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Entrainment during Human Locomotion Using a Lightweight Soft Robotic Hip Exosuit (SR-HExo)

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***Abstract*—A gait entrainment study was conducted using a lightweight soft robotic hip exosuit (SR-HExo) that can apply perturbations at the hip joint during treadmill walking. Periodic mechanical perturbations were applied by flat fabric Pneumatic Artificial Muscle (ff-PAM) actuators starting at a subject's preferred gait frequency and increasing up to 15% higher in 3% increments. Anterior hip flexion perturbations and posterior hip extension perturbations were tested in two separate experiments. All 11 healthy participants showed successful entrainment in all 12 experimental conditions (i.e., from preferred gait frequency to 15% higher in both flexion and extension perturbation directions). This study confirmed that there exists a single stable point attractor during gait entrainment to unilateral, unidirectional hip perturbations, which is consistent with previous ankle studies. Phase-locking was consistently observed around toe-off phase of the gait cycle (GC). Group averaged results showed gait synchronization with extension perturbations occurred earlier in the gait cycle (around 50% GC where the hip angle reaches maximum extension) than with flexion perturbations (just after 60% GC where the transition from maximum hip extension towards hip flexion occurs). Other gait entrainment characteristics (specifically, success rate of entrainment, basin of entrainment, and transient response) observed in this study posits the potential of the SR-HExo for entrainment-based gait training in rehabilitative contexts.**

***Index Terms*—Wearable Robotics, Soft Robot Applications, Rehabilitation Robotics**

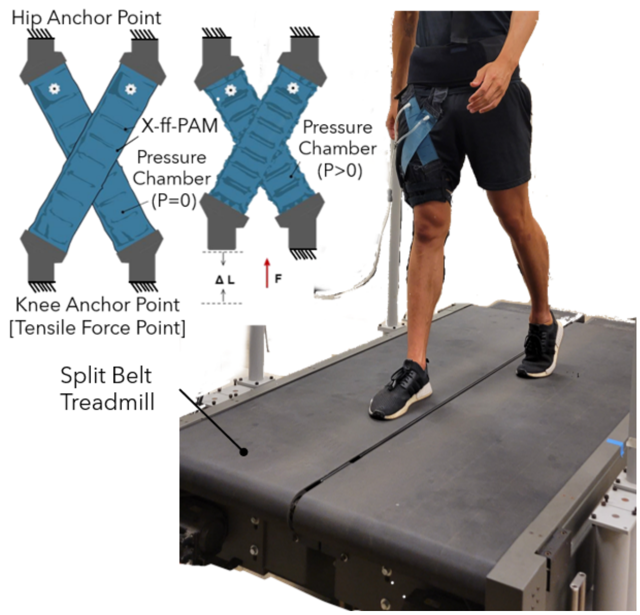

Fig. 1. Head on-view of the soft actuators (X-ff-PAM) used to generate perturbations both posterior and anterior to the leg, in addition to the SR-HExo exosuit on a subject participating in a treadmill walking study.

I. Introduction

LOWER-LIMB exoskeleton robots are becoming more commonplace as a rehabilitative solution to treat pathophysiological gait patterns such as slow and asymmetric gait [1], [2]. Many conventional robot-aided gait therapies have used position controllers imposing predefined kinematic trajectories or impedance/admittance controllers manipulating the degree of assistance or resistance during gait training [3].

More recently, a new approach utilizing the entrainment phenomenon and wearable exoskeleton robots during gait training has been introduced to facilitate patient engagement and allow for natural oscillatory dynamics of walking [4]–[7]. Entrainment explains the phenomenon of the synchronization of a pair of periodic systems and occurs when the period of stimuli from one system is close to the other system's natural oscillatory dynamics. It has been observed in many nonlinear dynamical systems including pure mechanical systems [8], non-human vertebrates, and humans [4]–[7], [9], [10]. In gait rehabilitation settings, the entrainment strategy can be used to encourage gradual synchronization of impaired gait to desired gait patterns (e.g., faster and more symmetric gait) by the application of a series of periodic perturbations.

Previous gait entrainment studies have demonstrated that periodic perturbations by wearable exoskeleton/exosuit robots can successfully induce entrainment in both healthy individuals and those who exhibit gait abnormalities following neurological impairments [4]–[6], [11]. A pioneering study using a rigid ankle exoskeleton robot showed that the majority of healthy human subjects could get entrained during treadmill walking in response to a series of periodic torque perturbations up to 7% higher than the subject's preferred gait frequency [4]. A subsequent overground study using the same ankle robot also showed that gait entrainment can be further enhanced in the absence of a constant speed constraint, evidenced by more frequent and faster entrainment than the treadmill walking condition [5]. In both the treadmill and overground walking studies, phase-locking was always observed around the toe-off phase suggesting a single strong stable point attractor

