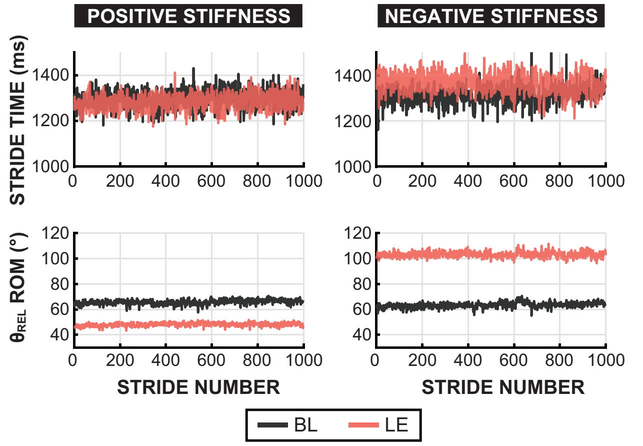

Fig. 2. Representative subject data from baseline (BL) and long-exposure (LE) trials. Stride time and θ_{REL} RoM over strides in the LE (red) trials and baseline (black) trials for a representative subject in the positive (left panel) and negative (right panel) stiffness conditions.

TABLE I
2(TRIAL: BL VS LE) X 2(BLOCK: INITIAL VS TERMINAL) ANOVA

Measure	Positive Stiffness		Negative Stiffness	
	Trial	Block	Trial	Block
Mean stride time	$F_{1,3} = 10.27$ p = 4.9e-02	ns	$F_{1,3} = 11.61$ p = 4.2e-02	ns
SD stride time	ns	ns	ns	ns
Mean θ_{REL} RoM	$F_{1,3} = 149.79$ p = 1.2e-03	ns	$F_{1,3} = 107.35$ p = 1.9e-03	ns
Mean θ_{L} RoM	$F_{1,3} = 75.15$ p = 3.2e-03	ns	$F_{1,3} = 99.89$ p = 2.1e-03	ns
Mean θ_{R} RoM	$F_{1,3} = 185.78$ p = 8.5e-04	$F_{1,3} = 10.37$ p = 4.9e-02	$F_{1,3} = 83.08$ p = 2.8e-03	ns
Mean max θ_{L}	$F_{1,3} = 11.17$ p = 4.4e-02	ns	$F_{1,3} = 41.29$ p = 7.6e-03	ns
Mean max θ_{R}	$F_{1,3} = 14.25$ p = 3.3e-02	ns	$F_{1,3} = 60.36$ p = 4.0e-03	ns
Mean min θ_{L}	ns	ns	$F_{1,3} = 41.21$ p = 7.7e-03	ns
Mean min θ_{R}	ns	ns	$F_{1,3} = 26.10$ p = 1.5e-02	ns

There was no significant effects of interactions on any dependent measure. ns indiciates non-significant effect (p >0.05).

There was no significant effect of block nor interaction on any of these spatial measures ($ps > 0.05$).

3) Summary: As predicted, applying stiffness induced changes in hip kinematics. Applying positive stiffness resulted in both reduced hip RoM and stride time, whereas applying negative stiffness resulted in both increased hip RoM and stride time compared to baseline. Counter to our predictions, however, the effects of applied stiffness did not vary with with time as indicated by the lack of significant trial $\times$ block interaction.

IV. SHORT EXPOSURE RESULTS

The following analysis assessed the effects of applying stiffness evolved over repeated, short exposures (60 strides). Fig. 4 exemplifies how the gait patterns changed over strides in SE trials for the same representative subject in Fig. 2.

