IEEE Journal of Translational Engineering in Health and Medicine

Received 10 June 2013; revised 16 November 2013; accepted 15 December 2013. Date of publication 30 January 2014; date of current version 13 February 2014.

Digital Object Identifier 10.1109/JTEHM.2014.2303807

Hardware Development and Locomotion Control Strategy for an Over-Ground Gait Trainer: *NaTUre-Gaits*

TRIEU PHAT LUU[1], KIN HUAT LOW[1], XINGDA QU[1], HUP BOON LIM[2], AND KAY HIANG HOON[1]

[1]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798
[2]Singapore Polytechnic, Singapore 139651

CORRESPONDING AUTHOR: T. P. LUU (luut0004@e.ntu.edu.sg)

This work was supported by the National Medical Research Council (NMRC) under Grant NMRC 1051/2006.

ABSTRACT Therapist-assisted body weight supported (TABWS) gait rehabilitation was introduced two decades ago. The benefit of TABWS in functional recovery of walking in spinal cord injury and stroke patients has been demonstrated and reported. However, shortage of therapists, labor-intensiveness, and short duration of training are some limitations of this approach. To overcome these deficiencies, robotic-assisted gait rehabilitation systems have been suggested. These systems have gained attentions from researchers and clinical practitioner in recent years. To achieve the same objective, an over-ground gait rehabilitation system, *NaTUre-gaits*, was developed at the Nanyang Technological University. The design was based on a clinical approach to provide four main features, which are pelvic motion, body weight support, over-ground walking experience, and lower limb assistance. These features can be achieved by three main modules of *NaTUre-gaits*: 1) pelvic assistance mechanism, mobile platform, and robotic orthosis. Predefined gait patterns are required for a robotic assisted system to follow. In this paper, the gait pattern planning for *NaTUre-gaits* was accomplished by an individual-specific gait pattern prediction model. The model generates gait patterns that resemble natural gait patterns of the targeted subjects. The features of *NaTUre-gaits* have been demonstrated by walking trials with several subjects. The trials have been evaluated by therapists and doctors. The results show that 10-m walking trial with a reduction in manpower. The task-specific repetitive training approach and natural walking gait patterns were also successfully achieved.

INDEX TERMS Robotic gait rehabilitation, gait pattern planning, over-ground gait trainer.

I. INTRODUCTION

Spinal cord injury (SCI) and stroke are the leading cause of disability around the world. In the United States, approximately 795,000 people have a new or recurrent stroke annually [1], and an estimated 232,000 to 316,000 persons live with SCI [2]. Loss of walking ability is a debilitating outcome in post-stroke and spinal cord injury, with more than 50% of the post-stroke patients demonstrating persistent walking deficits, and more than 90% of the SCI patients lose their sensory and motor control of the lower limbs. Majority of these patients have to go through gait rehabilitation in order to regain the ability of independent walking. Body weight supported (BWS) treadmill training has been applied in gait rehabilitation for patients, who have neurological gait disorders after stroke or incomplete spinal cord injury (iSCI) [3]. The method of suspending a patient over a treadmill for gait rehabilitation was first reported by Barbeau *et al.* in 1987 [4]. This method is developed based on the observation of spinalized cats that could be trained to walk on a treadmill with partial unweighting of their hindlimbs [5], [6]. Several studies have also demonstrated that BWS treadmill training can improve walking in patients with iSCI [7]–[11]. It has been found out that 80% of wheelchair-bounded patients with chronic SCI gained functional walking ability after training [7], [12], [13]. This approach has the advantages of being task-specific and repetitive, but it is often physically intensive for therapists [14], [15]. As a result, robotic assisted gait rehabilitation systems have been developed to address these deficiencies. The systems have gained extensive attentions from researchers and therapists in recent years.

Based on the method of progression, robotic assisted gait trainers can be categorized into three main groups: BWS treadmill-based, footplate-based and over-ground walking based rehabilitation. Regularly, the training environment in the first group includes a BWS system that either partially or fully supports the body weight of the subject, a robotic orthosis that moves the lower limb follow pre-defined trajectories and a treadmill.

Lokomat [16] is the first commercialized product of BWS treadmill training system, which was first introduced in 2000 (developed by Hocoma AG, Switzerland). Lokomat comes with four modules: body weight offloading, robotic orthosis, computer system and treadmill. Studies have shown that Lokomat was effective in improving the walking ability of individuals with iSCI [17], [18]. ALEX [19] (developed in University of Delaware, Newark [19]) is another treadmill-based rehabilitation system. ALEX has four main modules: walker, robotic orthosis, computer system and treadmill. The robotic orthosis is carried by the walker that can be considered as a portable module to use with different treadmill system. LOPES [20] (developed in University of Twente, The Netherlands) also belongs to the first group. LOPES consists of a cable driven exoskeleton for lower limb assistance and an end effector for the pelvic assistance. In total, LOPES has eight actuated degrees of freedom (DoFs); two DOFs for the horizontal pelvic translation and three rotational joints for each limb. PAM and POGO [21] are two devices developed by University of California, USA. PAM assists the pelvic motion during stepping by using BWS treadmill, whereas POGO provides assistance for the leg swing by actuating the hip and knee joints in sagittal plane. Locomotion devices in footplate-based rehabilitation mainly focus on controlling foot movements for locomotor task-specific training (e.g. walking on floor or stepping staircases). So far, only a few devices have been developed based on the principle of programmable footplates. HapticWalker and GT-II [22], [23] (developed by Charite University Hospital, Berlin, Germany) are the two examples in the second group.

For the last group, automated rehabilitation devices in over-ground walking have been developed to focus on the sensation improvement of over-ground walking. The patients being trained with these systems are allowed to have progression during walking compared to the treadmill-based training. WalkTrainer [24] (Swiss Foundation of Cyberthosis), Kine-Assist [25], ReWalk (Bionics Research Inc.) and Robotic Exoskeleton (REX Bionics Ltd.) are some examples in over-ground based rehabilitation systems. Though each system has its own unique features, majority of gait training devices focus primarily on providing lower limb movements via lower limb orthosis. An essential feature, pelvic movement assistance, is however missing or constrained by the body weight support apparatus. Body weight shifting is a training process of conventional over-ground gait rehabilitation. Only a few research groups have developed robotic assisted devices that incorporate pelvic mechanism (e.g. PAM/POGO, WalkTrainer) to allow pelvic motions. Works on pelvic motion assistance in those devices can be found in [21] and [24]. PAM can be considered as a teach-and-play device that drives the pelvis toward reference trajectories [21], [26]. To generate predefined pelvic trajectories that closely mimic natural movement of the targeted subject during gait rehabilitation training process, WalkTrainer research group introduced a pelvic amplitude prediction model. For implementation purpose, a simple linear model was used with only one input factor (walking speed). The model assumed that pelvic motion always have only their magnitude varies [27].