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[4], [5]. A feasibility study with stroke and multiple sclerosis patients also showed their successful entrainment to the periodic torque perturbations (50 ms faster than the preferred stride period) by the ankle robot with phase-locking around the toe-off phase [11]. While these studies confirmed the potential of the entrainment strategy in gait rehabilitation, its practical application was still limited due to the narrow basin of entrainment (only about 7% of preferred gait frequency), possibly due to the use of the heavy ankle robot (3.5 *kg*). Narrow basin of entrainment would limit not only the capacity to correct asymmetric gait patterns but also the degree of walking speed increase. Considering a clinically significant increase in rehabilitative walking speed (0.05 m/s) [12] and the average walking speed of 0.6 m/s for stroke patients [13], the narrow basin of entrainment (7%) cannot lead to clinically significant outcomes.

With an overarching goal to overcome the limitations of previous studies with a heavy and rigid ankle robot and to explore the potential of a soft robotic device in enhancing the effectiveness of gait entrainment, we recently performed a similar gait entrainment study using a lightweight, soft wearable ankle exosuit (206 *g*). The ankle exosuit consists of dual flat fabric Pneumatic Artificial Muscle (ff-PAM) actuators that provide plantarflexion torque perturbations at the ankle joint during walking [6]. Compared to previous studies, a significantly wider basin of entrainment (14.2% during walking with preferred speed and about 40% with increased treadmill speed proportional to the increase in perturbation frequency) and a faster transient response (the number of strides until the onset of phase-locking was 22 when averaged across all test conditions) were observed in experiments using the SR-AFO [6]. Phase-locking was always found around toe-off, as is consistent with the outcomes of the previous studies [4].

To investigate the generality of the entrainment paradigm tested in the ankle studies, one recent study investigated gait entrainment to periodic perturbations applied at the hip. The hip joint was selected as a target since it provides approximately 40-50% of the positive power required in healthy human locomotion, which is statistically comparable to the positive power by the ankle joint [14]. This study utilized a lightweight (2.1 *kg*) yet rigid hip exoskeleton robot to provide flexion and extension torque perturbations to opposite hip joints of healthy subjects during overground walking, switching hips every stride [7]. A fixed torque pulse period of 25 ms faster than the preferred stride period was used throughout the experiments. Over 70% of the trials showed successful entrainment and phase-locking was observed around two distinct gait phases – 52% and 79% gait phase. Transient response was rather slow and sometimes more than 50 strides were needed until the onset of phase-locking. Although this study presented the potential of using hip exoskeleton devices for gait entrainment, it did so with bilaterally applied unidirectional perturbations, which is in contrast to most entrainment research done at the ankle, which applied unilateral and unidirectional perturbations.

Building upon our recent development of a lightweight soft robotic hip exosuit (SR-HExo), this study investigated the potential use of the soft hip exosuit to facilitate gait entrainment. The three objectives of this study were as follows: 1) Investigate how many stable-point attractors exist during gait entrainment to hip-based perturbations by applying perturbations on a single leg in a single direction (unilateral, unidirectional perturbations applied in either flexion or extension), as in previous ankle studies [4], [6], [11], [15]; 2) Investigate gait entrainment characteristics specifically, success rate of entrainment, basin of entrainment, phase locking, and transient response; 3) Investigate if these characteristics are different for perturbations applied in flexion and extension directions.

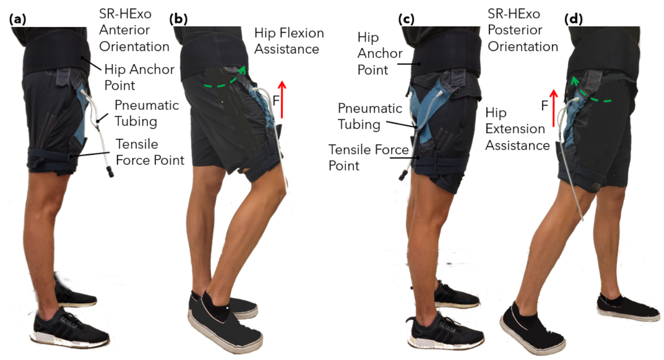

Fig. 2. The SR-HExo shown on the right hip of a user on (a) the anterior side of the hip with actuators passive, (b) the anterior side of the hip with actuators active, (c) the posterior side of the hip with actuators passive, and (d) the posterior side of the hip with actuators active.

II. METHODS

A. Soft Robotic Hip Exosuit (SR-HExo) and Actuator Characterization

The SR-HExo is a soft robotic hip exosuit constructed from fabric to create a lightweight (0.40 *kg*), low profile (0.5 *mm* and 13.3 *mm* when the actuator is passive and active, respectively), wearable device for gait assistance and rehabilitation. The tensile force point, also referred to as the knee anchor point, is constructed from neoprene, Spandex, and hook-and-loop fabric that securely fits the thigh circumference of most users and translates force from the actuators to create a consistent torque moment about the hip (Fig. 2). The hip anchor point consists of two hook-and-loop bands that wrap securely around the user's hip to provide mounting points for the top of the actuators. Adjustments can be made to the length of the actuator attachment and medial location via the hook-and-loop belt.