A. Effect of Positive stiffness

1) Temporal measures: While applying positive stiffness decreased mean stride time in the LE trial, mean stride time

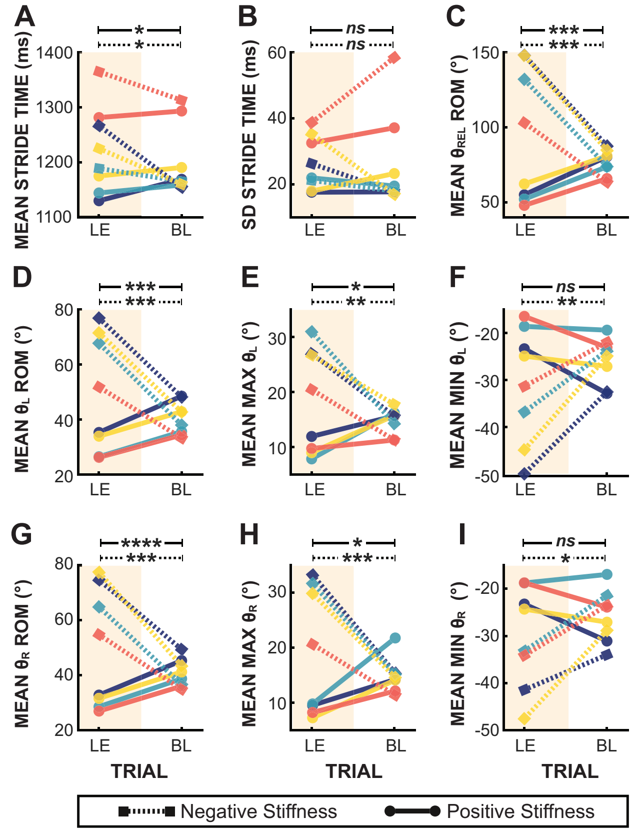

Fig. 3. Long-exposure (LE) and baseline (BL) trial results. Average dependent measures for each subject (represented by different colors) in the LE trials and BL trials. Dashed lines represent trials on the days negative stiffness was applied in the LE trial, and solid lines represent trials on the days positive stiffness was applied. *ns* indicates a non-significant effect of trial. *, **, ***, and **** indicate a significant effect of trial with $p < 0.05$, $p < 0.01$, $p < 0.005$, $p < 0.001$, respectively.

was not significantly different when the positive stiffness controller was on compared to when it was off in the SE trial (Fig. 5a). There was no significant effect of block nor interaction on mean stride time ($ps > 0.05$). Neither the effects nor interaction on the standard deviation of stride time and the r of stride time over the initial strides ($M = 0.0093$) were significant ($ps > 0.05$) (Fig. 5b,c).

2) Spatial measures: The effect of controller state on all spatial measures was significant. Consistent with the effect of applying positive stiffness in the LE trial, mean θ_{REL}, θ_{R}, and θ_{L} RoM were significantly reduced when the positive stiffness controller was on compared to when it was off (Fig. 6a,b,e). The maximum values of θ_{R} and θ_{L} were significantly decreased when the controller was on (Fig. 6c,f). While applying positive stiffness did not significantly affect the minimum values of θ_{R} and θ_{L} in the LE trial, these minimum values were significantly increased when the controller was on in the SE trial 6d,g). The effect of block and interaction of block was not statistically significant on any of these spatial measures (ps> 0.05).

Neither the effects nor interaction on r of θ_{REL} over initial strides ($M = 0.0036$) were significant ($ps > 0.05$) (Fig. 6h).

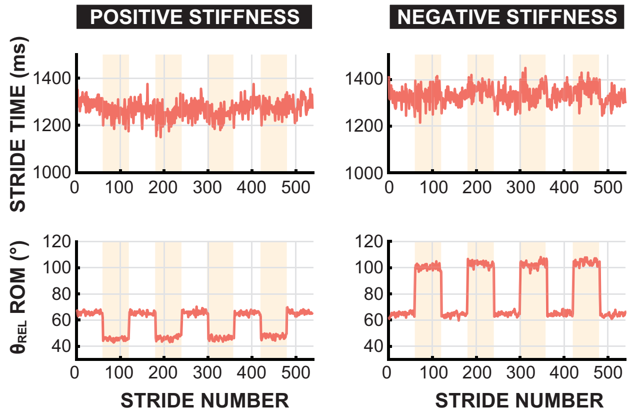

Fig. 4. Representative subject data from short-exposure (SE) trials. Stride time and θ_{REL} RoM over strides in the SE trials for a representative subject (same as in Fig. 2) in the positive (left panel) and negative (right panel) stiffness conditions. Shaded regions represent when the stiffness controller was on.

