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Short Paper

Synchronous Position and Compliance Regulation on a Bi-Joint Gait Exoskeleton Driven by Pneumatic Muscles

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Abstract—A previously-developed pneumatic muscles (PM) actuated gait exoskeleton (with only knee joint) has been demonstrated in achieving appropriate actuation torque, range of motion (ROM), and control bandwidth for task-specific gait training. While the adopted multi-input-multi-output (MIMO) sliding mode (SM) strategy has preliminarily implemented simultaneous control of the exoskeleton's angular trajectory and compliance, its efficacy with human users during gait cycles has not been investigated. This short paper presents an improved Bi-joint Gait Rehabilitation Exoskeleton (BiGREX) with integrated human hip and knee joints. Results with 12 healthy subjects demonstrated that the system's compliance can be effectively adjusted while guiding the subjects walking in predefined trajectories.

Note to Practitioners—This paper was motivated by achieving compliant interaction between PM-actuated exoskeletons and human when conducting task-specific gait training. Due to the intrinsic nonlinearity of PM, it's challenging to establish a mathematical model to precisely predict real-time compliance of the powered joints. This paper suggests a new strategy that adopts the average pressure of flexor and extensor PMs as the feedback to synchronously realize the joint position control and compliance regulation. A novel experimental approach was adopted to validate the system capability on adjusting the compliance from human users' perception. This paper provides a new insight between the controlled PM pressure and desired joint-compliance, which would be essential for the future design of PM-actuated exoskeletons.

Index Terms—MIMO control, compliant interaction, PM lower limb exoskeleton.

I. INTRODUCTION

Cao et al. [1] developed a MIMO SM controller on a knee joint mechanism driven by antagonistic PMs to simultaneously track the mechanism's angular trajectory and average antagonistic PM pressure. The robotic behaviors are comparable to algorithms of variable impedance reported on motor-driven gait rehabilitation devices [2]. However, the MIMO SM based compliance adaptation performance has not been investigated during fully actuated human gait cycles.

This paper is an extended study based on the MIMO SM control strategy [1] with two major contributions. One is the improved BiGREX system integrated with both human hip and knee joints to mimic natural gait cycles, and the other is to experimentally investigate if the MIMO SM technique can vary the robotic assistance provided to human users while guiding them to walk along a reference gait trajectory. To the best authors' knowledge, it is the first attempt to implement variable compliance on a fully PM actuated gait exoskeleton with systematic experimental validation.

II. SYSTEM AND MODELING

Fig. 1 presents the configuration of BiGREX, control diagram of the MIMO SM controller and its use with BiGREX system on a human user. A myRIO platform by National Instruments is employed for data acquisition (at 1000 Hz) and real-time control processing (at 100 Hz). A custom printed circuit board was also designed for physical hardware interfacing the myRIO. The BiGREX system mainly consists of a trunk mechanism with three unactuated degrees of freedoms (DoFs) and a bi-joint mechanism with two powered joints. Detailed description of single joint kinetics, load dynamics of single joint and the dynamics of chosen FESTO PM can refer to [1]. The modeling of stiffness **S** which can be defined as $\Delta\tau/\Delta\theta$ is required to vary the compliance when controlling the position. The theoretical stiffness can be derived from different models, like dynamic model from our previous work [1, 3] or static force models proposed in [4-6], etc.

The first approach to calculate joint compliance is using the PM's dynamic force model. Based on our previous work, the output torque of the bi-directional PMs can be expressed as equation (1) [1]:

$$\tau = \tau_F - \tau_E = 2r[F(P_F) + B(P_F)\dot{x_F} + K(P_F)x_F - (F(P_E) + B(P_E)\dot{x_E} + K(P_E)x_E)] \qquad (1)$$

where *F(P)*, *B(P)* and *K(P)* denote the pressure-dependent force, damping and spring parameters based on the classic dynamic model of pneumatic muscle in [7]; x denotes the contracting length of extensor and flexor PMs; r denotes pulley radius of an actuated joint; and parameters with subscripts F and E are corresponding to the flexion and extension motion, respectively. Nevertheless, the joint compliance is dominated by the nominal pressure of the PMs [8]. Hence, by extracting the spring parameter forms in (1), the output torque of the joint's spring force terms can be derived as:

$$\begin{aligned}\tau = \tau_F - \tau_E &= 2r[K(P_F)x_F - K(P_E)x_E] \\ &= 2r\big[(K_0 + K_1(P_{avg} + \Delta P_F\big)r\theta) \\ &\quad - (K_0 + K_1(P_{avg} - \Delta P_E)r(-\theta)] \qquad (2)\end{aligned}$$

here the P_{avg} denotes the desired average antagonistic PM pressure; ΔP_F and ΔP_E denote the difference of the nominal pressure and P_{avg} of the flexor and extensor; K_0 and K_1 were determined experimentally; θ denotes the joint angle. Hence, the defined joint compliance $\mathbb{C}$ can be expressed as:

