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Procedia IUTAM 2 (2011) 109–127
Procedia IUTAM
www.elsevier.com/locate/procedia

2011 Symposium on Human Body Dynamics

Subject-oriented overground walking pattern generation on a rehabilitation robot based on foot and pelvic trajectories

K. H. Low*

School of Mechanical and Aerospace Engineering
Nanyang Technological University (NTU)
Singapore 639798, Republic of Singapore

Abstract

Robotic devices have been designed to enhance motor recovery by replicating clinical motion pattern training. A rehabilitation gait system has been developed to assist the subject-centric gait rehabilitation on overground walking. Environment constraints are presented such as intermittent ground contact, impact between foot and ground, and foot clearance requirement. A subject-oriented gait pattern generation is proposed with respect to the pelvic and foot trajectory of the human gait. For simplicity, ten designated points over one gait cycle are defined to express an individual walking pattern with specific stride height and length. Gait and posture on these points are studied in terms of the trajectory of ankle and metatarsal. Furthermore, the pelvic motion serves as compensation to fulfill those pre-described foot trajectory, while the joint angles for the robotic orthosis attached to the lower limb are calculated based on the solving of inverse kinematics. Results of the initial testing indicate the effectiveness and smoothness of the desired motion generated by the gait system. The labor saving of using the developed gait system is highlighted and the performance of the gait system is evaluated by the EMG analysis of selected lower limb muscles.

Peer-review under responsibility of John McPhee and József Kövecses

Keywords: rehabilitation; pelvic control; gait pattern; gait cycle; orthosis; robotics; kinematics; human motion

1. Introduction

Spinal cord injury and stroke are considered to be the leading causes of permanent disability around the world. Because of the neurological damage caused by SCI and stroke, the patients suffered muscle

* Corresponding author. Tel: +65-67905755 ; fax: +65-67935921
E-mail address: mkhlow@ntu.edu.sg

doi:10.1016/j.piutam.2011.04.012

weakness, reduction of sensation, and difficulty in controlling movement [1-2]. The loss of the walking ability is especially serious because walking is an indispensible function for human to be able to accomplish most daily activities. In fact, most stroke patients considered the restoration of walking ability as their most important rehabilitation goals [3-4]. As a result, the rehabilitation on restoration on walking ability is an important area in rehabilitation research. Moreover, neurons cannot be regenerated with medicine alone.

Clinicians found that the neuron has the property called neuroplasticity, which is the ability of the nervous system to reorganize [5-6]. This theory has provided the fundamental guidance for rehabilitation that is to provide patients with exercises to help the brain structure to change adaptively with the environment changes. Though it has been shown that 82% of the stroke patients in America regained the ability of walking [7], the conventional body weight support gait rehabilitation relying on manual assistance limits the effectiveness of gait training. First of all, those conventional training procedures may require up to three physical therapists to lift, support, and assist the patient. In addition, therapists have to manually facilitate movement of the patient in a slow way such that walking is simulated. Therefore, the rehabilitation on gait is often labor-intensive and physically challenging for the therapists [8]. Due to the high costs of labor and the shortage of professional therapists, few patients can afford and benefit from this manually assisted therapy. In addition, the potential risk of falling and injury when patient and therapists are fatigue during the training process will shorten the therapy session. Hence, proper and sufficient task-specific gait rehabilitation is denied.

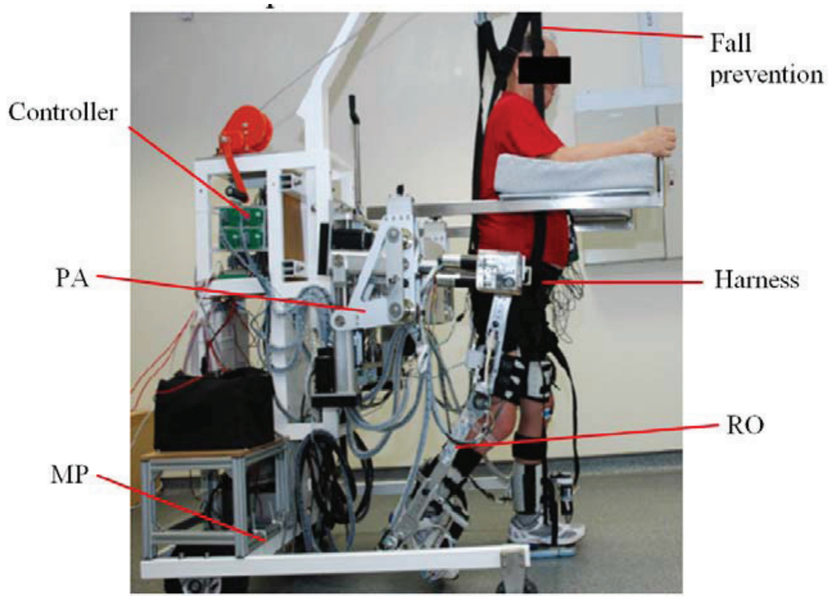


Fig. 1. Overview of *NaTUre-gaits* with 14 DoFs: PA – pelvic arm to provide pelvis motion and body weight support (BWS); RO – robotic orthosis for active assistance to hip, knee, and ankle joints in the sagittal plane; and MP – mobile platform to allow the overground walking.

With the development of robotic, computer, and sensor technology, it has provided hope that an automated training system with motorized power can contribute in the field of neuro-rehabilitation. There have been dozens of robotic devices developed to automate the process of gait rehabilitation training process, such as Locomat [9], Walk Trainer [10], Haptic Walker [11], LOPES [12] and KineAssist [13].

These gait rehabilitation systems provide features, such as lower limb assistance, pelvic movement assistance, and body weight support (BWS). However, majority of these systems are treadmill based as opposed to overground walking. Furthermore, few of them provide the pelvic movement assistance, which has been highlighted by doctors and therapists that pelvic posture and its important role in coordinating overall patient movement. It would seem therefore that further investigations are needed in order to extend robotic-assisted motion beyond the lower limbs to include also the pelvic control.

As shown in Fig. 1, a natural and tunable rehabilitation gait system (*NaTUre-gaits*) [14] has been developed to assist the gait rehabilitation with body-weight support locomotion training (BWSLT), gait control (GC), balance control (BC), and pelvic control (PC). The overall objective of the research work is to initialize overground gait training by the robotic assistance coupled with standard physiotherapy so as to improve walking capabilities of patients.