In this work, a developed over-ground gait trainer (*NaTUre-gaits*) is introduced. The system was designed for the provision of unrestricted pelvic motion (thus allows body weight shifting), actuated assistance to the lower limb joints, body weight support, and over-ground walking. The proposed features obtained from clinical-based approach can be accomplished by three modules: Pelvic Assistance Mechanism (PA), Mobile Platform (MP) and Robotic Orthosis (RO). Most existing systems with pelvic assistance adopt conventional cable-harness body weight support (cBWS) apparatus, the Pelvic Assistance mechanism of *NaTUre-gaits* system is based on structure BWS concept (sBWS). The structure BWS supports the subject's body weight by holding their waist and control the pelvic movement at the same time. By using sBWS, the constraint of the pelvic movement could be reduced if compare to conventional cBWS. An adaptive control strategy with pelvic motion assistance could also be applied [28]. An individual-specific gait pattern generation model was developed to predict the walking gait patterns for inter-subject differences. The predicted gait patterns were then stored in a controller of *NaTUre-gaits* as predefined walking trajectories. The system is expected to induce natural walking patterns that tailored to the targeted subjects. Experiment protocols for some healthy subjects and clinical trials with an iSCI patient have been carried out. Preliminary assessments from participants and physiotherapists reveal that *NaTUre-gaits* is capable of providing secure locomotor training environment, reducing manpower and labor involvement during rehabilitation training process, and inducing comfortable (or natural) gait patterns on the subject walking with the gait system.

II. INTRODUCTION TO AN OVER-GROUND GAIT TRAINER: NATURE-GAITS

A. CLINICAL-BASED APPROACH FOR THE DESIGN OF NATURE-GAITS

Motor learning of neurological injury rehabilitation relies on three principles: practice, specificity and effort [29], [30]. With all other things being equal, more practice will result in more learning [31]. The clear benefits of intensive repetitive therapy have been demonstrated by Kwakkel *et al.* [32]. Specificity is the second principle, which states that the best way to improve performance of a motor task is to execute a specific motor task [33], [34]. The last principle, effort, indicates that a high degree of participation and involvement of individuals is required to facilitate motor learning [35], [36].

The conceptual idea of the modules contained in the robotic gait rehabilitation system is shown in Figure 1. To fulfill the first two principles, four features (pelvic assistance, body weight support, over-ground mobility and lower limb assistance) have been defined as guidelines for the design of the system. The third principle can be achieved by an assist as needed control strategy. These features are summarized as follows.

1) *Pelvic motion*
   - Unrestricted pelvic movements play an important role in normal locomotion and thus it is included as one of the essential features in this work.
   - Promote body weight shifting during gait rehabilitation.
2) *Body weight support*
   - Unique body weight support approach, without restricting of pelvic movements.
3) *Over-ground mobility*
   - Provides gait practicing in functional over-ground walking, as opposed to treadmills.
4) *Reciprocal stepping*
   - Assist motion of hip, knee and ankle in sagittal plane and provide actual functional over-ground walking.

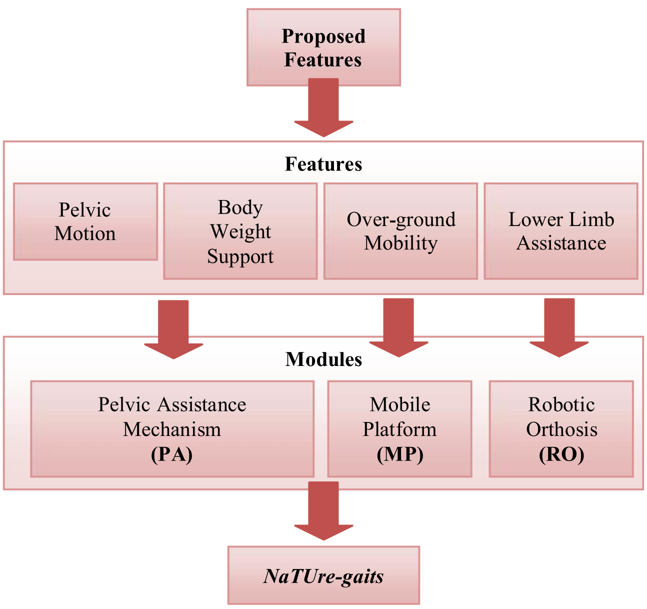

FIGURE 1. **Proposed feature and modules of *NaTUre-gaits*.**

B. PROTOTYPE OF NATURE-GAITS AND ITS MODULES

The robotic system, named as *NaTUre-gaits* (**Na**tural and **tu**ne-able **re**habilitation **gait** system), was designed to allow natural and tune-able gait locomotion during rehabilitation. The overview of *NaTUre-gaits* and its modules are shown in Figure 2. *NaTUre-gaits* has been designed to fit different sizes of human subjects according to the anthropometric data as listed in Table 1.

TABLE 1. **Anthropometric data of targeted users.**

	Minimum	*Maximum*
Body Weight (kg)	-	80
ASIS# Breadth (mm)	250	550
Thigh Length (mm)	330	400
Shank Length (mm)	330	400

ASIS#: Anterior Superior Iliac Spine.

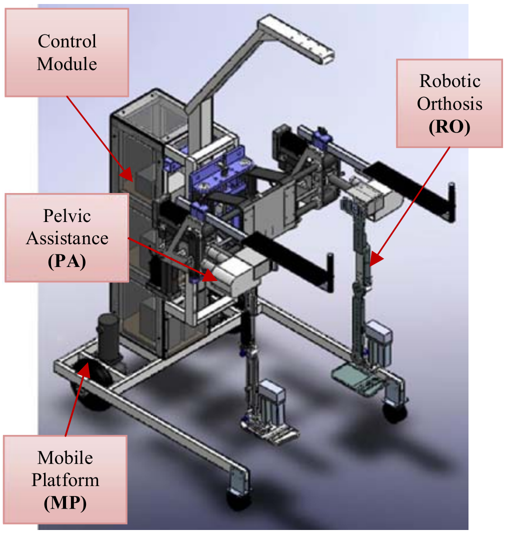

FIGURE 2. **Schematic view of *NaTUre-gaits* and its modules.**

Each of the proposed features could be achieved by a module on the robotic system. These modules were controlled to synchronize together throughout the operation to achieve the desired gait locomotion. In order to provide over-ground walking, a mobile platform (MP) was incorporated in the system. The mobile platform follows the subject throughout gait rehabilitation, while supporting all other modules with it. A pair of robotic arms of Pelvic Assistance (PA) mechanism is attached to the mobile platform. The end effectors of the arms connect to the waist of the patient, to provide BWS and pelvic control. Lastly, a lower limb robotic orthosis (RO) is attached to the end of the robotic arm, which induces gait locomotion to the subject during the gait training.

