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Locomotion Synchronization and Gait Performance While Walking With an Overground Body Weight Support System

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Abstract— **Rehabilitation robotics offers new alternatives to patients and therapists to efficiently support walking training using Body Weight Support (BWS) systems. Automating the locomotion of overground BWS systems is one of the feasible approaches to free therapists from manual operation. However, the effect of locomotion control strategies of BWS system on participant's gait performance have not been studied sufficiently. For this reason, in this paper we introduced locomotion synchronization between a participant, a therapist, and a BWS system as control criteria, and investigated its effect on participant's gait performance during walking with an overground BWS system. In the experiment, four healthy participants walked with a BWS system under different BWS conditions, and with/without wearing orthosis which simulates asymmetric gait of actual patients. As the result, it was observed a significant relationship between locomotion synchronization and participants' gait performance, such as walking speed and step time.**

Clinical relevance - **Controlling an overground BWS system's locomotion in synchronizing with the participant's gait has the potential to facilitate the effect of gait rehabilitation.**

I. INTRODUCTION

For patients with gait disabilities it is vital to go through rehabilitation training not only to recover functional walking ability [1], but also to potentially improve their emotional and social well-being [2]. In recent years, robotic and electro-mechanical systems have become a popular and feasible solution due to their potential to simplify the repetitive and time-consuming interventions needed for patients to have positive outcomes [3] [4]. Robotic systems can also provide tools to tailor the treatment to patients' needs. For example, they can describe gait characteristics and autonomously adapt to the patient, or they can provide therapists with meaningful data that describes the patient performance [5].

In gait rehabilitation training using robotic systems, Body Weight Support (BWS) systems are effective in improving weight distribution and facilitating an erected body posture [6] [7]. BWS systems are commonly used together with treadmills to control the walking speed and to facilitate a symmetrical and constant gait. In contrast, overground systems with BWS offer a different walking support in terms of balance and propulsion. While both approaches have shown evidence of meaningful improvements in different gait features, having patients actively moving overground in an upright position, safely and independently, might increase the gait rehabilitation efficacy [8]. There are different approaches to control an overground BWS system. One characteristic of traditional gait rehabilitation using overground systems is the presence of a therapist walking together with the patient. Especially on repetitive actions such as walking, it is expected that some coordination will emerge.

Behavior coordination or synchronization can be described as the dynamic and mutual adaptation of the temporal structure of behaviors between interactive entities [9]. Interpersonal synchronization between the patient and the therapist in clinical settings has been reported [10] and it was pointed out a potential relationship with a more positive experience in interventions. Interpersonal synchronization in cooperative walking has been modeled into a virtual robot, showing mutual adaptation capabilities between the system and patients [11]. However, no study has investigated the locomotion synchronization in interventions using BWS systems. A patient walking supported by an overground BWS system simultaneously interacts with the therapist and with the BWS system. By understanding the motion dynamics between them we might obtain insights on how these features can be used to control the system's locomotion in a way that positively impact on the patient's gait.

This study aims to understand the relationship between locomotion synchronization and gait performance during walking with BWS. Previous to this study, we developed an overground BWS system with embedded sensors to analyze the patient's gait [12]. In this study, we evaluate the dynamics between three different entities present in walking rehabilitation with BWS: a participant using the overground BWS system, a therapist pulling the BWS system, and the BWS system. By following the methodology proposed by [13], we described the movement dynamics among three entities as *Synchronization Index*. Then, we evaluated the effect of synchronization on different gait features during a walking task with a BWS system.

II. METHODOLOGY

A. Overground Body Weight Support System

Fig.1 illustrates the overview of the proposed approach. Participants were mechanically supported using a harness attached to both arms of an overground BWS system (All-in-One Walking Trainer, Ropox A/S, Naestved, Denmark). The harness supported the participant on the pelvis and the abdomen, and the amount of body weight unloading can

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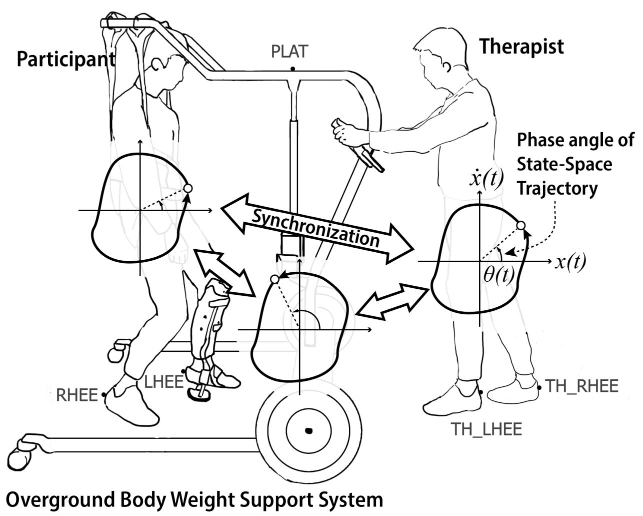

Fig. 1. Analysis of locomotion synchronization between the participant, the therapist, and the BWS system during gait rehabilitation.