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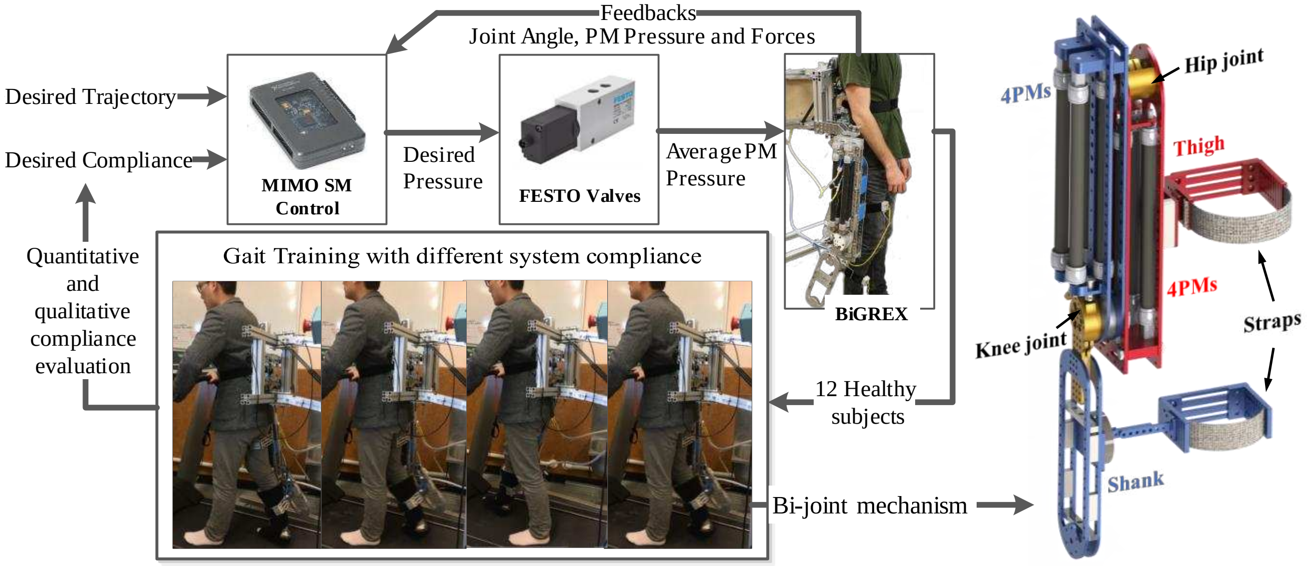

Fig. 1 The control diagram of the MIMO SM controller and its use with the BiGREX system on a human user. And the Bi-joint mechanism is illustrated in the right, both the thigh (in red) and shank (in blue) segments are powered by four pneumatic muscles.

$$\mathbb{C} = \frac{1}{S} = \frac{\theta}{\tau} = \frac{1}{2r^2[(2K_0+2K_1P_{avg}+K_1(\Delta P_F-\Delta P_E)]} \quad (3)$$

When the MIMO SM controller can perfectly track the desired average antagonistic PM pressure ($\Delta P_F = \Delta P_E$), the joint stiffness is linearly dependent on the set average pressure. With both K_0 and K_1 being set as positive constants, the compliance $\mathbb{C}$ decreases as P_{avg} increases.

The second approach is applying a static force model by Chou and Hannaford [4], which expresses the PM instant contractile force F as:

$$F = \left(\frac{3(l_0-x)^2-b^2}{4\pi n^2}\right)P \quad (4)$$

where l_0 is the original length of the PM; b and n are constants related to the geometry of the PM; P denotes the instant pressure of antagonistic PMs, and equation (4) is appropriate for both flexor and extensor PM. Through substituting F into equation (1) and extracting only the spring parameter forms, the desired compliance, when the average pressure can be tracked as expected ($\Delta P_F = \Delta P_E$), can be calculated as:

$$\mathbb{C} = \frac{\pi n^2}{3r^2\left[-2l_0 + r(\theta_{E0} - \theta_{F0})P_{avg} + (x_F - x_E)\Delta P\right]} \quad (5)$$

where θ_{E0} and θ_{F0} denote joint angular positions when the extensor and flexor PMs are at their original lengths.