1) PELVIC ASSISTANCE MECHANISM (PA)

The PA mechanism has a pair of robotic arms. Each arm consists of a sub-mechanism and a lateral shift mechanism. The two robotic arms hold the subject at both sides of pelvis. The subject is secured onto the robotic arms through a special designed harness (Figure 3). PA mechanism supports the subject's body weight by holding his/her pelvis and controls the pelvic movement at the same time. This approach reduces the constraint of the pelvis movement if compared to conventional cable-harness BWS apparatus. An adaptive control strategy with pelvic motion assistance can also be applied [28].

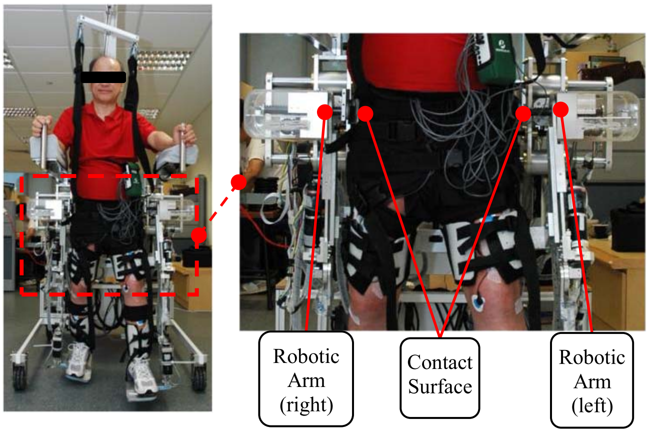

FIGURE 3. Configuration of robotic arms of PA mechanism with a subject.

Sub-mechanism of PA comprises actuators 1 and 2 and provides the motion in the sagittal plane. Actuator 3 is connected to the end effector of the sub-mechanism, which provides the lateral shifting motion as shown in Figure 4. The position of the end effector is indicated by balloon 1. The sagittal plane's motion (x_{g3}, z_{g3}) of pelvis is provided by the linear motion of s_{g1} and s_{g2}. The pelvic motion in the *y-axis* (lateral movement) is controlled by actuator 3 through a rack and pinion mechanism.

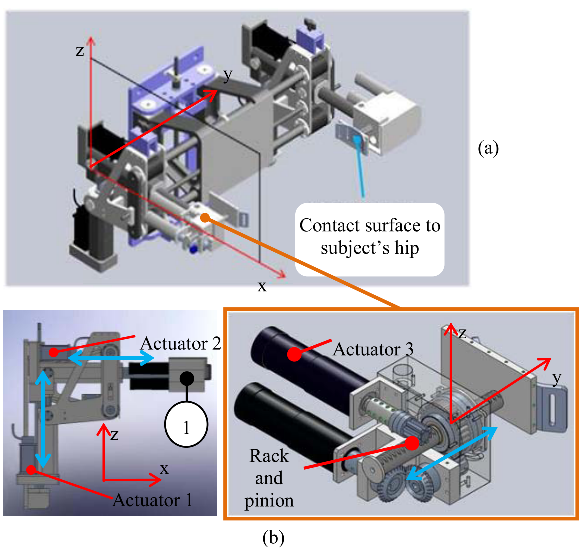

FIGURE 4. CAD illustration of PA mechanism: (a) Movement of PA in the sagittal plane of the right side; (b) Lateral shift mechanism of the right side.

2) REALIZATION OF OVER-GROUND MOBILITY FOR ROBOTIC ASSISTED GAIT REHABILITATION

Mobile platform in Figure 2 forms the base of *NaTUre-gaits*. The main function of the mobile platform is to provide the progression for the entire system and the subject during gait rehabilitation. Mobile platform also serves as the carrier of the robotic orthosis, pelvic assistance mechanism, controller, power source, and any other electronic components of *NaTUre-gaits*. Two motorized wheels are mounted at the rear of mobile platform. As each wheel is independently controlled, it is possible for the mobile platform to follow straight or curved path. Therefore, the gait rehabilitation is not limited to progression in a straight line.

3) PROVISION OF RECIPROCAL LOWER LIMB STEPPING WITH ROBOTIC ORTHOSIS (RO)

The robotic orthosis has a total of six degrees of freedom (DoFs) with three DoFs on each side as shown in Figure 5. It is designed as a pair of anthropomorphic legs. The length of the robotic orthosis for the thigh and shank can be adjusted to fit different subjects. The designed range of motion (ROM) for each joint is provided in Table 2. The ROM is limited by hardware limiter to ensure the safety of the users.

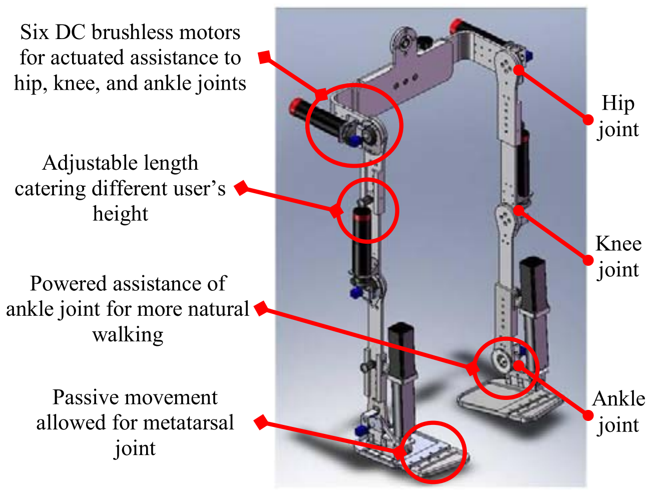

FIGURE 5. Design and features of robotic orthosis for *NaTUre-gaits*.

4) CONTROL MODULE

Three modules of *NaTUre-gaits*, such as Pelvic Assistance (PA), Robotic Orthosis (RO), and Mobile Platform (MP), consist of twelve DC motors in total. These motors are controlled to follow pre-defined trajectories. The control module of *NaTUre-gaits* is able to response with the planning the trajectories in real time and provides control signal to DC amplifier to drive all the motors to follow desired trajectories.