Meanwhile, in view of the difference in gait profiles of each individual patient, it is crucial to include the respective patient gait profile as a factor to be considered for subject-based gait rehabilitation planning [15]. Most developed system set the pre-programmed gait trajectory without the consideration of patient's parameters. It has been reported that some patients developed a compensated walking pattern, which will change the motion for the affected joint; a non-adjustable walking motion will injure the joint and the muscle. Effective gait rehabilitation requires that subject-orientated lower limb joint waveforms can be specified for different subjects and the waveform can be updated easily by changing the gait parameters (stride length, cadence, etc.) during training process.

Another aim of the present work is to develop a robotic system for the provision of unrestricted pelvic motion and to allow body weight shifting, actuated assistance to the lower limb joints (hip, knee, and ankle), body weight support, and functional overground walking. We hope to provide an alternative approach for gait rehabilitation, in contrast to existing rehabilitation device; and provide subject-oriented walking pattern generation by offering a wide range of walking speed and lower limb joint waveforms for various training conditions.

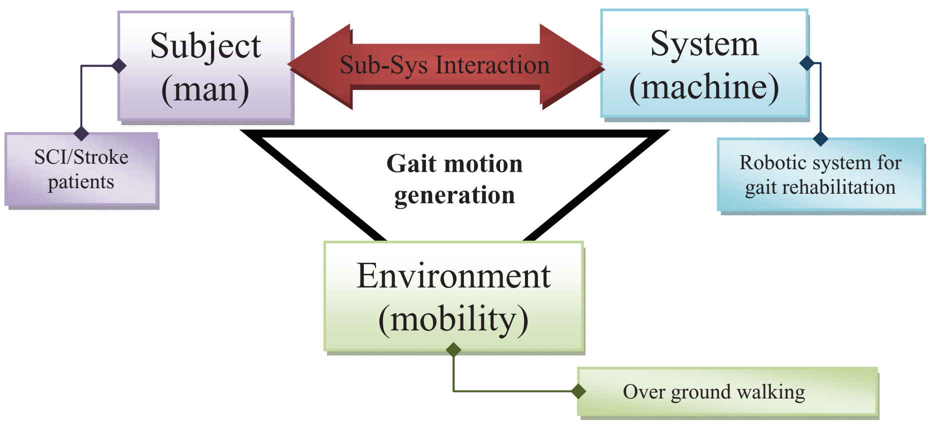


Fig. 2. Subject, system, and environment are the three main areas in this research work.

2. Approach and Scope

A clinical-engineering approach, including subject, system, and environment, are introduced for an effective rehabilitation. Also in this section, a clinical-based robotics rehabilitation procedure is presented. We aimed to apply engineering knowledge to solve clinical-relevant problems for the improvement of healthcare. To be effective, the whole rehabilitation process can be formed into three areas: subject, system, and environment. The interaction between the three areas is shown in Fig. 2. Subject refers to the targeted user of the proposed work, which are spinal cord injury (SCI) and stroke patients. System is the proposed robotic system for the provision of gait rehabilitation. Lastly, environment is the potential situation that the gait rehabilitation can be carried out, for example, overground walking requires intermittent ground contact that needs to satisfy, terrain conditions, like walking on slope or stair climbing, etc.

2.1. Subject (man)

Targeted subjects of this research work are SCI and stroke patients. Majority of patients undergoing gait rehabilitation are these two groups of patients. SCI and stroke are briefly introduced next.

Human motor signal flows from brain to the peripheral nerves to activate the muscle in order to complete the intended movement. However, this operation will be disrupted if the signal transmitting pathway, i.e. the spinal cord, is injured. Most spinal cord injuries are caused by direct or indirect trauma to the vertebral column, resulting in either temporary or permanent change in normal motor, sensory or autonomic function.

Stroke or 'brain attack' is a type of cardiovascular disease. It occurs when a blood clot blocks an artery or a blood vessel bursts and interrupts the blood flow to an area of the brain. As either one occurs, part of the brain cannot obtain the blood (or oxygen) it needs, the brain cells start to die and the affected part of the brain is damaged.

Despite of the fact that SCI and stroke patients exhibit different gait conditions, most of the existing robotic gait rehabilitation systems do not provide customized gait rehabilitation based on the patient condition. Quite often, the gait rehabilitation provided by current robotic gait rehabilitation system is standardized for all patients, with limited customization options available. Through the discussion with doctors and therapists in Singapore's Tan Tock Seng Hospital, it is felt that no standardized program can cater for all patients. For example, stroke usually resulted in paralysis or weakness of one side of the body. Current robotic gait rehabilitation system can only provide lower limb motion assistance for both legs, which will not benefit the unaffected leg. It is envisioned that, with the modular design and highly customizable gait rehabilitation system proposed in this work, a subject-based gait rehabilitation intervention can be designed for each patient in certain gait condition. Accordingly, for stroke patients, the gait locomotion assistance can be provided for the leg with weakness only. As for SCI patients, the gait locomotion assistance can be focused on the whole lower limb joints.

2.2. System (machine)

Four essential features are proposed for robotic assisted gait rehabilitation in this work. These features are pelvic motion assistance (and body weight shifting), body weight support, overground walking, and lower limb motion assistance. A unique feature is proposed in the present work to include the pelvic motion assistance and body weight support at waist with the same mechanism. The pelvic motion assistance in current robotic gait rehabilitation systems is constrained by the body weight support apparatus. Providing both features with one mechanism reduce the motion conflicts between the two. The proposed robotic system features a total of fourteen degrees of freedom for the accomplishment of overground gait locomotion assistance. The detail of the proposed robotic system will be described later.