It's obviously demonstrated by equations (3) and (5) that the relationship between compliance and pressure is inversely proportional. However, we can also notice that the joint compliance cannot be precisely derived from the PM models which have been proved to be practical in certain cases, because (1) both models are simplified due to the nonlinearity of the PM; (2) different models present varied results. Note that, no extra mechanism was implemented to measure the real-time compliance magnitude and feedback it for control. Hence, it would be essential to conduct experiments to prove the feasibility of the proposed MIMO SM algorithm with close-loop average PM pressure control model during human gait. The performance of adaptive compliance control will be presented in Section III-C.

III. EXPERIMENTS AND RESULTS

Comparing to the preliminary experiments on knee joint in [1], three sets of experiments were designed in this study with natural human walking gait aiming to comprehensively evaluate the effectiveness of the MIMO SM control with the compliance adaptable BiGREX system, results will be presented in section A to C.

Ethical approval for experiments was granted by the University of Auckland Human Participants Ethics Committee (014970). Written informed consent had been obtained from all the participants prior to conducting any experiments.

A. Technical Validation of BiGREX's Control System

This experiment aims to validate the control system's ability to track the desired gait trajectories and average pressures of both actuated joints simultaneously. The experiment was performed without human subject attached. During the experiment, both the hip and knee joints of BiGREX was programmed to track reference gait trajectories in joint space. The desired average antagonistic PM pressures of both actuated joints were set to 270 KPa, a moderate level of system compliance, with the experimental results shown in Fig.2.

It can be observed from Fig. 2 that the proposed MIMO SM control system is able to track a gait trajectory while maintaining the average PM pressures of both actuated joints. In general, the hip joint performed better in both trajectory (RMSE being 0.022 rad for hip and 0.125 rad for knee) and average PM pressure tracking (RMSE being 0.746 KPa for hip and 16 KPa for knee). This could be due to that the desired knee joint trajectory has higher ROM and was more challenging for the controller to track. Considering the safety and nature of

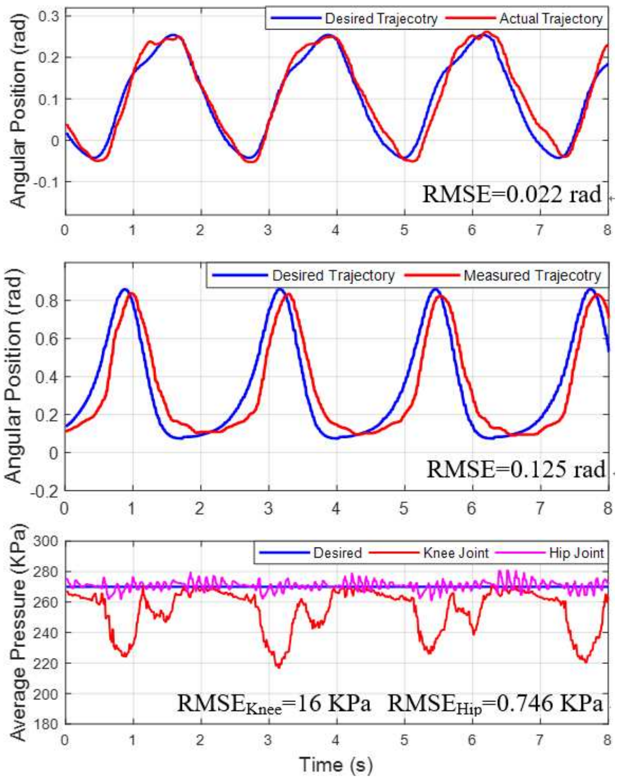

Fig. 2 The joint space trajectory and average PM pressure tracking performance for both actuated joints of GAREX. **Top**: the trajectory tracking performance of the hip joint. **Middle**: the trajectory tracking performance of the knee joint. **Bottom**: the average pressure control performance of both the hip and knee joints. RMSE: Root mean square error.

robotic gait rehabilitation, angular trajectory tracking needs to be prioritized among the two control objectives. This was implemented by the tuning parameters that let angular trajectory tracking take the dominant role in the overall control actions. As a result, the pressure tracking performance was slightly sacrificed, especially when the desired rate of position change is significant. This is the reason that pressure tracking performance is better on the hip joint.