Three modules of *NaTUre-gaits* are controlled by a control module using PXI system from National Instrument. PXI system is a rugged PC-based platform for measurement and automation systems. A PXI system consists of four main components: rugged chassis, system controller, peripheral

TABLE 2. Lower limb range of motion (ROM) of robotic orthosis in sagittal plane.

Lower Limb Joint Angles		Range of Motion in Sagittal Plane (degrees)		
		Permissible [37]	Walking [38]	Designed
Hip	Flexion	122	20	50
	Extension#	10	11	15
Knee	Flexion	134	60	80
	Hyper-extension	0	0	0
Ankle	Dorsi-flexion	13	9	10
	Plantar-flexion	56	18	20

The permissible range of hip extension is 10° as reported in reference [37]. As recorded in reference [39], the permissible range has a range of 10° to 30°. The discrepancies of the value could be due to measuring method. The designed ROM for hip extension is 15°.

modules, and software. The chassis used in control module is NI-PXIe 1062Q, which provides one PXIe system slot for controller, one PXIe peripheral slot, two Hybrid slots, and four PXI slots. The embedded controller NI PXIe-8115 used in control module includes standard features, such as integrated CPU, hard drive, memory, Ethernet, video, serial, USB and other peripherals. The embedded controller is compatible with both Window OS and Labview Real-Time. Two motion controller cards (NI PXI-7358), which offer 8 axes for stepper/servo motor, were used in control module. NI Labview and Matlab were used as programming environments for *NaTUre-gaits*. The overview of control module for *NaTUre-gaits* is shown in Figure 6.

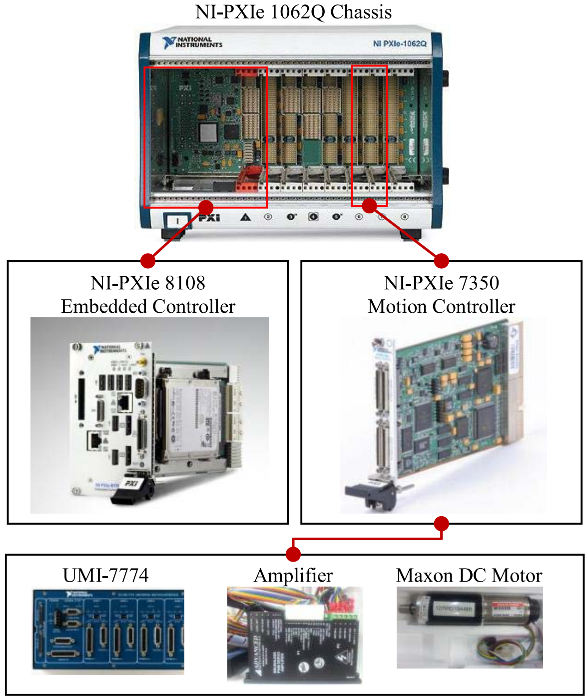

FIGURE 6. Control module for *NaTUre-gaits*.

III. LOCOMOTION CONTROL STRATEGY FOR NATURE-GAITS

Robotic gait rehabilitation systems require a pre-defined pattern of gait locomotion, in order to carry out the gait training. To achieve an optimal afferent input to the spinal cord and maximize the functional locomotor outcomes, the pre-defined movement inputs should be in physiological manner or natural gait-like pattern [16], [40]. In manual assisted BWS treadmill gait rehabilitation, the therapists move the patient's leg and pelvis using visual feedback and feel. The assistance provided can vary greatly between therapists and between training sessions [41]. In comparison, robotic orthosis found on those robotic gait rehabilitation systems adopts simplified approach to replicate the leg kinematics [16].

Lokomat took a step further by allowing the gait pattern to be set according to the patients height and range of motion of the lower limb joint [42]. Every individual displays certain personal peculiarities superimposed on the basic pattern of bipedal locomotion during walking. To maximize the therapeutic outcomes, it is crucial to induce a gait pattern that resembles natural human gait pattern during gait rehabilitation [16], [41]. For this reason, a locomotion control strategy based on a gait pattern prediction model, which generates walking pattern tailored to subjects anthropometric data, has been developed and illustrated in Figure 7.

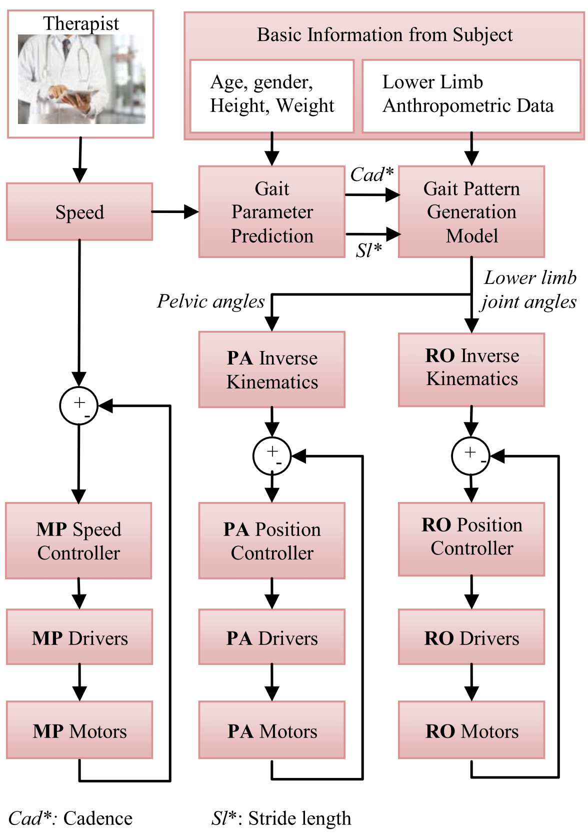

FIGURE 7. Motion Generation for *NaTUre-gaits*.

Based on the literature [43]–[45], gait parameters (for example, walking speed, stride length and cadence) were found to be the key factors influencing the walking gait pattern. In this work, a gait parameter prediction model was proposed to predict natural gait speed, stride length, and cadence for a specific subject, given his/her anatomical parameters (age, gender, height, and weight) and a desired state of walking speed (slow or normal). The first step in Figure 7 is to obtain the basic information and to measure the anthropometry parameters of the subjects. The input of walking speed could be determined by the therapists or selected from the suggested range of walking speed from the Gait Parameter Prediction model. Subsequently, gait parameters and anthropometric data of selected subjects are used as the input for Gait Pattern Prediction Model to plan a reference gait pattern for each individual.