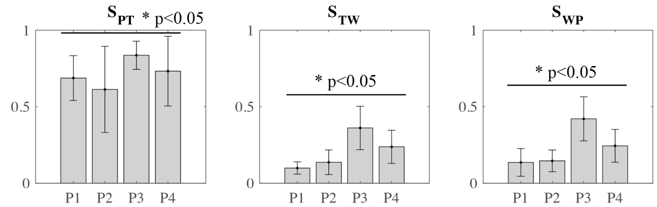

Fig. 2. Average and standard deviation of synchronization indices in terms of participants.

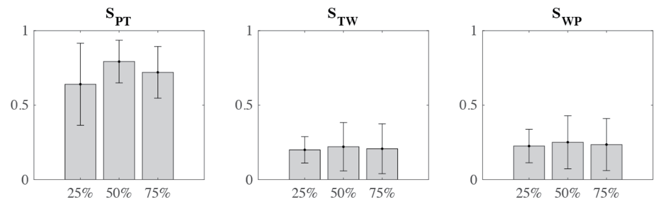

Fig. 3. Average and standard deviation of synchronization indices in terms of body weight support conditions.

be adjusted by changing the height of the arms. During gait rehabilitation, the therapist manually operates the BWS system by pulling the handle according to the participant's gait.

B. Synchronization Index

Synchronization of coupled dynamical systems has been modeled in the past following different approaches. One study used wearable step sensors and estimated the walking phase between an user and a virtual agent [11]. A different study proposed a state-space method to model joint tasks dynamics [13], and representing synchronization as single value called Synchronization Index. This method was found especially appropriated for our application, thus the following section summarizes it, and describes the way it was implemented for this scenario.

A two-dimensional state-space composed of time-series data and its time derivative $[x(t), \dot{x}(t)]$ is determined for each interacting agent. Then, the phase of oscillatory movement θ of each agent can be derived as the angle in the state-space as below:

$$\theta(t) = \operatorname{atan}\left(\frac{\dot{x}(t)}{x(t)}\right). \tag{1}$$

Having calculated the individual phase θ, we obtain the relative phase difference ϕ between two agents (e.g. A and B) as follows:

$$\phi_{AB}(t) = \theta_A(t) - \theta_B(t) \tag{2}$$

By using the relative phase difference, the synchronization index S is determined using the circular variance (CV) of the relative phase:

$$S_{AB} = \left| \frac{1}{N} \sum_{j=1}^{N} e^{i\phi_{AB}(j)} \right| = 1 - CV \tag{3}$$

Value of S varies between 0 and 1: S becomes 0 when phase differences $\phi(t)$ were uniformly distributed from 0° to 180°, while it becomes 1 with a constant phase difference.

For human entities (the participant and the therapist), we defined $x(t)$ as the step distance between right and left foot:

$$x(t) = P_{LHEE} - P_{RHEE} \tag{4}$$

where p_{LHEE}, p_{RHEE} denote the position of left and right heel markers along the walking axis.

For the BWS system, we defined $x(t)$ as its velocity described as the time derivative of its position:

$$x(t) = \dot{P}_{PLAT} \tag{5}$$

The offset component of $x(t)$ was removed by subtracting its mean with a moving time window as follows:

$$x(t) \leftarrow x(t) - \frac{1}{K} \sum_{j=t-\frac{K}{2}}^{t+\frac{K}{2}} x(j) \tag{6}$$

Note that, feet position of the participant (P_{LHEE}, P_{RHEE}) and the therapist (P_{TH_LHEE}, P_{TH_RHEE}), and the position of the BWS system (P_{PLAT}) were measured using an optical motion capture system (VICON MX System with 16 T20S Cameras, 100Hz capture). The maker locations are illustrated in Fig. 1.

III. Experiment

A. Experiment Procedure

The experimental procedures involving human subjects described in this paper were approved by the Institutional Review Board of University of Tsukuba Hospital. Four young and healthy participants (2 males and 2 females) with no previous experience using BWS systems participated in this experiment. They were equipped with the harness, and retro-reflective markers were placed on the heels (Figure 1).