B. Task-specific Gait Training Pilot

The automated treadmill-based gait training performance of BiGREX with human users will be investigated in this section. One healthy subject with the medium build (male, 172 cm, 68 kg) participated in the validation experiment of the robotic gait training. The exoskeleton was adjusted according to the participant's anthropometric data. During the experiment, programmed with the MIMO SM controller, BiGREX guided the subject to walk in a predefined gait trajectory on the treadmill with a speed of 1.5 km/h. The participant was asked to relax his leg strapped to the exoskeleton and let BiGREX in charge. The participant also adapted unactuated leg's movements to achieve stable walking on the treadmill. Four two-minute experiments were conducted and in between two experiments, there was a break of two minutes. In each experiment, the average PM pressures of the hip and knee joints were controlled to the same magnitude. The desired average antagonistic PM pressures were in turn 160, 240, 320 and 400 KPa for four experiments. Combining the dynamic algorithm from average antagonistic PM pressure to joint compliance described in [9], the ideal joint compliance under these four experimental conditions were 0.0158, 0.0152, 0.0147 and 0.0143 rad/Nm, respectively.

During the training process, this participant was able to walk smoothly on the treadmill with the guidance from BiGREX with different joint compliance levels. His gait trajectories of the two actuated joints are presented in Fig. 3, where gait data over the 2-minute experimental intervals were averaged, and the trajectory tracking performance was evaluated with the RMSE value. It is obvious that the RMSE had a trend of decrease as the controlled average PM pressure increased, indicating that BiGREX became less compliant and gave the subject less freedom around the desired trajectory, and providing a statistical basis for the optimal predefinition of joint compliance to a specific user.

C. Validation of Controllable Compliance

As shown in Fig.1, the average pressures of PMs were adopted in the closed-loop control algorithm. To further validate whether the proposed controller is capable of tracking predefined gait trajectory and simultaneously adjusting the actuation compliance to modify the assistance provided, the third set of experiments was conducted. A total of 12 (10 males and 2 females) subjects of ages between 23 and 31 were involved, with height ranging from 164 to 188 cm and weight from 49 to 100 kg. Before a participant starting experiments, the concept of compliance had been explained.

Each participant was required to conduct four experiments. Each experiment lasted approximated three minutes in between the two experiments there was a break of two minutes. Similar to the experiment described in Section III-B, all participants were assisted by the robot to walk on the treadmill at the speed of 1.5 km/h. The average PM pressures of the hip and knee joints were controlled at 160, 240, 320 and 400 KPa.

Each participant was required to experience four experiments with different pressures in a randomized order, and he/she was not informed of the controlled average pressure. Each of them was asked to relax and let the BiGREX guide the leg movement for the first half of an experiment. In the second half, he/she was asked to actively walk with the assistance from the exoskeleton and/or try to walk in his/her preferred gait pattern disregarding the assistance from the exoskeleton, so that the subject would have the impression of the compliance of the exoskeleton. After completing the first two and three trials, the subject was asked to rank the compliance levels of the experiment he/she had completed. After finishing all four trials, the subject was able to rank the compliance level of each experiment with a discrete score of 1, 2, 3 or 4, with 1 being most compliant and 4 being least compliant. No matter what result was given after the four experiments, the researcher asked the subject if he/she wished to re-conduct any of the experiments to help him/her refresh memory or eliminate any uncertainty. Each participant could request up to two experiments to be replayed. For each controlled average pressure, the means and variances of the compliance scores rated by the participants were calculated. Such results are summarized in the first two rows of Table I. One-way Analysis of Variance (ANOVA) was thought to be suitable for examining if there is any statistical difference between the means of compliance scores. Before that, the *Levene* test was conducted to investigate the equality of