A. MOTION PLANNING BASED ON GAIT PATTERN PREDICTION MODEL

The gait pattern prediction model was designed based on a gait pattern database obtained from the motion capture experiment. Seventy healthy male subjects with ages ranging from 18 to 33 years (mean 23.6±2.2 years), height 156 to 192 cm (mean 171.1±6.2 cm) and body weight 49 to 120 kg (mean 64.3±11.5 kg) with no history of neurological disease or lower limb pathology participated in the study after giving informed consent. Each subject was instructed to walk ten times at their self-paced slow and normal walking speeds over a 12-meter walkway. The gait data were collected by using an eight camera motion analysis system (Eagle, Motion Analysis Corp). The kinematics of lower limb joints was calculated from the reflective markers and anthropometric data. The rotations of hip, knee and ankle joints in the sagittal plane (flexion-extension) obtained from 700 walks are shown in Figure 8. Details of the models can be found in [46] and [47]. Invert kinematics of Pelvic Assistance (PA) mechanism was used to convert pelvic angle waveforms to encoder counts for PA motors. A simple PID controller was applied for PA position control. The similar approach was used for Robotic Orthosis (RO) mechanism. For Mobile Platform (MP), the speed control was used so that the two wheels of MP mechanism moving at the desired walking speed in progression direction.

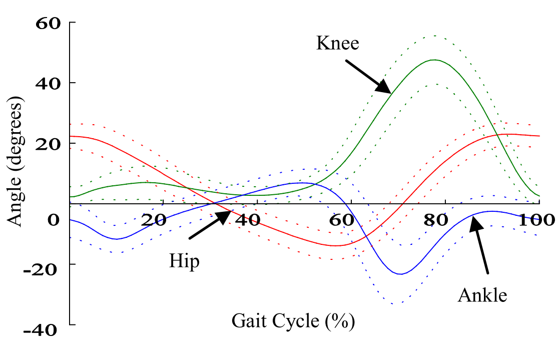

FIGURE 8. Lower limb kinematics of human walking associated with 700 walks (solid lines: average waveforms; dashed lines: one standard deviation).

B. SYNCHRONIZATION BETWEEN PELVIC MOTION AND PROGRESSION VELOCITY FOR OVER-GROUND WALKING

The average walking velocity in progression direction can be determined from the distance travel in one gait cycle time as follows:

$$\dot{X}_{PA,r} = \frac{X_{PA,r}(N) - X_{PA,r}(0)}{T} \tag{1}$$

where

$\dot{X}_{PA,r}$ is the average walking velocity of pelvic movement in progression direction or x-axis.

$X_{PA,r}(N)$ and $X_{PA,r}(0)$ are the right end effector position of PA at 100% gait cycle and 0% gait cycle, respectively.

T is the time taken to complete one gait cycle.

The pelvic trajectories during human walking in progression direction can be decomposed into a constant velocity movement at a speed $\dot{X}_{PA,r}$ and a localized pelvic motion. The conversion of pelvic motion in progression direction is illustrated in Figure 9.

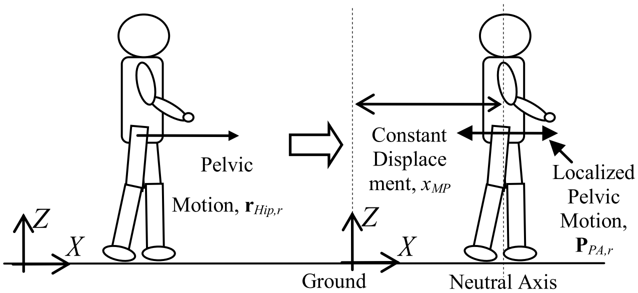

FIGURE 9. Conversion from pelvic motion to motion for mobile platform and pelvic assistance mechanism.

In *NaTUre-gaits*, the constant velocity movement in progression plane is accomplished by a two wheel Mobile Platform. The position of mobile platform is given by:

$$X_{MP} = \dot{X}_{PA,r} \times t_{GC} \tag{2}$$

where t_{GC} is the instant within one gait cycle, $0 \leq t_{GC} \leq T$.

The localized pelvic motion in progression direction is calculated as follows:

$$x_{PA,r} = X_{PA,r} - X_{MP} \tag{3}$$

Similarly, the localized pelvic motion in y-axis and z-axis are also analyzed and they can be calculated as follows:

$$\begin{aligned} y_{PA,r} &= Y_{PA,r} - \bar{Y}_{PA,r} \\ z_{PA,r} &= Z_{PA,r} - Z_{Hip} \end{aligned} \tag{4}$$

where Z_{Hip} is the subject's hip coordinate in z-axis at standing position.

The trajectory of left end effector is calculated from the right side with 50% phase lag. The localized movement of PA mechanism in 3D space is also analyzed and shown in Figure 10. It is noted that the left and right end effectors

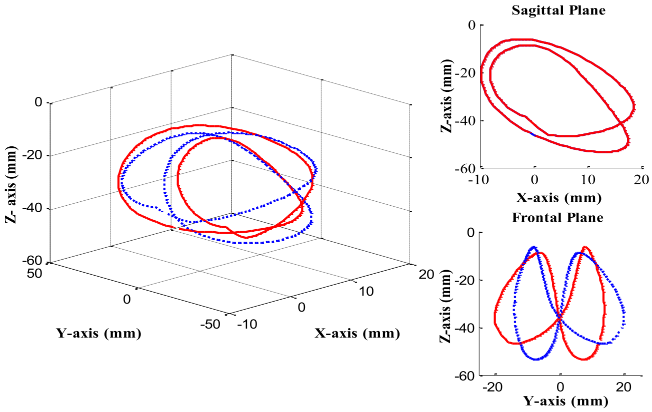

FIGURE 10. Motion planning for PA mechanism in 3D space (solid lines – right side; dotted lines – left side).

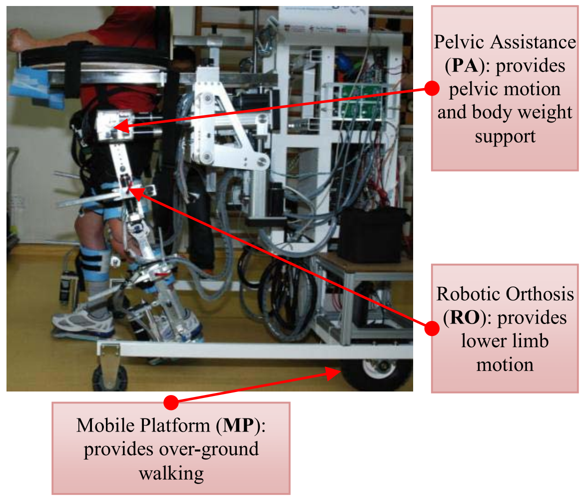

FIGURE 11. ***NaTUre-gaits*** **with an iSCI subject and its three main modules.**

of PA mechanism have the same trajectory in sagittal plane. In frontal plane, the trajectories have Figure 8. The results are agreed with previous pelvic motion study in [48].