In the development of the rehabilitation system, several discussion sessions and clinical attachments were organized with the rehabilitation team in Singapore's Tan Tock Seng Hospital, in order to incorporate user requirements in the design of a gait rehabilitation system. Several worth-mentioning issues for the system design are listed as follows:

- *Safety design for subjects*. Safety is always given the top priority during the whole rehabilitation training. The related issues considered include soft attachments and supports of subject-system interface, like cushion or padding and harness, torque limit, emergency stop, quick release during emergency, fall prevention, no sharp edges of the structure, non fire-hazard materials, mechanical limiter to prevent motion from travel beyond the designated range of motion, etc.
- *Mobility and environment constraint*. The developed robotic device should allow sufficient leg forward/backward swing and account for different physical size of subjects. However, the rehabilitation tasks, the moving areas, and the surrounding constraint must be considered to determine the dimensions and the mobility of the gait systems. These factors include height, width, and length constraints, corridor, entrance door, clinical layout, etc.
- *Natural walking pattern*. To ensure a "natural" walking, the smooth coordination and synchronization of walking among the respective modules of the *NaTUre-gaits* must be considered together with the subject motion and environment constraint (or ground). The overground walking requires intermittent ground contact over the course of walking cycles. During the contact, it is necessary to provide smooth impact between the foot and the ground at initial heel contact. Next, foot-ground contact conditions should avoid the foot dragging within the whole stance phase. Furthermore, requirements of single and double foot stance phase are provided when coordinating the right foot and the left foot. Finally, the foot clearance over the swing phase should be considered. These are the issues especially crucial to a subject going through a rehabilitation process in a "natural" walking him or her. In conclusion, the natural walking discussed is referred to a smooth interaction among the subject, system, and environment. This is to ensure that the motion constraint and discomfort to the subject is kept to a minimum in every rehabilitation stage. Note that the gait motion, the task performed, and the muscle exerted by the subject in every progressive rehabilitation stages will be different. The changing gait parameters can be updated and incorporated to the gait system for a "natural" walking.
- *Tunable implementation for specific subject*. For a tunable implementation, both the robot and the control software should be able to adapt for various physical dimensions of patients. For example, robotic orthosis is adjustable in terms of the length of lower limb, width of buttocks, etc. As for the software, a comprehensive set of parameters should be provided to customize gait pattern, walking speed, training duration, etc.
- *Modular design*. To accommodate for a broad range of physical disabilities, *NaTUre-gaits* has incorporated a modular concept for its modules to cover most of patient types. However, not all the modules may be required for patients in some conditions. Therefore, choices are available by reducing or combining a different set of modules. The modular concept can also provide ease of assembly/disassembly and saving the time of the rehabilitation process.

2.3. Environment (mobility)

Environment is where the system and subject come into contact with. The overground walking requires intermittent ground contact. During the contact, it is necessary to provide smooth contact between the foot and the ground at initial heel contact. After this, foot-ground contact conditions are required to keep out the foot dragging within the whole stance phase. Furthermore, requirements of single and double foot stance phase are provided during the coordination of the right and left feet. Finally, foot clearance requirement is provided in the swing phase. These are the issues especially crucial for subjects going through a rehabilitation process.

2.4. Methodology of Clinical Rehabilitation

A methodology of the clinical rehabilitation procedure is discussed in this section. The robotics gait rehabilitation system should also fulfill the function of clinical-based rehabilitation that normally covers five major functions: (1) enhancing muscle force, (2) maintaining balance control, (3) training walking locomotion including exercises for leg-propulsion and body weight support (BWS), (4) providing pelvic control, and (5) assisting mobility for activities of daily living (ADL) [6, 16-17]. The flowchart of the proposed gait rehabilitation program is depicted in Fig. 3, in which the relationship among major rehabilitation requirements is shown.

- *Requirement A: Enhancing muscle force*

Clinical rehabilitation, aimed at enhancing muscle force, encourages patients to train their own muscular power as much as possible. Circumduction, flexion and extension, and abduction/adduction of the joints lead to muscle training. For patients who cannot stand or walk due to weakness of their muscle, gait recovery is achievable via motor learning or brain plasticity after repeated exercises.

- *Requirement B: Maintaining of balance*

After the training on enhancing the muscle force, therapists provide exercises for balance control. Balance control is fundamental to independent walking. Patients may fall down if they do not have good balance control. In such an exercise, patients are required to keep their upper body upright when in a sitting or standing position, through which they re-learn their trunk control. Center of Pressure (CoP) is an effective method of evaluating the balance control ability.

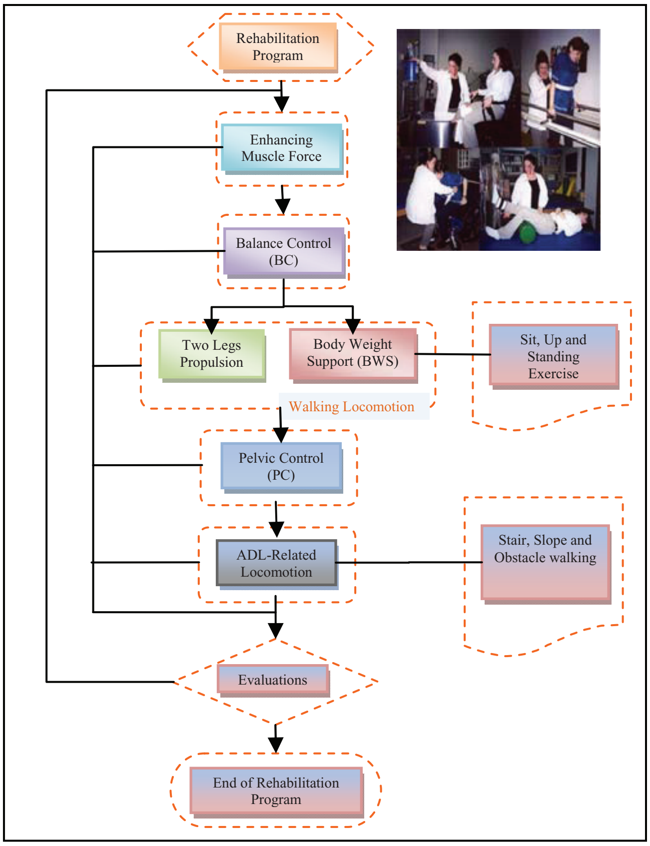


Fig. 3. Process of clinical-based gait rehabilitation.

- *Requirement C: Training of walking locomotion*

With improvement of muscular force and sense of balance, patients continue to practice rehabilitation exercises for walking locomotion. In order to achieve walking locomotion, the legs need to be trained specifically in two aspects providing propulsion and body weight support (BWS). BWS is one of the essential functions of walking. In this training program, therapists assist each patient by supporting his/her body weight when necessary. However, it is laborious for manual assistance and guidance. As such, BWS device, passive or active, has been used in hospitals. The BWS device also helps in ensuring safety of patients, whose ability to support their body weight are in recovery mode. In addition, a way to compensate for the lack of BWS is to attach an arm-support onto the frame of the MP.

Either with the regained BWS ability or with external off-loading assistance, patients carry out the next exercise, which concerns leg propulsion. In many cases, the muscular strength of the limbs of the patients is weak, though it may allow for slow walking locomotion. Therapists emphasize the muscle activation through leg movement that stimulates the nervous system to recall normal walking.