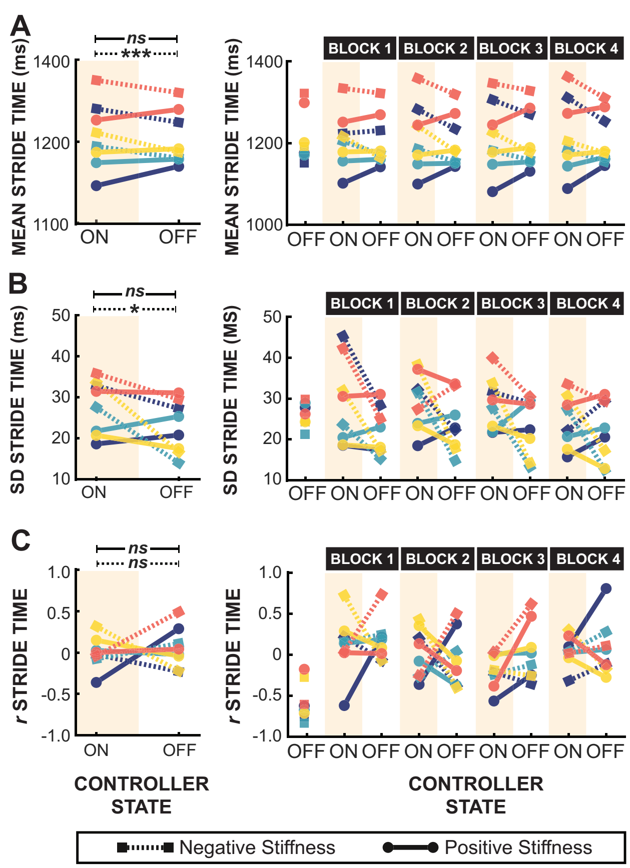

Fig. 5. Short-exposure (SE) trial temporal measure results. Average temporal dependent measures for each subject (represented by different colors) when controller state was on and off in the SE trials. Dashed lines represent trials on the days negative stiffness was applied in the SE trial, and solid lines represent trials on the days positive stiffness was applied. *ns* indicates a non-significant effect of trial. *, **, ***, and **** indicate a significant effect of trial with $p < 0.05$, $p < 0.01$, $p < 0.005$, $p < 0.001$, respectively.

TABLE II
2(Controller state: On vs Off) x 4(Block) ANOVA

Measure	Positive Stiffness		Negative Stiffness	
	State	Block	State	Block
Mean stride time	ns	ns	$F_{1,3} = 67.17$ p = 3.8e-03	ns
SD stride time	ns	ns	$F_{1,3} = 14.32$ p = 3.2e-02	ns
r of stride time	ns	ns	$F_{1,3} = 11.61$ p = 4.2e-02	ns
Mean θ_{REL} RoM	$F_{1,3} = 442.524$ p = 2.3e-04	ns	$F_{1,3} = 135.66$ p = 1.4e-03	$F_{2.07,6.20} = 8.50$ p = 1.6e-02
Mean θ_{L} RoM	$F_{1,3} = 216.29$ p = 6.8e-04	ns	$F_{1,3} = 131.65$ p = 1.4e-03	$F_{1.97,5.92} = 9.06$ p = 1.6e-02
Mean θ_{R} RoM	$F_{1,3} = 454.12$ p = 2.3e-04	$F_{1,3} = 10.37$ p = 4.9e-02	$F_{1,3} = 99.55$ p = 2.1e-03	ns
Mean max θ_{L}	$F_{1,3} = 141.60$ p = 1.3e-03	ns	$F_{1,3} = 541.34$ p = 1.7e-04	ns
Mean max θ_{R}	$F_{1,3} = 77.14$ p = 3.1e-03	ns	$F_{1,3} = 146.43$ p = 1.2e-03	ns
Mean min θ_{L}	$F_{1,3} = 40.19$ p = 7.9e-03	ns	$F_{1,3} = 54.29$ p = 5.2e-03	ns
Mean min θ_{R}	$F_{1,3} = 29.23$ p = 1.2e-02	ns	$F_{1,3} = 74.68$ p = 3.3e-03	ns
r of θ_{REL} RoM	ns	ns	ns	ns

There was no significant effects of interactions on any dependent measure. ns indiciates non-significant effect (p >0.05).