The actuators are a pair of flat fabric pneumatic artificial muscles (ff-PAM), which are placed on either the anterior or posterior side of the right hip to provide hip flexion and extension torque perturbations, respectively. Earlier developments of these actuators feature the geometric and volumetric optimization of dual ff-PAM actuators [16], and preliminary SR-HExo design [17]. The actuators are pneumatically powered to contract and generate a pulling force along the length of the thigh. The torque output of the actuator can be described as $\tau = Fr_{thigh}$, where τ is the torque applied to the hip by the SR-HExo, F is the tensile force generated during actuator contraction, and r_{thigh} is the perpendicular lever arm distance

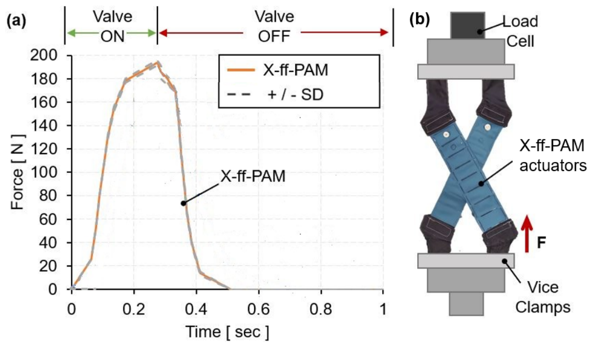

Fig. 3. (a) Tensile force output as a function of time when the X-ff-PAM is actuated at a valve impulse lasting 0.3 seconds. (b) Experimental setup to analyze the force output.

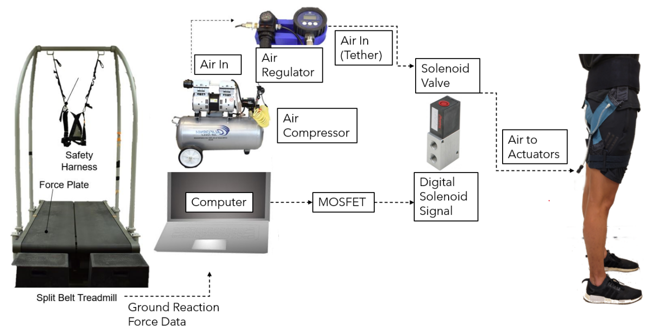

Fig. 4. Overview of the SR-HExo, electronics, and pneumatic system integration. Triggering of the pneumatic valve is controlled via a MOSFET featured in the control box and is monitored by a real-time computer system. Back-pressure of the portable air compressor is set manually before each trial to ensure appropriate force output.

from the center of the hip joint to the leading edge of the thigh at the knee anchor point (or, approximately the thickness of the user's thigh). These ff-PAM actuators are oriented in an 'X' configuration referred to as X-ff-PAM to hug the user's leg closely, thus enabling maximum force transmission without inhibiting the user's natural range of motion.

The dynamic response of the X-ff-PAM actuator was characterized using a universal testing machine (UTM) (Instron 5565, Instron Corp., High Wycombe, United Kingdom) (Fig. 3a). The free ends of the X-ff-PAM were mounted via a stationary clamp at the base of the UTM and a vice clamp positioned below the load cell (Fig. 3b). A fabric connector interfaced between the X-ff-PAM and vice clamps to maintain an actuator crossing at exactly halfway down the length of the actuators and a center-to-center distance at the bottom of each actuator of 14 *cm*. Instantaneous pressure was set to 200 *kPa* and supplied to the air chambers of the X-ff-PAM in a pulse of 1 *sec*, with the valve remaining open for 0.3 *sec* and closed for 0.7 *sec* as in previous studies and evaluations [18]. With all testing conditions held constant for 3 trials, the actuator could generate 100 *N* tensile force in 0.1 *sec* and a peak force of 193.7 $\pm$ 2.1 *N* in 0.24 *sec*.

B. Control and Hardware of SR-HExo

Entrainment as a rehabilitative paradigm relies upon the natural synchronization of the human gait as a periodic system to periodically applied perturbations. Once the appropriate level of perturbation magnitude (determined by the level of air pressure) and perturbation frequency is determined for a given subject in a given trial, this method requires no closed-loop feedback.

This open-loop control scheme enables voluntary participation and allows for natural dynamics of human locomotion since the subject aligns gait with the robot rather than the robot predicting and reacting to the user in a closed-loop fashion. This simplistic control methodology behind entrainment is also computationally cheap, requires no additional time to tune the controller parameters, and easily accessible for use inside and outside of rehabilitative facilities, potentially with more affordable controllers.