- *Requirement D: Providing pelvic control*

Many patients walk in an abnormal way because of the loss of their pelvic control. Without proper pelvic control, incorrect posture, which adversely affects walking stability, may be observed. In this situation, oral reminder or necessary assistance may be provided. An example of assistance is through placing of both hands on the hips of a patient and moving with the patient while correcting the problems with the trajectory of pelvic movement.

- *Requirement E: Assisting mobility for activities of daily living (ADL)*

ADL-related activities are provided when patients can walk slowly by themselves. Tasks such as stair climbing, slope walking, tuning and obstacle avoiding are common locomotion tasks in ADL. Those activities enable individuals to get ready for their day and get themselves to their place of employment, school, and/or recreation. In this stage, the improvement of walking ability to perform ADL is targeted. Design, development and testing of key rehabilitation exercise related to specified ADL task is important.

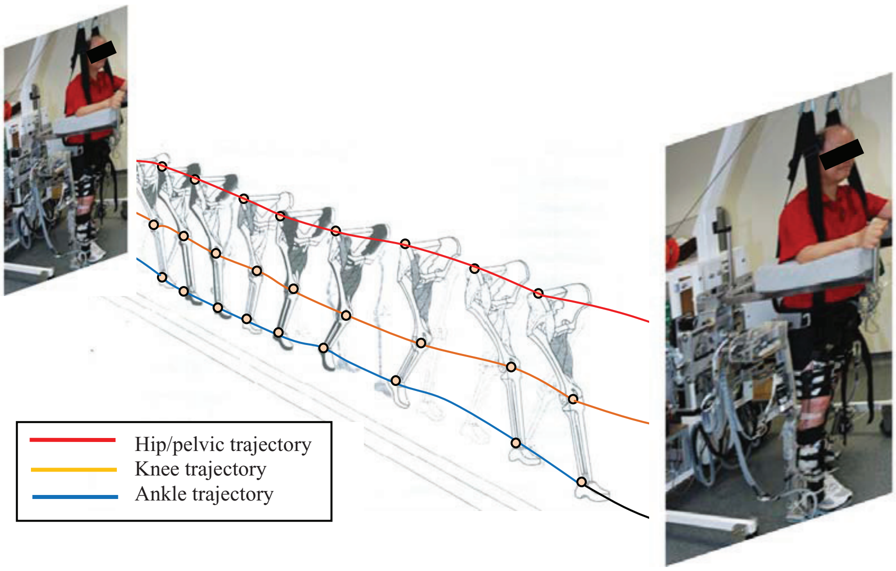


Fig. 4. A patient walks with *NaTUre_gaits*, in which the hip/pelvic, knee and ankle trajectories over a gait cycle are illustrated.

Fig. 4 shows a patient with spinal cord injury (SCI) walking with our developed system for the overground environment. The hip/pelvic, knee and ankle trajectories are given in the figure for illustration. The patient is a 66-year old Asian male, C5 spinal cord injury, with resulting in loss of function below shoulder. Progressive physical exercises have improved his sense of control. However, routines to strengthen his muscles are costly, with training involving at least three assistants. He required assistance for his lower limbs, pelvis, trunk and upper body in order to be able to transfer, support, balance, and ambulate per session. Through the rehabilitation, he hopes to improve ambulation abilities as well recovery of motor function. Safety precaution certification and approval from the local ethics committee were obtained and documented before the trial. It is worth mentioning that the subject was excited throughout the walking testing with *NaTUre-gaits*. He felt physiologically to be able to walk again, without the assistance by any caregiver.

3. Robotic Assistive Gait Rehabilitation with *NaTUre-gaits*

The developed robotic system is named as *NaTUre-gaits*, as ***Na**tural and **TU**nable **re**habilitation **gait** system*. Natural and tunable are two core concepts proposed for this research work and for the robotic system. The overall design of *NaTUre-gaits* is provided in Fig. 5. The feature of each module is briefly explained in the subsequent sections.

3.1. Pelvic Control

The PA mechanism consists of a pair of robotic arms. Each robotic arm consists of three actuated motions [14, 18]. Each of this motion is achieved by a linear sliding mechanism, actuated by a DC servo motor. The layout and configuration of the robotic arm at the right side are illustrated. The two robotic arms hold the subject at both sides of pelvis. The subject is secured to the robotic arm at the attachment plate with a specially designed harness.

With the two robotic arms, the three translational movements and two rotational movements of the pelvis can be achieved. The pelvic rotation about the mediolateral axis is passive, with the range of motion restricted by the harness to ± 5°. The PA mechanism is mounted on a mobile platform. Note that the pelvic motion in the *x*-axis is provided by the combined motions of PA mechanism and mobile platform in the axis. The trajectory of pelvis is provided as $f(x, y, z)$, where $x = A_x \sin(2t + \theta_x)$, $y = A_y cos(2t + \theta_y)$, and $z = A_z \sin(t + \theta_z)$ [19].

3.2. Mobile Platform

Mobile platform is the movable 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. To avoid the loading exerted to the subject, the mobile platform also serves as the carrier of the robotic orthosis, pelvis assistance mechanism, controller, power source, and other electronics components of *NaTUre-gaits*. Two motorized wheels are mounted at the rear of mobile platform. Each wheel is independently controlled, and it is possible for the mobile platform to follow straight or curved path. Therefore, the gait rehabilitation system can provide mobility in forward walking and turning as well.

The speed of the mobile platform is designed and customized based on several considerations, such as comfortable normal walking speed of a healthy person and patient. The average natural walking speed for a healthy adult is 1.50 m/s (aged 20 – 65 years) [20]. In our gait study, 30 healthy subjects of sampled population (aged 22 – 51 years) shows average normal walking speed of 1.22 m/s and average slow walking speed of 0.75 m/s. The mobile platform has maximum operational speed of 1.00 m/s.