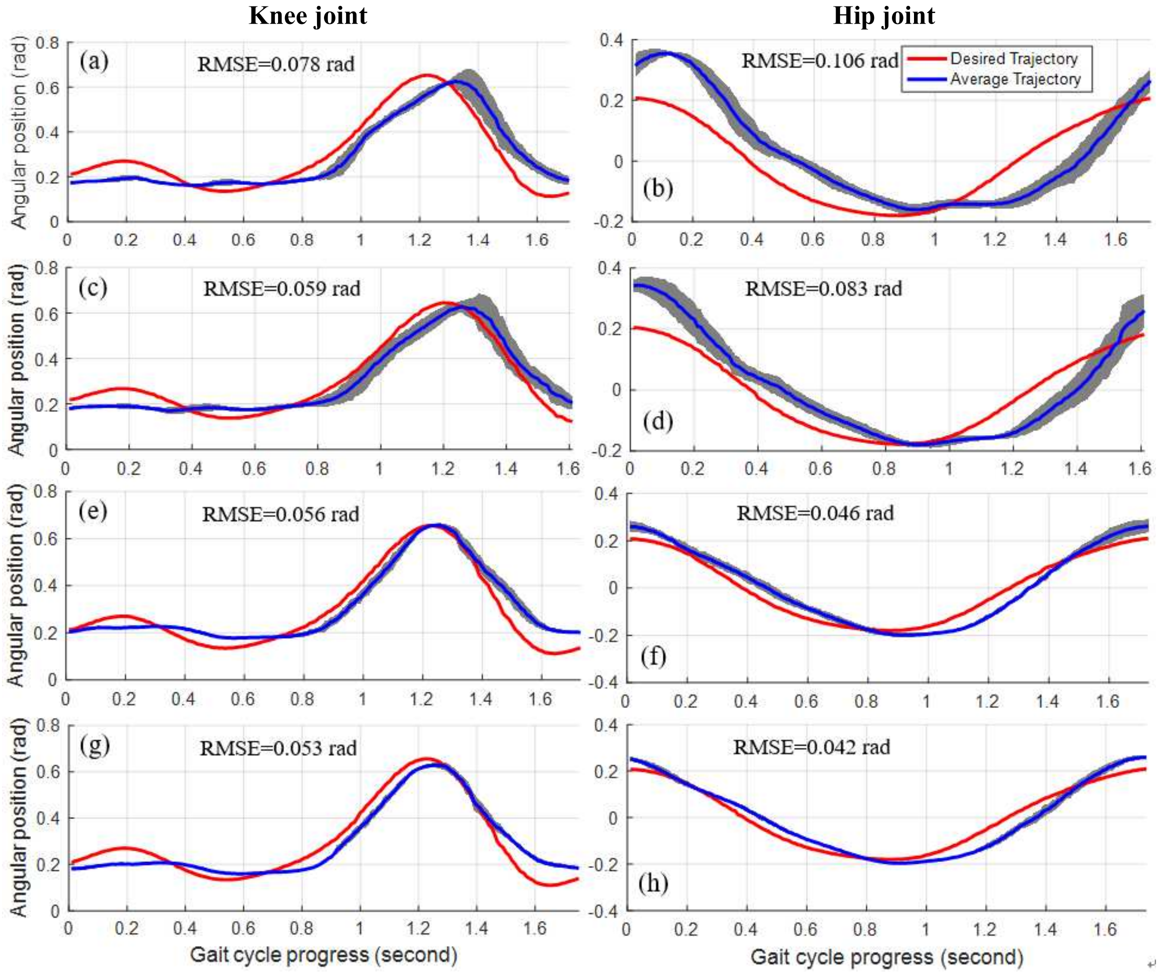

Fig. 3 The comparison between the desired and actual gait trajectories of the two actuated joints during the validation experiments. The trajectories have been normalized to one gait cycle. The red lines are the predefined reference gait trajectory. The blue lines represent the average gait trajectories over the experimental period. The shaded area stands for the standard deviations of the average trajectories over the recorded gait cycles. Subplots (a, c, e, g) are the trajectories of the knee joint and subplots (b, d, f, h) are for the hip joint. The subplots in the top, second, third and bottom rows are for experiments with desired average antagonistic PM pressures 160, 240, 320 and 400 KPa respectively.

variance of the experimental data. The test's *p-value* of 0.032 rejects the null hypothesis that all four groups have equal variance. A commonly used logarithm transformation of the original experimental data has been performed and the means and variances of the transformed data are listed in the third and fourth rows of Table I. The *Levene* test of transformed results gave a *p-value* of 0.462, which means the assumption of equal variance is not violated.