A portable air compressor (Model8010A, California Air Tools, USA) applies fixed, controlled perturbations to the user by pressurizing the chambers of the soft actuators for a specified inflation time. The pneumatic air lines from this compressor to the actuators were loosely mounted on the treadmill to prevent it from tapping a user while in use. The frequency of these applied perturbations are updated for each trial through the open-loop control strategy designed in Simulink (Mathworks, MA, USA). The controller provides damped perturbations via the pneumatic actuators as no overshoot was seen in Fig. 3a and Fig. 5c.

Perturbations applied to users consisted of 0.2 *sec* pulses of inflation for the X-ff-PAM at a consistent 200 *kPa*. According to Fig. 3, this would yield about 180 *N* force and the corresponding hip torque is 18 *Nm* assuming a 10 cm moment arm from the actuator to the hip joint. This torque value is approximately 16% of the average maximum hip torque of healthy adults [19]. It is worth noting that prior hip entrainment studies were preformed with a heavier robot (2.1 *kg*) at a maximum hip torque of 6 *Nm* [7] which is about 5% of the average maximum hip torque of healthy adults [19].

C. Experimental Setup

Gait entrainment experiments were performed on an instrumented treadmill (Bertec Treadmill, OH, USA) that collected ground reaction forces for the right leg for gait phase analysis. Treadmill force sensors were calibrated prior to each experiment and zeroed between trials to reduce noise.

The SR-HExo was controlled using a Simulink Real-Time system (Mathworks, MA, USA) on a real-time target machine (Baseline Real-Time Target Machine, Speedgoat, Bern, Switzerland). The actuators were pressurized with a 3-way, 2-channeled solenoid valve (320-12 VDC, Humphrey, USA) which was controlled via a MOSFET (IRF520 MOSFET Driver Module) driver module (Fig. 4).

It should be noted that this study only analyzed results of entrainment with the SR-HExo worn over the right hip, which is fundamentally different from the prior hip entrainment study which applied bilateral perturbations to both the left and right hips [7].

D. Subjects and Experimental Protocol

A total of 11 young, healthy subjects (age: 20-26, weight: 40.8-83.9 *kg*, height: 160.0-195.6 *cm*, sex: 6 male/5 female) participated in the study, which was approved by the Institutional Review Board of Arizona State University (STUDY00012099). All subjects provided a written consent prior to participation.

The SR-HExo was donned over the right hip of the subject with X-ff-PAM actuators on either the anterior or posterior side. A safety harness was used throughout the experiments to ensure subject safety during treadmill walking and prevent potential falls.

The subject's preferred walking speed was first determined by gradually increasing the treadmill speed by units of 0.05 *m/s* starting from a low speed (0.8 *m/s*) until the subject indicated the speed was too fast to walk comfortably. The speed was then decreased until the subject indicated the speed was too slow to walk comfortably. The midpoint of these values was presented to the subject for confirmation that it is a comfortable walking rate. This speed was maintained as the subject's preferred walking speed throughout the experiments. Preferred walking speed ranged from 0.95 - 1.30 m/s across all subjects. The gait frequency at the preferred walking speed, namely preferred gait frequency (f_{PWS}), was used as a base to determine perturbation frequency levels.

The study was composed of two separate experiments, one with hip flexion perturbations and the other with hip extension perturbations, conducted in randomized order. For each experiment, 6 different perturbation frequency levels were tested, from a subject's preferred gait frequency $1.0 \cdot f_{PWS}$ up to 15% higher ($1.15 \cdot f_{PWS}$) with steps of 3%. These 6 conditions were further divided into two sets of 3 trials. The first set contained perturbation conditions of f_{PWS}, $1.03 \cdot f_{PWS}$, and $1.06 \cdot f_{PWS}$ in randomized order, and the second set contained $1.09 \cdot f_{PWS}$, $1.12 \cdot f_{PWS}$, and $1.15 \cdot f_{PWS}$. The first set included perturbation frequencies that had been previously used to evaluate if the subjects could successfully get entrained in this frequency range with the rigid hip exoskeleton robot [7]. The second set was used to evaluate the potential of the SR-HExo in extending the basin of entrainment.

For each trial, subjects were instructed to walk for 3 minutes as comfortably as possible. They were informed that they would feel the pull of the exosuit device and allowed to adjust their step length and pace until they could comfortably walk with the device. As in prior treadmill studies, entrainment to faster perturbation frequencies than the subject's natural frequency requires the subjects to shorten their step length to maintain the constant walking speed in the constrained treadmill setting [4], [6].