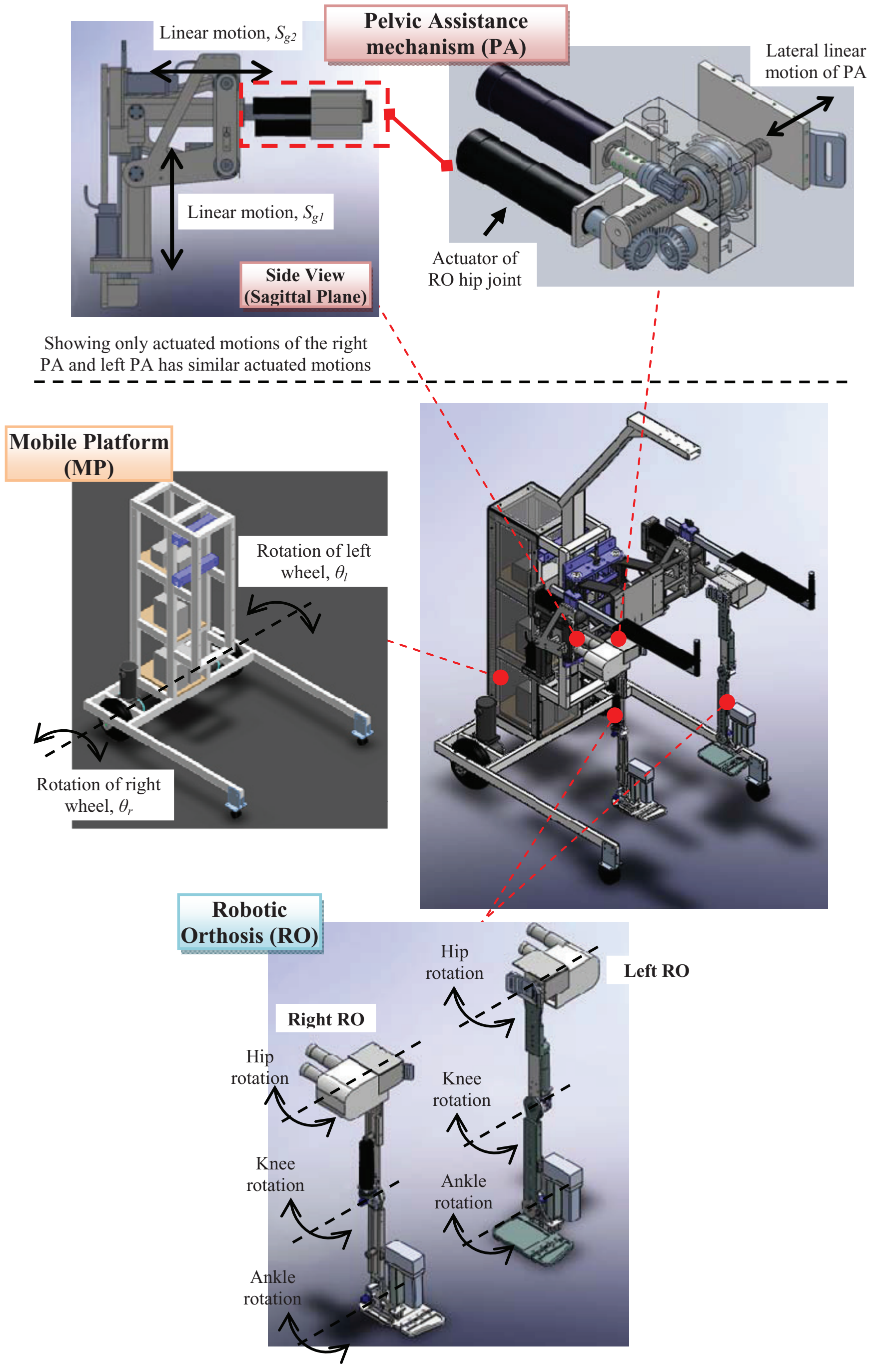


Fig. 5. Main modules on *NaTUre-gaits* and corresponding fourteen joint motions.

3.3. Robotic Orthosis

Robotic orthosis provides actuated assistance at the lower limb to perform specified gait locomotion. Six degrees of freedom (DoFs) are found on human leg, three at the hip, one at the knee, and two at the ankle. The determination of the DoFs require for an orthosis depends on the task requirement. To achieve a relatively normal walking locomotion, the hip and knee flexion are necessary. If the forward propulsion is to be provided by foot alone (not by upper body with clutch or other walking aids), the plantar flexion of the ankle is required [21]. After literature review and discussion with clinical practitioners, the robotic orthosis in simplified form is designed to provide assistance in only the sagittal plane, for hip, knee, and ankle joints. The kinematics model of the system is

$$\begin{cases} x_{knee} = x_{hip} + l_{thigh} sin\theta_{hip} \\ y_{knee} = y_{hip} + l_{thigh} cos\theta_{hip} \end{cases} \tag{1}$$

$$\begin{cases} x_{ankle} = x_{knee} + l_{calf} sin\theta_{knee} \\ y_{ankle} = y_{knee} + l_{calf} cos\theta_{knee} \end{cases} \tag{2}$$

$$\begin{cases} x_{metatarsal} = x_{ankle} + l_{metatarsal} cos\theta_{ankle} \\ y_{metatarsal} = y_{ankle} + l_{metatarsal} sin\theta_{ankle} \end{cases} \tag{3}$$

The stride length and stride height are the given by

$$L_l = |x_{metatarsal-right} - x_{metatarsal-left}| \tag{4}$$

$$L_h = |\, y_{metatarsal-right} - y_{metatarsal-left}| \tag{5}$$

4. Natural Walking Motion during Gait Rehabilitation

In this section, the coordination and synchronization walking requirements for the modules of *NaTUre-gaits* are explained. The pelvic trajectory is described as mentioned. In order to generate foot trajectories, key points on the trajectory are designated at first. In view of human walking, five key events are selected: heel contact (HC) [22], foot flat (FF), heel off (HO), toe off (TO), and toe high (TH). The same event markers are provided for both the left and the right legs. Therefore, ten points are picked up for one complete gait cycle. The occurrence of these events and the stick diagram of walking pattern are shown in Fig. 6. The ankle and metatarsal positions on these specified points are estimated from the designated step length and height.