The one-way ANOVA analysis is then performed on the transformed data and its *p-value* of 0.000 suggests a very strong evidence to reject the null hypothesis that all the samples have equal means. Multiple comparisons via Tukey's test was also conducted to investigate whether there are statistical differences between all the combinations of two different groups. The analytical results again expressed by *p-values* are exhaustively listed in the second half of TABLE I. As seen from the table, there is highly significant difference (*p-values:* 0.000) in means between groups whose average pressure levels are not adjacent. For adjacent groups, there is very strong evidence for the difference in means between 160 and 240 KPa. There is strong evidence for the difference in means between 240 and 400 KPa groups. However, there is not significant statistical difference in means between the 320 and 400 KPa groups.

The above statistical analysis further approves that there is an inversely proportional relationship between the controlled average pressure of the PM actuation system and the

TABLE I
RESULTS OF COMPLIANCE SCORES AND ANOVA ANALYSIS

	Controlled Average PM Pressures			
	160KPa	240KPa	320KPa	400KPa
Mean	1.083	2.333	3.000	3.583
Variance	0.083	0.606	0.545	0.447
Mean Transformed	0.025	0.320	0.464	0.571
Variance Transformed	0.008	0.016	0.013	0.003
160 KPa	▨	0.000	0.000	0.000
240 KPa	▨	▨	0.005	0.000
320 KPa	▨	▨	▨	0.056

Note: The upper half of the table shows a bunch of statistic values of tested compliance. The bottom half shows all the possible *p-values* between groups via the Tukey's test. Gray colored grids denote nonsignificant difference.

exoskeleton compliance. However, the relationship is not linear. For the same difference interval in average pressure, the change in compliance is more significant when the average pressure is lower. Understanding such a trend is important since further development of the BiGREX system may require the automatic adaption of the compliance level based on the patient's performance or ability assessment during rehabilitation training.

IV. REMARKS AND CONCLUSIONS

A unilateral robotic gait rehabilitation system- BiGREX actuated by PMs has been well evaluated with human users. Only a few PM driven gait rehabilitation exoskeletons have been reported and to our knowledge, none of them have conducted detailed compliance analysis to verify the system's ability to provide task-specific gait training. BiGREX was designed with future clinical applications in mind and possibilities of combining with extra ankle rehabilitation mechanisms to form a full limb exoskeleton [5, 10]. The system is capable to provide sufficient torque for the knee and hip joint rotations in the sagittal planes to facilitate gait rehabilitation for a patient weighing up to 100 kg.

It's worth noting that task-specific robotic gait training imposes ROM and bandwidth requirements to the system development. While the previous PM driven robotic rehabilitation system usually ignored the intrinsic slow pressure dynamics of PMs by using pressure regulating valves, which could potentially affect the controlled bandwidth [11]. For BiGREX, the use of the analogue valves enabled the researchers to obtain the entire system model that encompasses all major uncertainties.

Based on such a model, the MIMO SM controller was thus developed and tuned to deliver robust control performance. Currently, BiGREX can comfortably guide treadmill based gait training at a speed of 1.5 km/h, which is similar to the slower speed adopted for clinical trials on motor-driven gait rehabilitation exoskeleton [12]. At the moment, the controlled bandwidth is limited by the pneumatic supply system and the mechanical design. To further increase the bandwidth the following changes could be made: 1) increasing current pneumatic supply pressure (6 bar); 2) using larger diameter tubes and valves; 3) optimizing the exoskeleton design to further reduce its weight.

The means of using average pressure to represent actuation compliance is not new. Due to the system simplification with pressure regulating valves, the joint space trajectory and average PM pressure controller are separated and the average PM pressure was adjusted through an open-loop controller. The actuation compliance is again calculated from the average PM pressure using the force dynamics model of the PM. There were also no dedicated experiments to investigate if such a compliance adjusting approach could vary the extent of guidance during robotic gait rehabilitation.

BiGREX's MIMO SM control system considers PM pressures as state variables and allows more direct manipulation of the average PM pressure compared to [13-15]. A novel experimental approach was adopted to validate the system capability on adjusting the compliance from participant's perception, which guarantees a safe and compliant human-robot interaction so as to enhance the patients' trust in robots. It was demonstrated in another of our researches that compliant interaction and trust in robots are key factors that contribute to enhanced rehabilitation performance [16]. Moreover, statistical analysis indicated the system is able to provide different levels of assistance via changing the compliance when providing task-specific gait training.

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