To prevent visual entrainment, subjects were instructed to look at a blank wall and were indicated visually by the experimenters to shift left or right to maintain appropriate positioning on the treadmill. In addition, to prevent auditory entrainment, subjects wore foam earplugs (Noise Reduction Rating (NRR) of 32 decibels) and noise cancelling headphones (WH1000XM3, SONY, Japan) that generated white noise at full volume. No information was provided regarding the hypotheses in this study, and sufficient rest time was provided between trials to prevent fatigue.

E. Data Processing and Analysis

Synchronization between the user and perturbations was determined through processing of vertical ground reaction forces and valve logic states (ON/OFF). Ground reaction forces of the right leg as collected by the treadmill were processed to determine the instance of heel strike in each cycle. From this information, the timing of each stride and the number of strides per trial was calculated. These were used to normalize each stride into gait cycle percentages (%GC) from heel strike of the right leg to the next heel strike of the same leg. The valve logic states were monitored and their timing in the gait cycle was calculated.

Each trial was assessed for various gait entrainment characteristics: success rate of entrainment, phase-locking value, variability of phase-locking value, consecutive strides in the entrainment window, and strides until the onset of phase-locking. A trial was considered successfully entrained if perturbation timing was confined within a window of $\pm 15\%$ GC from the running average for at least 50 consecutive strides (phase-locked). This window was referred to as entrainment window. Note that the margin of deviation was expanded to $\pm 15\%$ GC from the $\pm 10\%$ GC used in the previous ankle study [6] since experimental results sometimes showed a wider variation than $\pm 10\%$ GC, but still fluctuated about the average, rather than exhibiting the drifting behavior (Fig. 5(a)).

To evaluate how well human gait and the perturbations were synchronized, the mean of absolute deviation from the mean value within the entrainment window was calculated and is referred to as variability of phase-locking. In addition, the number of consecutive strides in the entrainment window was calculated. The number of strides until the onset of phase-locking was quantified to evaluate how quickly a subject can get entrained, which is one important transient characteristic of gait entrainment.

In addition, to investigate if entrainment characteristics depend on perturbation frequencies, one-way repeated measures ANOVA tests were performed for each perturbation direction (i.e., frequency level as the within-subject factor). Separate analysis was performed for each of the following dependent variables: phase-locking value, variability of phase-locking, consecutive strides in the entrainment window, and strides until the onset of phase-locking. Mauchly's test of sphericity was used to formally test the assumption of sphericity. If the assumption was violated, the degrees-of-freedom were adjusted using the Greenhouse–Geisser correction before calculating the p-value. As most of this analysis showed statistically insignificant or minimal difference across the 6 tested perturbation frequencies, subsequent analyses were performed by aggregating all trials in the same perturbation direction.

Lastly, to identify if entrainment characteristics are dependent on perturbation direction, paired t-tests were performed. The same dependent variables used in the ANOVA analysis were used. All statistical tests were made using the SPSS statistical package (IBM, NY) at a significance level of $p <$

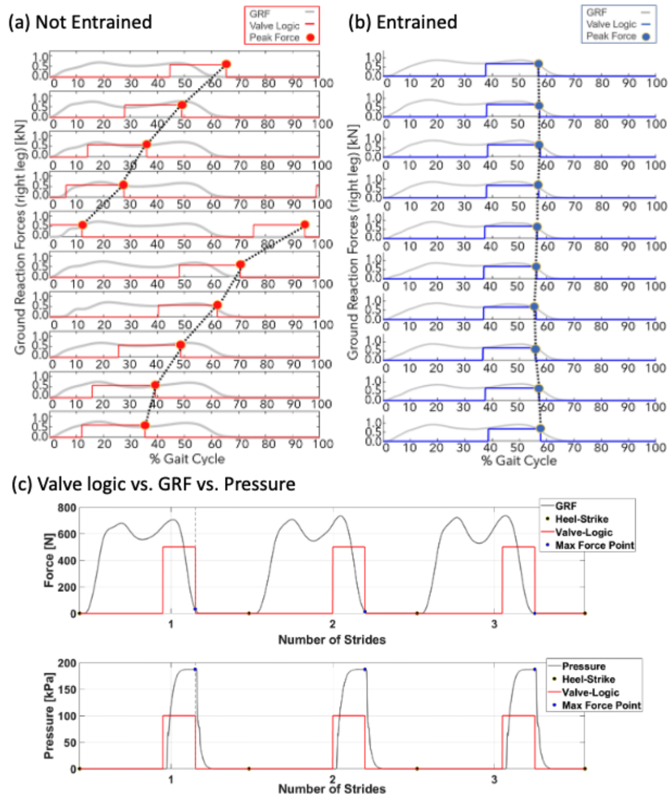

Fig. 5. Sample results of a representative subject (a) showing no entrainment as indicated by the shift in perturbation pulse across each of the gait cycles, and (b) showing entrainment, where the perturbation pulse consistently aligns to toe-off. (c) The valve ON/OFF logic, ground reaction force, and actuator pressure during an entrained trial. An example for 1.15$\cdot f_{PWS}$ flexion perturbations and a treadmill speed of 1.3 m/s is shown.