For the overground walking, those key points from the initial point at right heel contact to toe off are located at stance phase. The ankle trajectory is fixed on the ground from heel contact to heel off while the metatarsal trajectory is fixed on the ground from foot flat to toe off [23]. The distance between these two fixed points is the length between heel and metatarsal joint. In the swing phase, the stride height reaches the maximum at the toe high (TH) as we specified in this method. The curve fitting of all those key points is to obtain a trajectory that meets overground walking requirement. The joint angles can be calculated by solving the inverse kinematics of the system:

$$\sigma_a = \frac{X^2+Y^2+l_3^2-l_4^2}{2l_3\sqrt{X^2+Y^2}} \quad \text{and} \quad \sigma_b = \frac{X^2+Y^2-l_3^2+l_4^2}{2l_3 l_4} - 1 \tag{6}$$

$$\theta_{hip} = sin^{-1}\sigma_a - tan^{-1}\frac{X}{Y} \tag{7}$$

$$\theta_{knee} = \theta_{hip} + cos^{-1}\sigma_b \tag{8}$$

$$\alpha_{ankle} = sin^{-1}\frac{y_a - y_m}{l_5} \tag{9}$$

where $X = X_a - X_h$ and $Y = Y_a - Y_h$

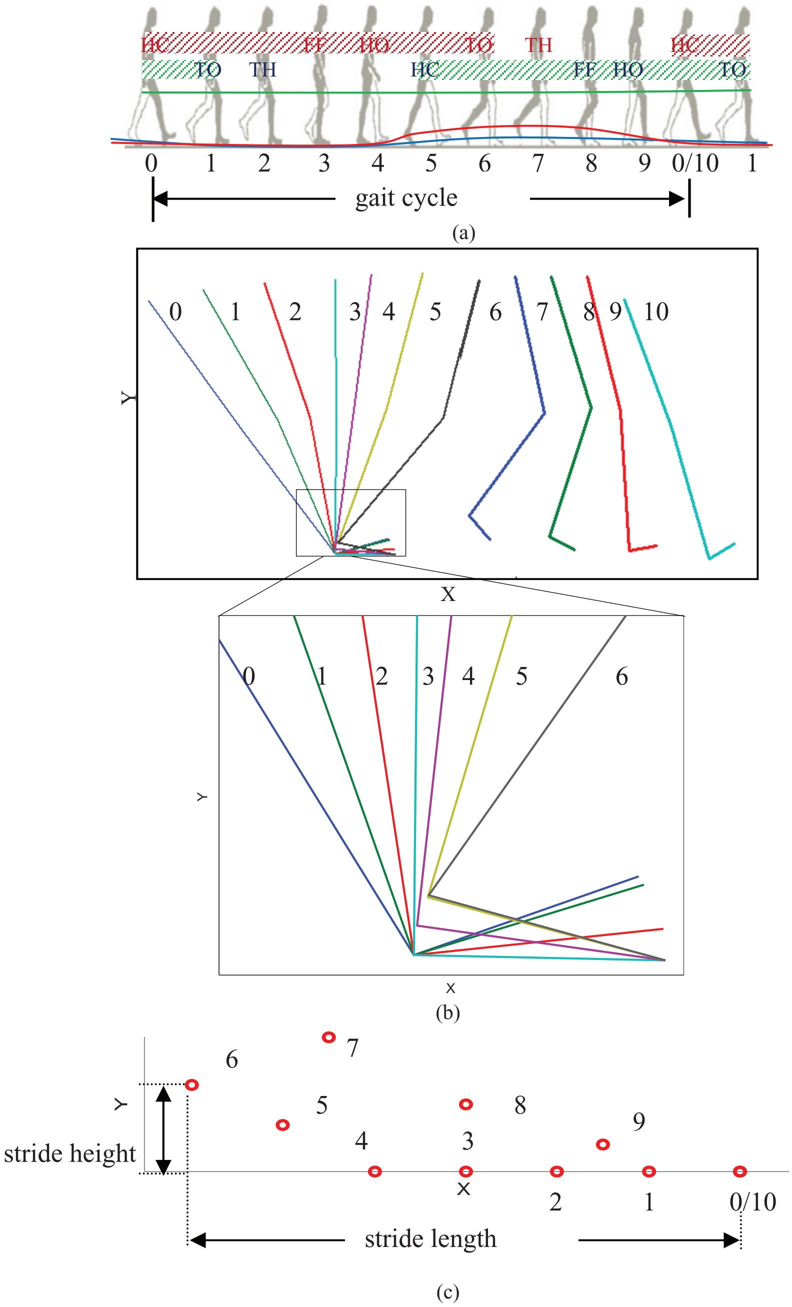
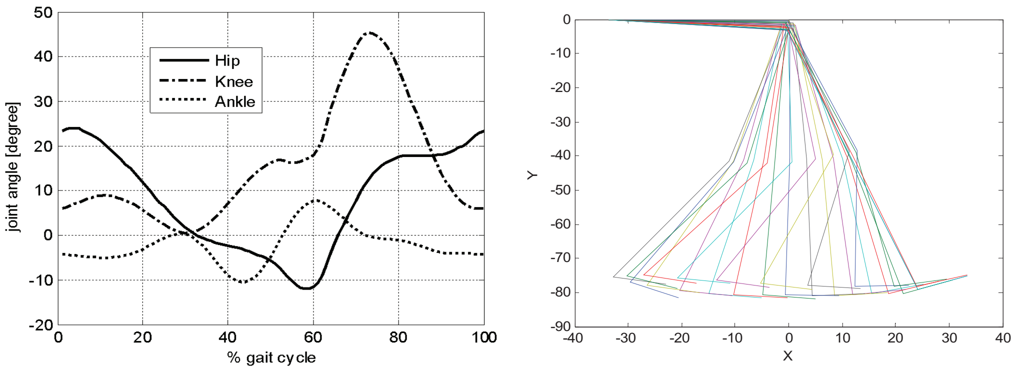


Fig. 6. Definition of ten points as seen from fixed external observer (a) event markers for one gait cycle, the red color shadow indicate the stance phase of the right side which the green for the left. The single support duration (SSD), double support duration (DSD) and swing duration (SD) are labeled. The trajectory for the knee, ankle, and metatarsal joints is each demonstrated; (b) stick diagram of the walking pattern, with zooming in the stance phase. (c) ten points generated by proposed method.

Some angles are undefined corresponding to the pre-defined trajectories, if they are out of trajectory range. For example, the following condition cannot be satisfied in this case:

$$\sqrt{(x_h - x_a)^2 + (y_h - y_a)^2} < l_3 + l_4 \tag{10}$$

where $(x_h, y_h) \in workspace\ of\ hip$ and $(x_a, y_a) \in workspace\ of\ ankle$.



(a) (b)

Fig. 7. Trajectory generated by the ten points. (a) The generated joint angles for hip, knee, and ankle; (b) Lower limb motion as seen from an external observer moving with pelvic velocity in *x* direction.