IV. CLINICAL STUDY

Clinical study has been carried out to verify the performance of *NaTUre-gaits* in gait rehabilitation training. A 64 year old male subject with incomplete spinal cord injury (iSCI) participated in the study after giving informed consent. The clinical trial was carried out in a local rehabilitation center, Tan Tock Seng Hospital. During the trials, the ability of providing pelvic motion assistance, complete body weight support, lower limb assistance, and the experience of over ground walking by *NaTUre-gaits* were observed visually. Quantitative analysis is not planned for this initial trial of the system. The main objective of this trial is to complete 10-meter walk assisted by *NaTUre-gaits* without any disruption. Basic information of the subject (age, gender, height, weight) was recorded and anthropometric data were measured. With the determined walking speed for training, the gait parameters (stride length and cadence) were estimated and the gait pattern prediction model was applied to generate walking gait patterns for the subject.

The blood pressure and heart rate of the subjects were measured normal during trials. Average time for harness setup and strapping the subject to *NaTUre-gaits* was 13 minutes. The subject was instructed to perform four cycles of ten meter walk with *NaTUre-gaits*. It took about 18 minutes to complete one cycle of the walking gait training. Figure 11 shows the *NaTUre-gaits* with subject in the gait rehabilitation training process. A survey form was completed by the subject after the clinical trial. The results revealed that the constraints from harness and strapping devices of *NaTUre-gaits* were acceptable. The lack of physical comfort when being assisted by the system to complete the gait locomotion was not felt by the subject. Through the clinical trial, we confirm the ability of *NaTUre-gaits* in providing gait locomotion assistance to iSCI subjects. Although two persons were needed for the strapping setup process, only one person was required for the control of *NaTUre-gaits* during the locomotion training process.

V. CONCLUSION

A newly proposed robotic gait rehabilitation system, *NaTUre-gaits*, has been presented in this work. Essential features of robotic assisted gait rehabilitation, such as unrestricted pelvic motion assistance, lower limb motion assistance, body weight support, and over-ground walking experience have been made possible with *NaTUre-gaits*.

Three robotic modules have been introduced in this work to enable the robotic gait rehabilitation system to provide body weight support gait rehabilitation, with assistance provided to hip and lower limb movement, in the context of over-ground walking. The unique feature found on *NaTUre-gaits* is the provision of pelvic motion assistance and body weight support with the pelvic assistance mechanism.

Clinical trials have been successfully carried out for one male iSCI subject. The recruited subject tolerated the device well throughout the one hour trial. The trials confirm the ability of *NaTUre-gaits* in the provision of gait locomotion assistance. The significant reduction on the laborious demanding of human helpers for over-ground gait training has been demonstrated. The next phase of this work will be embarking on the study of the advantage brought by pelvic motion assistance during gait locomotion training. The procedure of harness wearing and the design of the harness shall be refined such that it can be worn with least possibility of misalignment and in shorten time.

Currently, *NaTUre-gaits* only moves the subject along predefined trajectories and does not adapt the gait pattern to the activity of the subject. This is a position controlled training (also known as passive training). If subjects are trained with totally passive training strategy, they tend to train with reduced activity of muscles and metabolism. For example, people with SCI who walk in a robotic gait training device with position control consumed 60% less energy than in traditional therapist assisted therapy [49]. Hidler *et al.* [50] showed that conventional gait training appears to be more effective than robotic-assisted gait training and robotic guidance may reduce volitional muscle activity. Cooperative control strategies are expected to stimulate active participation from the subjects. Therefore, it is assumed that *subject-cooperative* control strategies will maximize the therapeutic outcome. A *subject-cooperative* control strategy named speed adaptation control strategy is being developed for *NaTUre-gaits* to improve the therapeutic outcomes of locomotor training process. In this control strategy, gait pattern will be adapted to follow a desired walking speed based on the performance and effort from the subject during the training process.

ACKNOWLEDGMENT

The authors would like to thank the Department of the Rehabilitation Medicine at the Tan Tock Seng Hospital (TTSH) for the contribution of clinical trials related to the present work. The support of Robotic Research Center (RRC) of the Nanyang Technological University (NTU) in various areas is appreciated. The authors would like to thank the reviewers for their constructive comments, which have greatly improved the quality of the revised manuscript. The authors would also like to acknowledge W. Q. Tan, S. J. Lim, J. J. Lim and T. M. Aung for their assistance in the data collection. The assistance and discussion from the teammates, P. Wang and L. Li, are acknowledged. Last but not least, the consent of subjects participating in the walking experiments is greatly appreciated.

REFERENCES

[1] S. J. Karve, R. Balkrishnan, Y. M. Mohammad, and D. A. Levine, ''Racial/ethnic disparities in emergency department waiting time for stroke patients in the United States,'' *J. Stroke Cerebrovascular Diseases*, vol. 20, no. 1, pp. 30–40, 2011.

[2] E. V. Kuklina and R. J. Kryscio, ''Is spinal cord injury a new emerging risk factor for stroke?'' *Neurology*, vol. 78, no. 14, pp. 1034–1035, Apr. 2012.

[3] K. J. Sullivan, D. A. Brown, T. Klassen, S. Mulroy, T. Ge, S. P. Azen, *et al.*, ''Effects of task-specific locomotor and strength training in adults who were ambulatory after stroke: Results of the STEPS randomized clinical trial,'' *Phys. Therapy*, vol. 87, no. 12, pp. 1580–1602, 2007.

[4] H. Barbeau, M. Wainberg, and L. Finch, ''Description and application of a system for locomotor rehabilitation,'' *Med. Biol. Eng. Comput.*, vol. 25, no. 3, pp. 341–344, 1987.

[5] R. G. Lovely, R. J. Gregor, R. R. Roy, and V. R. Edgerton, ''Effects of training on the recovery of full-weight-bearing stepping in the adult spinal cat,'' *Experim. Neurol.*, vol. 92, no. 2, pp. 421–435, 1986.