B. Effect of Negative stiffness

1) Temporal measures: Mean stride time was significantly higher when the negative stiffness controller was on compared to off (Fig. 5a). Standard deviation of stride time was significantly higher when the negative stiffness controller was on (Fig. 5b). There was neither a significant effect of block nor interaction on either temporal measure ($ps > 0.05$). The effects and interaction on r of stride time over initial strides ($M = 0.040$) were also not significant ($ps > 0.05$) (Fig. 5c).

2) Spatial measures: Similar to the LE trial, the effect of controller state on all spatial measures was significant. Mean θ_{REL}, θ_{R}, and θ_{L} RoM were significantly increased when the negative stiffness controller was on compared to when it was off (Fig. 6a,b,e). The maximum values of θ_{R} and θ_{L} were significantly increased (Fig. 6c,f), and the minimum values of θ_{R} and θ_{L} were also significantly decreased when negative stiffness was applied (Fig. 6d,g).

The effect of block on mean θ_{REL} RoM was statistically significant, as was the effect of block on θ_{L} RoM. While statistically significant, neither the overall change in mean θ_{REL} RoM over blocks (Block 1: $M = 103.48\,\mathrm{deg}$, Block 2: $M = 104.22\,\mathrm{deg}$, Block 3: $M = 105.25\,\mathrm{deg}$, Block 4: $M = 105.02\,\mathrm{deg}$; Fig. 6a) nor the overall change in mean θ_{REL} RoM over blocks (Block 1: $M = 52.86\,\mathrm{deg}$, Block 2: $M = 53.23\,\mathrm{deg}$, Block 3: $M = 53.35\,\mathrm{deg}$, Block 4: $M = 53.49\,\mathrm{deg}$) was practically meaningful. The effect of block on the remaining spatial measures was not statistically significant ($ps > 0.05$). The interaction on any of the aforementioned spatial measures was also not statistically significant ($ps > 0.05$).

Neither the effects nor interaction on r of θ_{REL} RoM over initial strides ($M = -0.061$) were significant ($ps > 0.05$) (Fig. 6h).

C. Summary

When positive stiffness was applied in short, repeated bouts, hip RoM was reduced, and applying negative stiffness resulted in both increased hip RoM and stride time compared to baseline. The effects of applied stiffness did not vary with