For those points out of trajectory range, first compare the difference between the generated trajectory to the pre-described trajectory in y-direction. We then subtract the difference at pelvic motion in y-direction. Therefore, we use the pelvic motion to compensate the modification. The update pelvic trajectory compensates those derivations. Furthermore, a line space interpolation is used to set the movement in horizon direction is coordinate to the velocity of the mobile to avoid foot dragging on the ground during the stance phase. Assume that $l_3 = 40cm$, $l_4 = 40cm$, $l_5 = 10cm$, $S_L = 100cm$, $S_H = 10cm$, the specified joint angles for hip, knee and ankle are evaluated by inverse kinematics is shown in Fig. 7.

5. Trials on Patient and Healthy Subjects

The developed robotic gait rehabilitation system, *NaTUre-gaits* has been tested on a patient, together with the proposed gait pattern planning methodology. To evaluate the performance of the system, EMG signals of the three healthy subjects were first acquired in their individual walking. Analyses were carried out on the signals and comparisons are made among the signals. The result is presented in the subsequent section.

5.1. Patient Trial

To evaluate the performance of the proposed robotic system in providing gait rehabilitation, one patient (SCI, ASIA D, injury level C5) has been recruited for system trial. The main objectives of patient trial are:

- Study the acceptance of the patient toward the comfort level of the system during the rehabilitation process.
- Illustrate the significant reduction in manpower required in the overground walking rehabilitation.

During the manually-assisted overground walking training, the stronger side (left side) of the patient is balanced with a clutch, while the right side (affected leg) is supported by a trainer. The gait locomotion of the left side can be voluntarily completed by the patient, whereas the gait locomotion of the right side has to be completed by another by lifting the foot and place it one step forward. In this way, any proper gait locomotion training can only be administrated with the help of two persons. This clearly demonstrated the great requirement of manpower to provide overground gait locomotion training for the patient. Furthermore, a substantial laborious effort is required from both the trainers, in which one of the trainers is working at an ergonomically unfavorable posture. Fig. 8 shows the walking training process.

Fig. 8. Over ground walking training of the patient at pre-trial (a) The patient walk with the help of two trainers (b) The right leg of the patient is moved forward with the help of one trainer (the trainer is working at an ergonomically unfavorable posture).

On the other hand, through the patient trial with *NaTUre-gaits*, the system function to provide the gait locomotion assistance is clearly demonstrated. The comfort level of the system during the rehabilitation process is acceptable to the patient. It is also illustrated that the manpower requirement is significantly reduced for the provision of overground gait locomotion training. Although two persons are required for the harness strapping process for the gait locomotion training, only one person is required for the control of *NaTUre-gaits* during the gait locomotion training. A gait locomotion training of the patient with *NaTUre_gaits* is shown in Fig. 9.

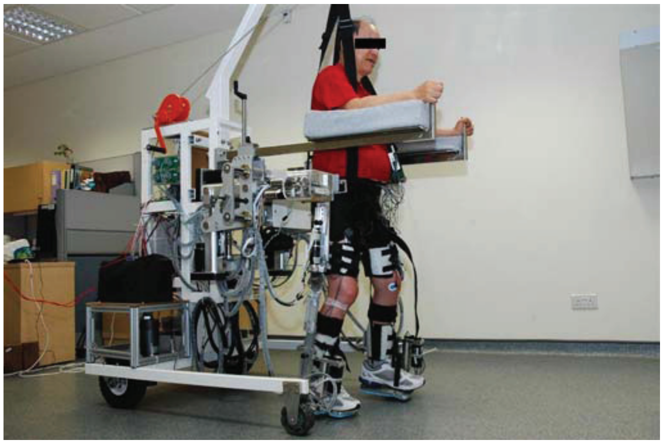


Fig. 9. Gait locomotion assistance for the patient.

5.2. EMG Evaluation of System Performance

The performance of the overground gait training with *NaTUre-gaits* is evaluated by comparing the EMG signals from the muscles on the lower limbs of subjects. With several disturbance factors such as walking speed, step length, and kinematics data influencing the evaluation, it poses a restriction on the validity of evaluation results by virtue of the average pattern analysis commonly used in the treadmill walking. Repetitive walking trials are conducted to evaluation the effectiveness of the system performance.

5.2.1. Leg muscles EMG data collection and processing

Every walking trial is video-recorded and the corresponding EMG signals are recorded via wireless communication. Three silver/silver chloride (Ag/AgCl) surface electrodes (Ambu Blue Sensors diameter 8mm) with conductive medium inside are used for collection. They are adhesive to the skin of eight lower limb muscles: soleus (SO), tibialis anterior (TA), gastrocnemius medialis (MG), vastus lateralis (VL), rectus femoris (RF), bicep femoris (BF), semitendinosus/semimembranous (ST), and gluteus maximus (GM). After the electrodes have been placed, the experiment is conducted 10 minutes later. This is to allow the skin impedance to stabilize. All those EMG raw data will be sent simultaneously to the host computer by TeleMyoTM 2400 G2 Telemetry System. Since the EMG system attached to the subject's legs is portable, it allows the EMG measurement for the overground walking.

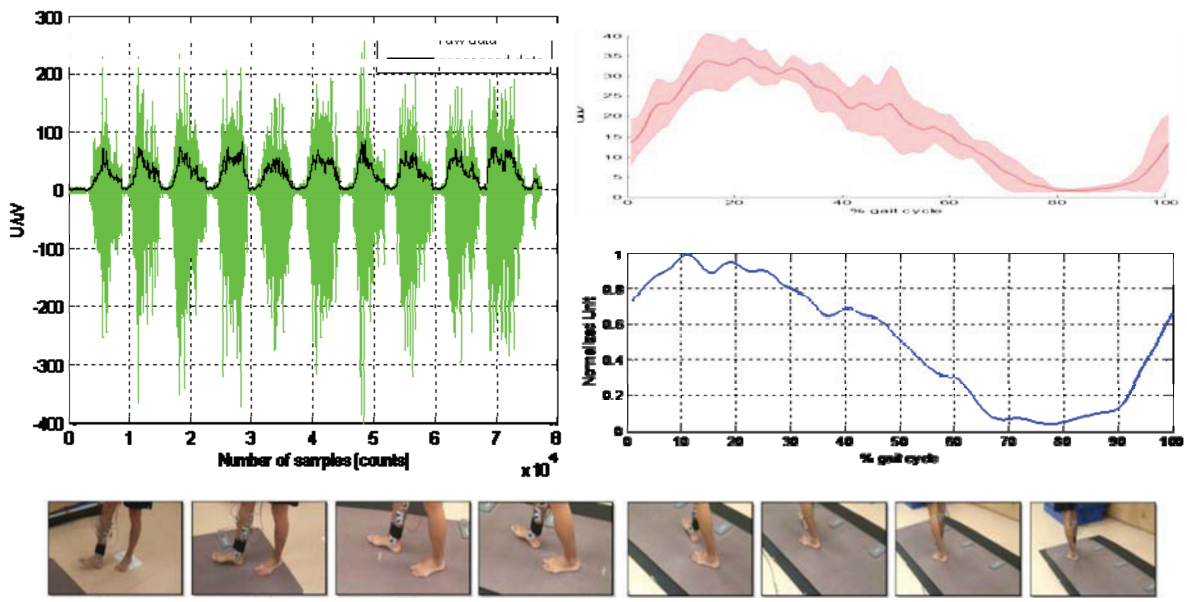
As for the signal processing, the signals will be fully-wave rectified. The processing will retain the signal energy, the Root Means Square (RMS) is then used for smoothing and the size of the window is set at 50 milliseconds. A 6Hz low-pass Infinite Impulse Response (IIR) filter has been used with Butterworth approximation [18]. The absolute magnitude of EMG is not consistent for individuals. Therefore, some works focus on the shape of EMG profile, times of peak or onset/cessation of myoelectric activity [24]. In this way, one can pick up profile information of the muscle pattern analysis.