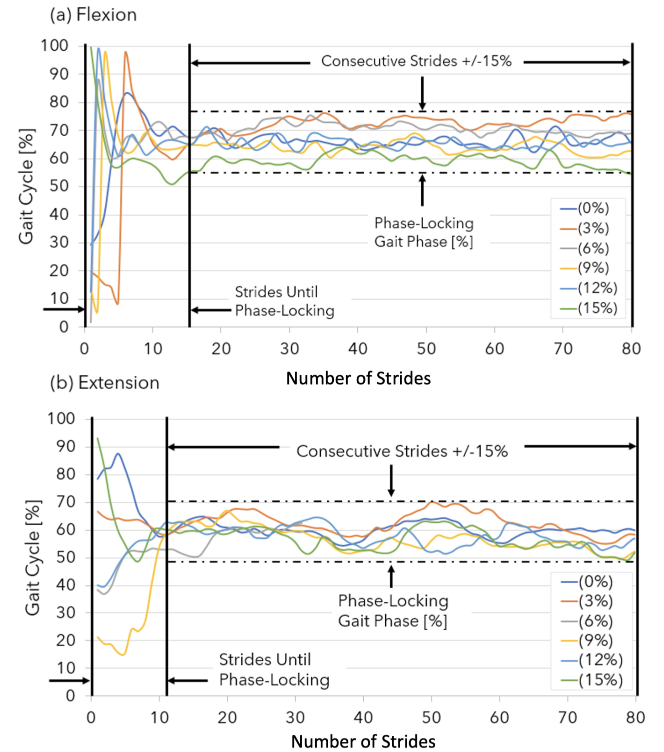

Fig. 6. Results of a representative subject for (a) flexion perturbations and (b) extension perturbations for the first 80 gait cycles. In all experimental condition, the initial transient response lasted only a few tens of gait cycles. Consistent phase locking around toe-off was observed, although the phase-locking value for extension perturbations was a bit earlier than for flexion perturbations.

0.05. Error bars in the result figures and values in parentheses were used to denote mean ±1 standard deviation (SD).

III. Results

A. Success of Entrainment and Phase-Locking

All 11 subjects were successfully entrained in all 12 experimental conditions: 6 frequencies (1.0$\cdot f_{PWS}$ − 1.15$\cdot f_{PWS}$) in both perturbation directions, which confirmed the effectiveness of the SR-HExo in inducing gait entrainment. In the initial transient phase where entrainment did not occur yet (Fig. 5 (a)), a clear drifting of the perturbation pulse (red lines) across each of the gait cycles was observed. After 10+ gait cycles, the perturbation pulse (blue lines) was consistently aligned with the toe-off phase demonstrating a strong phase-locking (Fig. 5 (b)). A comparison plot of the valve ON/OFF logic and actuator pressure showed that the bandwidth was large enough to allow for complete inflation and deflation of the actuators to induce the full range of perturbation without impeding upon more than a third of the gait cycle, even in the fastest walking cycle condition (i.e., perturbation frequency 15% faster than a user's preferred walking frequency) (Fig. 5 (c) bottom).

Results of a representative subject, selected for close appearance to the average, is shown in Fig. 6. For each experimental condition, perturbation phase consistently converged to a single final value around the toe-off phase, which confirmed the existence of a single stable point attractor during gait entrainment to unilateral, unidirectional hip perturbations.

When the maximum pressure point was used as a reference, the average phase-locking value for extension perturbations was 52.1±16.7% GC which corresponds to the phase where peak hip extension occurs. The value for flexion perturbations was 63.2±17.1% GC which is aligned with the rapid transition phase from full hip extension to hip flexion (Fig. 7(a)) [20]. Once phase-locking was achieved, the variability of phase-locking, quantified by the mean absolute deviation from the phase-locking value, on average was 2.9±0.8% GC for flexion trials and was 3.9±1.2% GC for extension trials, which further supports the existence of a strong single stable point attractor (Fig. 7(b)). The average amount of consecutive strides within the entrainment window was 148.2±30.7 and 135.8±34.6 in flexion and extension trials, respectively (Fig. 7(c)). The average amount of strides taken until successful phase-locking was 17.2±23.9 strides for flexion trials and 17.5±17.8 strides for extension trials (Fig. 7(d)).