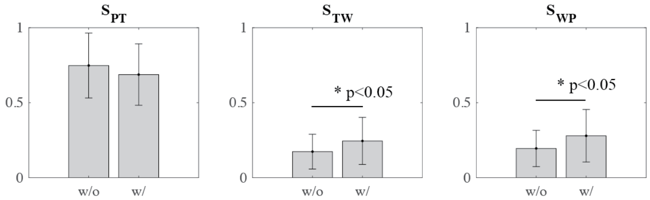

Fig. 4. Average and standard deviation of synchronization indices in terms of with or without wearing PTB orthosis.

Participants were on average 27.75 ± 3.86 years old, 1.68 ± 0.08 m tall, and weighted 60.0 ± 7.75 Kg.

Participants were instructed to walk at a comfortable pace, and a therapist controlled the locomotion of the BWS system. The therapist guided the participant based on the observed behavior. The therapist had experience on supporting gait rehabilitation using BWS, and he was asked to operate the BWS system as he usually does in interventions. None of them were instructed to synchronize their gait, nor were they aware of the purpose of the study. We simulated an abnormal gait using a Patellar-Tendon Bearing (PTB) orthosis, which constrains the ankle motion and reduces the pressure on the foot sole. Participants tried two conditions, walking without the orthosis followed by walking with the orthosis. Each condition consisted of six trials, and in each trial, participants were asked to walk 10m back and forth. Two trials each with different partial BWS: 25%, 50%, and 75%. The amounts of BWS were selected based on the need of different target patients. Post-stroke patients benefit from rehabilitation using overground BWS with values going from 20% to 40% [6]. According to the injury, spinal cord injury patients might require more substantial support that goes up to more than 70% on early stages of the rehabilitation process [7] [1].

Participants ran one trial (10m) to familiarize themselves with the system on each experimental condition. Then walked two trials under the different BWS values. After finishing the first condition, participants rested seated for about 5 minutes and were equipped with the orthosis to repeat the same walking task. The total duration of each session was 40 minutes.

IV. Results

We computed the following metrics as variables for evaluating gait performance, based on the measurement of motion capture system: *Step Length(SL)*, *Step Length Variance(SLV)*, *Step Time(ST)*, *Step Time Variance(STV)*, and *Walking Speed(SPD)*. In addition, S_{PT}, S_{TW}, S_{WP} denote synchronization indices between two agents among: Participant (P), Therapist (T), and BWS system (W).

A. Effects of Individual Difference, BWS and Orthosis

First, Analysis of Variance (ANOVA) with three factors: *Participant* (4 levels), *BWS* (3 levels), and *Orthosis* (2 levels) was conducted to analyze the effect of those factors on synchronization indices. Figure 2,3, and 4 show the average and standard deviation of synchronization indices in terms of each factors, respectively. As the result of ANOVA, the main effect of *Participant* factor was observed on: $S_{PT}(F(3,48) = 3.77, p < 0.05, \eta = 0.320)$, $S_{TW}(F(3,48) = 26.04, p < 0.05, \eta = 0.765)$, and $S_{WP}(F(3,48) = 24.46, p < 0.05, \eta = 0.754)$. Additionally, the main effect of *Orthosis* was also confirmed on S_{TW} $(F(1,48) = 9.59, p < 0.05, \eta = 0.285)$, and S_{WP} $(F(1,48) = 9.96, p < 0.05, \eta = 0.293)$.

B. Relationship between Synchronization Indices and Gait Performance

To clarify the relationship between synchronization indices and gait performance, multiple regression analysis was conducted using the synchronization indices S_{PT}, S_{TW}, S_{WP} as predictors. The following equation was used as the regression equation, and the regression coefficients **W** were optimized with least-square-method.

$$y = \mathbf{S} * \mathbf{W}^T \tag{7}$$

where **S** represents a predictor vector consisting of synchronization variables and their interactions as $\mathbf{S} = [S_{PT}, S_{TW}, S_{WP}, S_{PT} * S_{TW}, S_{TW} * S_{WP}, S_{WP} * S_{PT}]$.

As shown in the top row of the Figure 5, significant correlations were found on *SL* $(R^2 = 0.280, p < 0.05)$, *ST* $(R^2 = 0.610, p < 0.05)$, *STV* $(R^2 = 0.385, p < 0.05)$, and *SPD* $(R^2 = 0.663, p < 0.05)$. Especially, high R^2 values (more than 0.5) were obtained on *ST* and *SPD*. The coefficient value of predictors are shown in the bottom row of the Figure 5. The predictors indicated by asterisk (*) means that the effect of the predictor was confirmed significant $(p < 0.05)$. According to these plots, it's found that S_{TW} and S_{WP} have significant negative relationships with *Step Time*, and S_{PT} and S_{WP} have significant positive relationships with *Walking Speed*.