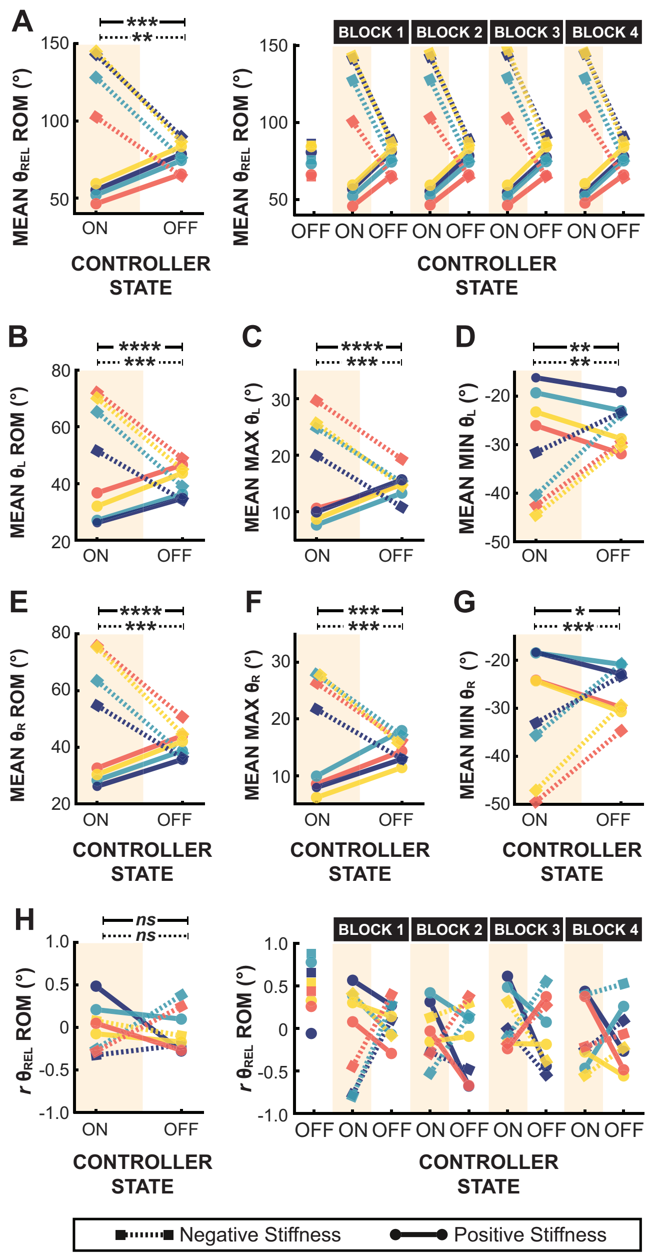

Fig. 6. Short-exposure (SE) trial spatial measure results. Average spatial dependent measures for each subject (represented by different colors) when controller state was on and off in the SE trials. Dashed lines represent trials on the days negative stiffness was applied in the SE trial, and solid lines represent trials on the days positive stiffness was applied. *ns* indicates a non-significant effect of trial. *, **, ***, and **** indicate a significant effect of trial with $p < 0.05$, $p < 0.01$, $p < 0.005$, $p < 0.001$, respectively.

repeated exposure as indicated by the lack of a significant controller state × block interaction. Moreover, there was minimal transient behavior in the dependent measures when the controller transitioned between on and off states.

V. DISCUSSION

This study examined how healthy subjects' gait patterns changed in response to the addition of positive and negative virtual springs between the two legs applied by the GEMS-H exoskeleton during treadmill walking. As predicted, the response was characterized by changes in spatio-temporal measures of gait behavior such as decreased/increased stride time and decreased/increased hip joint range of motion for positive/negative stiffness, respectively.

We also predicted that behavioral response would vary over strides, assuming that underlying neural controller of locomotion would gradually adapt to compensate for the stiffness applied externally by the robotic exoskeleton. However, we saw little evidence of such adaptation. There was no meaningful change in the behavioral response to applied stiffness over 1000 strides nor over shorter, repeated exposures. In addition, there was minimal transient behavior when the stiffness controller transitioned between on and off states and no systematic reduction in the transient behavior over repeated exposures (i.e., savings).

The lack of neural adaptation could be due to the fact that the effect of the reduced or increased range of motion was not perceived as an error that the nervous system needed to correct. It is also possible that the additional constraint of walking speed imposed by the treadmill may have suppressed subjects' natural adaptive response. For instance, Ochoa et al. found substantial differences in subjects' gait response to pulsed mechanical perturbations in treadmill walking compared to overground walking [13].

While we did not observe signatures of neural adaptation in response to applied hip stiffness, we cannot definitively rule out the possibility that it occurred. For example, adaptation might have occurred within a single stride as if a stride-based dead-beat controller existed. The hip joints contribute to upholding an upright posture and guiding foot placement, both of which are critical for maintaining balance during locomotion. Thus, it is feasible that adjustments to externally-induced changes in the hip joint mechanics would be rapid. It is also possible that subjects could have adjusted the behavior of the other leg joints (e.g., knee and ankle) to compensate for applied stiffness. Future analysis of additional measures of full leg gait kinematics and more direct measures of neural control such as muscle activity would shed further light on this open question.

VI. CONCLUSIONS

This study investigated the changes in spatio-temporal gait patterns induced by applying stiffness at the hip joints with the Samsung GEMS-H exoskeleton. We found that both stride time and hip joint range of motion were affected by the applied mechanical impedance, which was consistent over different subjects and repeated exposure. Moreover, we found little evidence of neural adaptation to applied stiffness. These results suggest that applying mechanical impedance using lower-limb exoskeleton robots may be an effective, minimally-encumbering intervention to restore healthy gait pattern.

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