B. Frequency- and Direction-Dependent Characteristics of Entrainment

Perturbation frequency had statistically insignificant or minimal impact on entrainment characteristics for the same direction of perturbation. Phase-locking value showed no statistical difference across all 6 different frequencies for the flexion perturbation direction (p = 0.69) and a marginal difference for

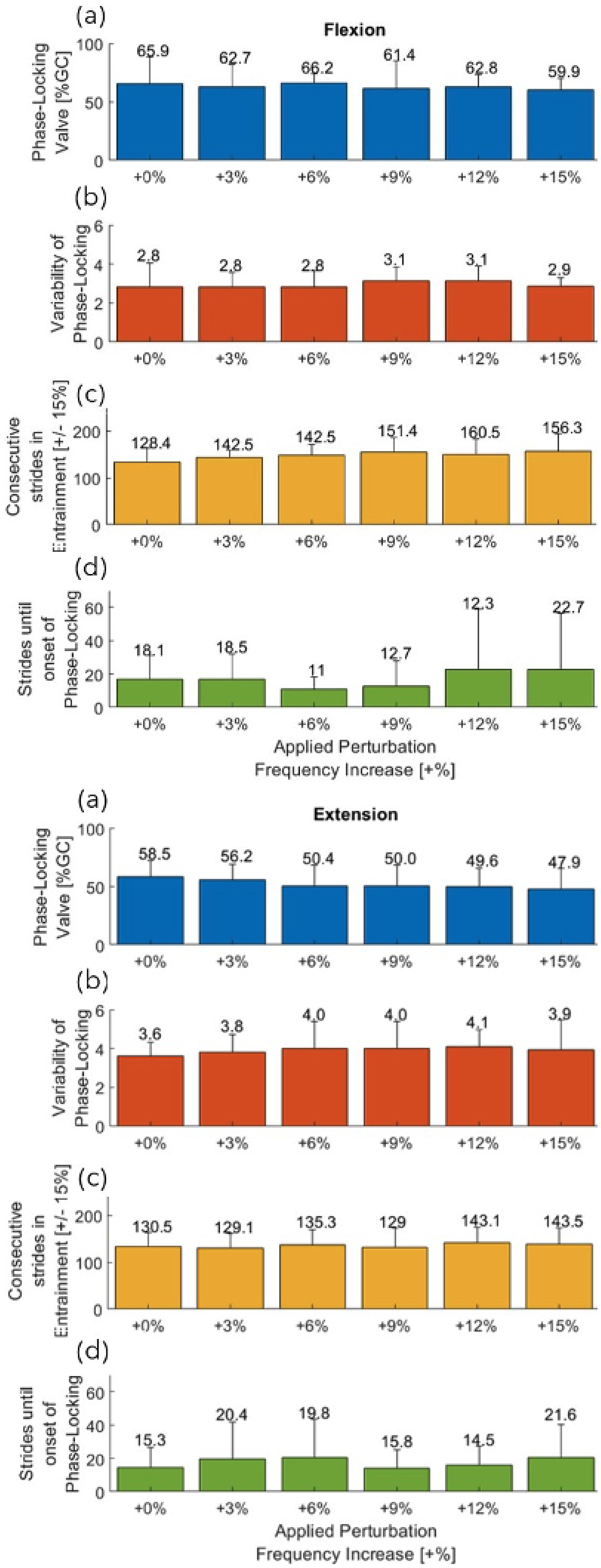

Fig. 7. Summary of group average results of 4 entrainment characteristics. Top: flexion trials, Bottom: extension trials. (a) Phase-locking value, (b) variability of phase-locking, (c) consecutive strides in the entrainment window, and (d) strides until the onset of phase-locking.

the extension perturbation direction (p = 0.031). Perturbation frequencies had no significant impact on all other entrainment characteristics: variability of phase-locking for flexion (p = 0.60) and extension (p = 0.93), consecutive strides in entrainment for flexion (p = 0.35) and extension (p = 0.80), and strides until the onset of phase-locking for flexion (p = 0.52) and extension (p = 0.75). Thus, in the follow-up analysis to investigate direction-dependent entrainment characteristics, all trials in the same perturbation direction were aggregated.

Perturbation direction had a significant impact on phase-locking value, variability of phase-locking, and consecutive strides in entrainment, but no impact on strides until the onset of phase-locking. When averaged across all subjects, the phase-locking value for flexion perturbations (63.2% GC) was significantly later ($p < 0.001$) than that for extension perturbations (52.1% GC). The variability of phase-locking for flexion perturbations was significantly smaller than for extension perturbations ($p < 0.001$). In addition, the number of consecutive strides in the entrainment window was significantly longer with flexion perturbations than extension perturbations (p = 0.003). However, there was no statistical difference in the strides until the onset of phase-locking between flexion and extension data (p = 0.95).

IV. Discussion

The motivation of this study was to investigate the potential of a soft robotic hip exosuit (SR-HExo) to expand the current capabilities of gait entrainment in rehabilitation context. The study recruited 11 healthy subjects to walk with the SR-HExo for a series of 12 trials with varying perturbation directions and frequencies, and monitored the average success rate of entrainment, phase-locking value, variability of phase-locking, consecutive strides within the entrainment window, and the number of strides until the onset of phase-locking.