V. Discussion

According to the results described in section IV-A, although significant differences in synchronization indices between participants were observed, the effect of different BWS or walking patterns (orthosis) within each participant was negligible (i.e. the mean differences of S_{TW} and S_{WP} in terms of orthosis were less than 0.1). These results imply the potential of locomotion synchronization indices as indicators to describe an individual's gait characteristics independent from the amount of BWS and asymmetry of gait.

Following this, the relationship between synchronization indices and gait performances was analyzed. According to the result shown in Figure 5, it can be observed that the step time and walking speed of participants can be explained by the overall synchronization among the three entities (i.e., participant, therapist, and BWS system). In particular, higher synchronization indices are relevant to reduce step time and increase walking speed, and vice-versa. This is especially meaningful as in rehabilitation, patients are often encouraged to practice walking steadily with increased step length and walking speed while reducing variability among steps. Since

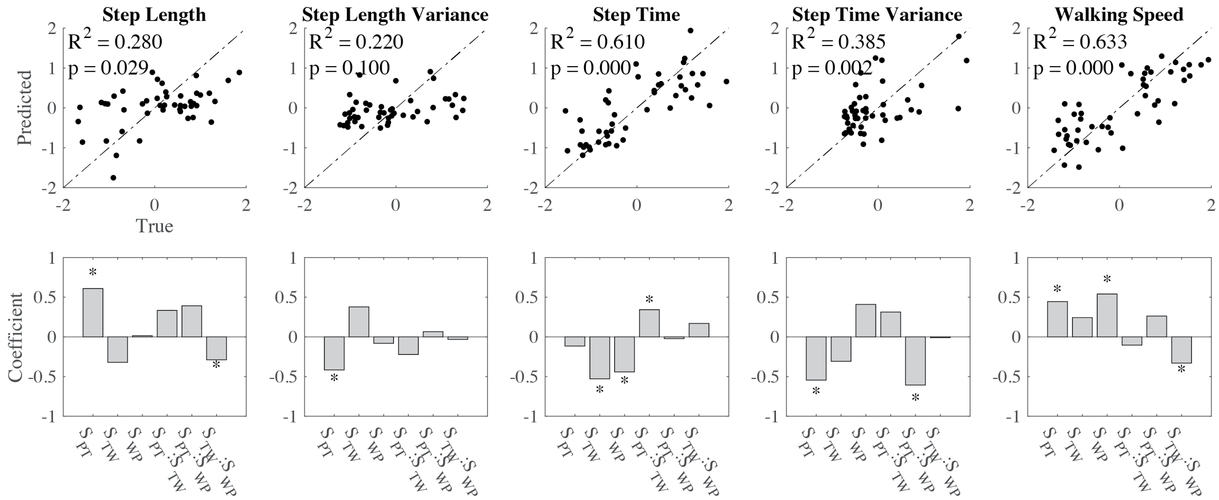

Fig. 5. Results of multiple regression analysis: correlations between gait performance and synchronization indices (Top row), and estimated coefficients (Bottom row). Asterisk (*) indicates that the predictor's p-value is less than the significance level ($\alpha = 0.05$).

these gait parameters are commonly used to assess the patient's gait performance, understanding the dynamics of the BWS system in terms of its synchronization with the patient's gait is important for designing an appropriate control strategy for an autonomous BWS system.

Although a preliminary evaluation involving healthy participants to set a baseline is a reasonable step, the small sample used in this study is one of the limitations. Moreover, the exploratory character of this study lacks a more rigorous experiment protocol. Therefore, our future work involves a study with a larger sample and counterbalanced conditions to confirm the insights found in this study regarding the locomotion synchronization.

VI. Conclusions

In this study we described the movement dynamics during a therapy setup, and evaluated the effect of locomotion synchronization on different gait features during a walking task with BWS. From the discovered relationship between synchronization indices and the participant's gait, controlling the robotic system autonomously to maintain higher synchronization may improve the gait performance independently from BWS values and gait asymmetry. This suggests a way to use the proposed methodology to estimate the movements dynamics as a predictor of the patient's performance. While these results are encouraging, they only represent the first step toward our goal. More research is needed to fully comprehend the impact of locomotion synchronization on gait performance and its consequences as a therapeutic tool.

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