[6] H. Barbeau and S. Rossignol, ''Recovery of locomotion after chronic spinalization in the adult cat,'' *Brain Res.*, vol. 412, no. 1, pp. 84–95, 1987.

[7] A. L. Behrman and S. J. Harkema, ''Locomotor training after human spinal cord injury: A series of case studies,'' *Phys. Therapy*, vol. 80, no. 7, pp. 688–700, 2000.

[8] R. Grasso, Y. P. Ivanenko, M. Zago, M. Molinari, G. Scivoletto, V. Castellano, *et al.*, ''Distributed plasticity of locomotor pattern generators in spinal cord injured patients,'' *Brain*, vol. 127, no. 5, pp. 1019–1034, 2004.

[9] M. Wirz, G. Colombo, and V. Dietz, ''Long term effects of locomotor training in spinal humans,'' *J. Neurol. Neurosurgery Psychiatry*, vol. 71, no. 1, pp. 93–96, 2001.

[10] H. Barbeau, K. Norman, J. Fung, M. Visintin, and M. Ladouceur, ''Does neurorehabilitation play a role in the recovery of walking in neurological populations?,'' in *Proc. Ann. New York Acad. Sci.*, vol. 860. Nov. 1998, pp. 377–392.

[11] A. Wernig, A. Nanassy, and S. Muller, ''Laufband (treadmill) therapy in incomplete paraplegia and tetraplegia,'' *J. Neurotrauma*, vol. 16, no. 8, pp. 719–726, 1999.

[12] A. Wernig, S. Muller, A. Nanassy, and E. Cagol, ''Laufband therapy based on 'rules of spinal locomotion' is effective in spinal cord injured persons,'' *Eur. J. Neurosci.*, vol. 7, no. 4, pp. 823–829, 1995.

[13] A. Wernig, A. Nanassy, and S. Muller, ''Maintenance of locomotor abilities following Laufband (treadmill) therapy in para- and tetraplegic persons: Follow-up studies,'' *Spinal Cord*, vol. 36, no. 11, pp. 744–749, 1998.

[14] D. J. Reinkensmeyer, D. Aoyagi, J. L. Emken, J. A. Galvez, W. Ichinose, G. Kerdanyan, *et al.*, ''Tools for understanding and optimizing robotic gait training,'' *J. Rehabil. Res. Develop.*, vol. 43, no. 5, pp. 657–670, 2006.

[15] S. Moughamir, J. Zaytoon, N. Manamanni, and L. Afilal, ''A system approach for control development of lower-limbs training machines,'' *Control Eng. Pract.*, vol. 10, no. 3, pp. 287–299, 2002.

[16] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, ''Treadmill training of paraplegic patients using a robotic orthosis,'' *J. Rehabil. Res. Develop.*, vol. 37, no. 6, pp. 693–700, 2000.

[17] T. G. Hornby, D. H. Zemon, and D. Campbell, ''Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury,'' *Phys. Therapy*, vol. 85, no. 1, pp. 52–66, 2005.

[18] M. Wirz, D. H. Zemon, R. Rupp, A. Scheel, G. Colombo, V. Dietz, *et al.*, ''Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial,'' *Archives Phys. Med. Rehabil.*, vol. 86, no. 4, pp. 672–680, 2005.

[19] S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz, ''Robot assisted gait training with active leg exoskeleton (ALEX),'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 17, no. 1, pp. 2–8, Feb. 2009.

[20] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, E. H. F. Van Asseldonk, and H. Van Der Kooij, ''Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation,'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 379–386, Sep. 2007.

[21] D. Aoyagi, W. E. Ichinose, S. J. Harkema, D. J. Reinkensmeyer, and J. E. Bobrow, ''A robot and control algorithm that can synchronously assist in naturalistic motion during body-weight-supported gait training following neurologic injury,'' *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 13, pp. 387–400, Sep. 2007.

[22] S. Hussein, H. Schmidt, S. Hesse, and J. Kruger, ''Effect of different training modes on ground reaction forces during robot assisted floor walking and stair climbing,'' in *Proc. IEEE Int. Conf. Rehabil. Robot.*, Kyoto, Japan, Jun. 2009, pp. 845–850.

[23] H. Schmidt, C. Werner, R. Bernhardt, S. Hesse, and J. Kruger, ''Gait rehabilitation machines based on programmable footplates,'' *J. Neuroeng. Rehabil.*, vol. 4, no. 2, pp. 2–9, 2007.

[24] M. Bouri, Y. Stauffer, C. Schmitt, Y. Allemand, S. Gnemmi, R. Clavel, *et al.*, ''The WalkTrainer: A robotic system for walking rehabilitation,'' in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Kunming, China, Dec. 2006, pp. 1616–1621.

[25] M. Peshkin, D. A. Brown, J. J. Santos-Munne, A. Makhlin, E. Lewis, J. E. Colgate, *et al.*, ''KineAssist: A robotic overground gait and balance training device,'' in *Proc. IEEE 9th Int. Conf. Rehabil. Robot.*, Chicago, Illinois, USA, Jun./Jul. 2005, pp. 241–246.

[26] W. E. Ichinose, D. J. Reinkensmeyer, D. Aoyagi, J. T. Lin, K. Ngai, V. R. Edgerton, *et al.*, ''A robotic device for measuring and controlling pelvic motion during locomotor rehabilitation,'' in *Proc. 25th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Sep. 2003, pp. 1690–1693.

[27] Y. Stauffer, F. Reynard, Y. Allemand, M. Bouri, J. Fournier, and R. Clavel, ''Pelvic motion implementation on the WalkTrainer,'' in *Proc. IEEE Int. Conf. Robot. Biomimetics*, Sanya, China, Dec. 2007, pp. 133–138.

[28] T. P. Luu, H. B. Lim, X. Qu, and K. H. Low, ''Pelvic motion assistance of NaTUre-gaits with adaptive body weight support,'' in *Proc. 8th Asian Control Conf.*, Kaohsiung, Taiwan, May 2011, pp. 950–955.

[29] C. Werner, S. Von Frankenberg, T. Treig, M. Konrad, and S. Hesse, ''Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: A randomized crossover study,'' *Stroke*, vol. 33, no. 12, pp. 2895–2901, 2002.

[30] D. P. Ferris, G. S. Sawicki, and A. R. Domingo, ''Powered lower limb orthoses for gait rehabilitation,'' *Topics Spinal Cord Injury Rehabil.*, vol. 11, no. 2, pp. 34–49, 2005.