All 11 subjects exhibited successful entrainment to perturbations significantly faster than 15% of their preferred gait frequency after an average of 17.5 strides. This result is significant for potential application in gait rehabilitation since extending the basin of entrainment has a higher capacity to correct asymmetric gait patterns. Spatio-temporal gait parameters of one leg can be modulated to a larger extent with a wider basin of entrainment when unilateral perturbations are implemented. In addition, a wider basin of entrainment could lead to a higher increase in walking speed during walking on a self-paced treadmill or overground walking.

In all experimental conditions, all subjects consistently showed a single phase-locking value around the toe-off phase, confirming the existence of a single stable point when unidirectional perturbations were applied to the hip joint. This result is consistent with previous ankle studies [4]–[6]. However, it should be noted that the results of this study are limited to the combined unilateral and unidirectional perturbation condition and cannot be generalized to bidirectional and/or bilateral perturbation conditions. The previous hip entrainment study with bilateral perturbations (flexion perturbation on one leg and extension perturbation on the other leg in a single session) resulted in phase-locking at two distinct gait phases [7]. Further investigation is warranted to investigate how different perturbation designs influence phase-locking behaviors.

A window of ±15% GC from the running average was used in identifying phase-locking to fully capture natural variability in human gait. In fact, the actual variability around the stable point attractor, quantified as the mean of absolute deviation from the phase-locking value, was substantially smaller than ±15% GC; once phase-locking was achieved, the variability of phase-locking on average was 2.9±0.8% GC for flexion trials and was 3.9±1.2% GC for extension trials, which further supports the existence of a strong single stable point attractor.

Phase-locking occurred significantly sooner in the gait cycle with extension perturbations than with flexion perturbations. On average, the extension perturbations occurred at 52.1% GC, where the hip angle reaches maximum extension. The flexion perturbations were phase-locked at 63.2% GC, where the transition from maximum hip extension towards hip flexion occurs [20]. While both the flexion and extension perturbations were aligned with hip movement directions, they did not provide assistive torques but resistive torques to the hip joint. The extension perturbations were locked to the timing of maximum hip flexion torque, and the flexion perturbations were aligned with the phase where hip flexion torque decreases towards the direction of hip extension torque [21].

This indicates mechanical assistance from periodic perturbations might not be a factor determining phase-locking in gait entrainment. In fact, previous gait entrainment studies using electrical perturbations on gastrocnemius demonstrated that entrainment can occur even with electrical stimulation that is too weak to induce significant assistive torque or mechanical benefit [9], [10]. One potential explanation for this may be that sensory cues are also an important factor for gait entrainment. Another potential explanation is that the human neuromuscular system might simply find the best time to easily reject external disturbances (perturbations) in order to maintain natural gait biomechanics, and the phase around toe-off might be the case.

Comparison of results for two different perturbation directions suggests that flexion perturbations may be better suited for their implementation in rehabilitation settings than those applied in extension. The variability of phase-locking, quantified by the mean absolute deviation from the phase-locking value, on average was smaller with flexion perturbations (2.9±0.8% GC) than with extension perturbations (3.9±1.2% GC). In addition, flexion perturbations induce entrainment for more consecutive strides on average (148.2±30.7) than extension perturbations (135.8±34.6). The differences of these two metrics were statistically significant.

One limitation of this study is the constraint on walking speed imposed by the treadmill. This speed constraint has been shown only to make entrainment less likely and last for fewer consecutive strides, as other studies have shown that the use of a treadmill otherwise does not impact the phase-locking value of successful entrainment studies [5]. This speed-constrained setting, while unideal, does mirror conventional rehabilitative facilities that may not have sophisticated treadmill setups. It is important to note that the use of the lightweight SR-HExo even under the constant treadmill speed condition allowed us to achieve clinically meaningful results such as a high success rate of entrainment, a wider basin of entrainment, and faster transient entrainment behavior. Investigation of the gait entrainment characteristics with the SR-HExo on a self-paced treadmill, which simulates overground walking by matching the subject's walking speed, will be investigated in the near future.

Future work will improve the bandwidth of the pneumatic actuator by increasing tubing size and pressure supply level, and investigate the impact of improved bandwidth on entrainment characteristics such as strides until phase locking. The extent to which the use of lightweight soft robotic hip exosuit can expand the basin of entrainment will also be explored on a self-paced treadmill by applying faster perturbations until entrainment failure occurs as in [6]. Further, the impact of device weight and perturbation magnitude on entrainment characteristics will be investigated to better understand the source of improvement of the entrainment characteristics with the SR-AFO. Finally, inspired by previous studies demonstrating the potential of resistant training to improve walking capabilities in stroke survivors [22], a future study will investigate whether strengthening the affected hip via entrainment to resistive hip torque perturbations is beneficial to promote faster self-selected walking in clinical populations post-training.

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