5.2.2. Leg muscles EMG data collection and processing

The healthy subjects and the patient were informed of the experiment procedures but did not know the purpose of the study to avoid potential bias. Safety precaution certification and approval from the local ethic committee were obtained and documented before the trial. It is worth noting that the patient was so excited to be able to walk with *NaTUre-gaits* that made him felt like walking again without the help of any caregiver, first time after the injury.

5.3. Average Muscle Pattern Activation Profile

The main purpose of averaged muscle activation profiles is to detect prototypical activation patterns during the cyclic walking motion. The averaging process requires a continuous, standardized repetition sequence [25]. Our studies demonstrate that the processed data proportionally reflects the magnitude/duration of muscle activation. Subsequently, the processed data are divided by cycles at every repetitive events of the right heel contact [26]. The cycles are obtained and presented with the corresponding +/- SD. It is commonly known that the absolute magnitude of EMG is not consistent for individuals. Therefore, researches focus on the shape of EMG profile, times of peak or onset/cessation of myoelectric activity [27]. The peak EMG values of the average muscle pattern were obtained for normalization [6]. The procedure of processing is demonstrated in Fig. 10.



(1) 6.96 s (2) 11.51 s (3) 16.77 s (4) 21.17 s (5) 26.15 s (6) 31.12 s (7) 35.95 s (8) 41.21 s

Fig. 10. Average muscle pattern of healthy subject walking begins with right heel contact.

5.3.1. Evaluation of the system performance

The average activation profile is a significant performance index of the overground walking. Although the walking speed and other gait parameters alter the dynamics [28], a standard activation pattern for healthy walking is presented. As the subject walks with the device, decreasing activation volumes are shown. The comparison is presented in Fig. 11 for patient walking with/without the gait device. Three healthy subjects walking without the device are taken as the control group. Muscle (gluteus maximus) for the thigh is taken as the reference. Although the muscle activation increases for the manual-assisted patient walking, the muscle activation pattern is different from that associated to healthy walking. In contrast, the muscle activation pattern of the patient walking with the gait device is closer to that of a healthy walking. As what we observed, the magnitude of the strength decreases if compared to that of the control group. This is the same to the healthy walking with the gait device, as the device compensates (or assist) the muscle force during the walking process. In addition, the activation volume increases with a faster walking.

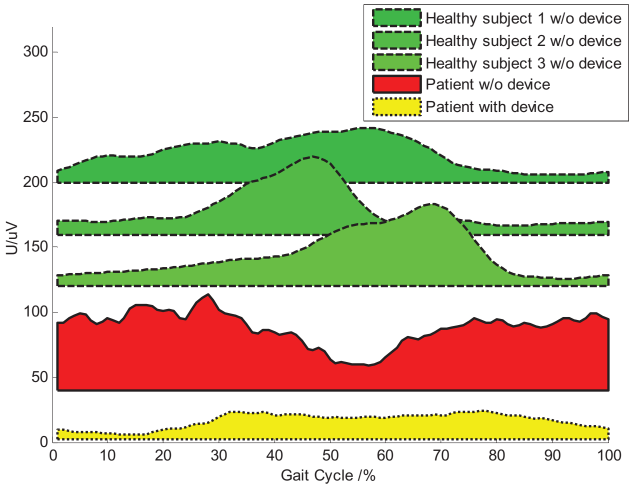


Fig. 11. Comparisons of muscle activation on Glut Max muscle: walking of three healthy subjects and one patient with/without the device.

6. Concluding Remarks

A gait rehabilitation system, *NaTUre-gaits*, has been developed to assist the gait rehabilitation for SCI and stroke patients. A synchronized motion is provided for overground walking. Ten designated time markers within one gait cycle are defined for individual walking pattern with specific stride height and length. Gait trajectory of these ten points is studied. The trajectory of ankle and metatarsal is planned based on these key points. Furthermore, the pelvic motion can serve as a compensation to fulfill the desired foot trajectory. The joint angles for the robotic orthosis attached to the lower limb are evaluated by solving the inverse kinematics.

Results of the initial testing indicates the effectiveness and smoothness of gait pattern implemented for the developed gait system. Patient trials confirmed the ability of the proposed system in the provision of overground gait rehabilitation. The labor saving of using the proposed system is illustrated by comparing to manually-assisted gait rehabilitation. Finally, by carrying out EMG study of selected muscles, the capability of the system in reducing the muscle activation level is shown. The EMG study in the patient trial shows that the patient can walk better with the help of *NaTUre-gaits*.

Acknowledgements

The author would like to express his appreciation to the Department of Rehabilitation Medicine of the Tan Tock Seng Hospital (TTSH) and the Robotics Research Center (RRC) of the Nanyang Technological University (NTU) for their supports provided throughout the tenure of the present work. The author would also like to thank Mr. Hup Boon Lim, Ms. Ping Wang, Mr. Trieu Phat Luu, and Mr. Lei Li for their assistance to the present work in various aspects. Thanks are also due to Mr. P. K. Neo and his family for their consent to the trials with *NaTUre-gaits*. The financial supports to the gait projects by the NMRC Research Grant 1051/2006 and Lee Foundation are acknowledged.

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