[31] R. Schmidt and T. Lee, *Motor Control and Learning: A Behavioral Emphasis*, 3rd ed. Champaign, IL, USA: Human Kinetics Publishers, 1999.

[32] G. Kwakkel, R. C. Wagenaar, J. W. R. Twisk, G. J. Lankhorst, and J. C. Koetsier, ''Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial,'' *Lancet*, vol. 354, no. 9174, pp. 191–196, 1999.

[33] F. M. Henry, *Specificity vs. Generality in Learning Motor Skill*. Englewood Cliffs, NJ, USA: Prentice-Hall, 1968.

[34] H. Barbeau, "Locomotor training in neurorehabilitation: Emerging rehabilitation concepts," *Neurorehabil. Neural Repair*, vol. 17, no. 1, pp. 3–11, 2003.
[35] A. Kaelin-Lane, L. Sawaki, and L. G. Cohen, "Role of voluntary drive in encoding an elementary motor memory," *J. Neurophysiol.*, vol. 93, no. 2, pp. 1099–1103, 2005.
[36] M. Lotze, C. Braun, N. Birbaumer, S. Anders, and L. G. Cohen, "Motor learning elicited by voluntary drive," *Brain*, vol. 126, pp. 866–872, Apr. 2003.
[37] D. C. Boone and S. P. Azen, "Normal range of motion of joints in male subjects," *J. Bone Joint Surgery—Series A*, vol. 61, no. 5, pp. 756–759, 1979.
[38] D. A. Winter, *The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological*, 2nd ed. Waterloo, ON, Canada: Waterloo Biomechanics, 1991.
[39] P. K. Levangie and C. C. Norkin, *Joint Structure And Function: A Comprehensive Analysis*, 4th ed. Philadelphia, PA, USA: Davis, 2005.
[40] M. K. Hasan, S. H. Park, S. J. Seo, D. H. Sohn, S. H. Hwang, and G. Khang, "A gait rehabilitation and training system based on task specific repetitive approach," in *Proc. 3rd ICBBE*, Jun. 2009, pp. 1–4.
[41] J. A. Galvez, G. Kerdanyan, S. Maneekobkunwong, R. Weber, M. Scott, S. J. Harkema, *et al.*, "Measuring human trainers' skill for the design of better robot control algorithms for gait training after spinal cord injury," in *Proc. IEEE 9th Int. Conf. Rehabil. Robot.*, Chicago, IL, USA, Jun./Jul. 2005, pp. 231–234.
[42] J. Hidler, W. Wisman, and N. Neckel, "Kinematic trajectories while walking within the Lokomat robotic gait-orthosis," *Clin. Biomech.*, vol. 23, no. 10, pp. 1251–1259, 2008.
[43] C. Kirtley, M. W. Whittle, and R. J. Jefferson, "Influence of walking speed on gait parameters," *J. Biomed. Eng.*, vol. 7, no. 4, pp. 282–288, 1985.
[44] J. L. Lelas, G. J. Merriman, P. O. Riley, and D. C. Kerrigan, "Predicting peak kinematic and kinetic parameters from gait speed," *Gait Posture*, vol. 17, no. 2, pp. 106–112, 2003.
[45] M. Hanlon and R. Anderson, "Prediction methods to account for the effect of gait speed on lower limb angular kinematics," *Gait Posture*, vol. 24, no. 3, pp. 280–287, 2006.
[46] H. B. Lim, T. P. Luu, K. H. Hoon, and K. H. Low, "Natural gait parameters prediction for gait rehabilitation via artificial neural network," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Taiwan, Oct. 2010, pp. 5398–5403.
[47] T. P. Luu, K. H. Low, X. Qu, H. B. Lim, and K. H. Hoon, "An individual-specific gait pattern prediction model based on generalized regression neural networks," *Gait Posture*, vol. 39, no. 1, pp. 443–448, 2014.
[48] J. Rose and J. G. Gamble, *Human Walking*, 3rd ed. Philadelphia, PA, USA: Lippincott Williams & Wilkins, 2006.
[49] J. F. Israel, D. D. Campbell, J. H. Kahn, and T. G. Hornby, "Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury," *Phys. Therapy*, vol. 86, no. 11, pp. 1466–1478, 2006.
[50] J. Hidler, D. Nichols, M. Pelliccio, K. Brady, D. D. Campbell, J. H. Kahn, *et al.*, "Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke," *Neurorehabil. Neural Repair*, vol. 23, no. 1, pp. 5–13, 2009.

TRIEU PHAT LUU received the B.E. degree in mechanical engineering from the Ho Chi Minh City University of Technology, Vietnam, and currently pursuing the Ph.D. degree with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His research interests are lower and upper limb motor control strategies, and robotic rehabilitation systems.

KIN HUAT LOW received the B.Sc. degree from National Cheng Kung University, Tainan, Taiwan, and the M.Sc. and Ph.D. degrees in mechanical engineering from the University of Waterloo, Waterloo, ON, Canada.

He is currently a Professor with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His teaching and research interests include robotics, vibrations, impacts, exoskeleton systems, mechatronics design, machines, and mechanisms. He is the author or co-author of over 250 journal and conference papers in the areas of biomimetics, robotics, rehabilitation, impacts, machine and mechanisms design, power transmission systems, structural dynamics, and vibrations.

Dr. Low won the Best Paper Awards/Finalists at several IEEE international conferences for his work on biomimetics, exoskeletons, and rehabilitation. He has been invited as a keynote speaker in the areas of robotics gait rehabilitation and bioinspired underwater robotics. He has contributed to several journals as an Associate Editor, including *Mechanism and Machine Theory*, the *Journal of Bionic Engineering*, the IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING, the *Journal of Robotics, and Mechatronics*. He has been a Guest Editor of several journal special issues on bioinspired systems and robotics rehabilitation. He is currently serving as the Chair of the Technical Committee on Biorobotics.

XINGDA QU received the B.S. and M.S. degrees in automation control from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 2001 and 2004, respectively, and the Ph.D. degree in industrial and systems engineering from Virginia Polytechnic Institute and State University, Blacksburg, in 2008. He is currently an Assistant Professor with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His research interests are in the areas of occupational biomechanics, and industrial ergonomics.

HUP BOON LIM received the B.E. degree from the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, in 2005 and 2012, respectively. He is currently a Mechanical Design Engineer with Singapore Polytechnic. His research interests are functional motor recovery and assisted rehabilitation devices.

KAY HIANG HOON is an Associate Professor with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. His research interest has been primary in stress analysis of structures and components, biomechanical analysis, design and development of assistive and rehabilitative gait devices.