Design of a Novel Robotic Over-ground Walking Device for Gait Rehabilitation

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Abstract—It is a well known fact that robotic-assisted gait rehabilitation can not only reduce labor intensity for therapists, but also potentially lead better functional outcomes than conventional therapy. Though current treadmill based devices are rather limited in their pelvic motions and can allow only one forward plane of motion. In this study, we present a novel robotic walking platform with an omni-directional mobile platform, an intuitive human-machine interface, an active body weight support (BWS) unit, and wearable motion capture system. The omni-directional platform coupled with BWS system allows unrestricted natural pelvic and trunk motion while walking. One can interacts with the system via an admittance control system based on a six degree-of-freedoms (DoFs) force/torque (FT) sensor. The admittance controller with virtual mass and damper parameters enables a natural and intuitive interface. In this study, we compared the velocities of the center of mass (CoM) of forward-backward, lateral and rotational movements with and without the device. Confirming the feasibility of the device, the result has shown that the forward-backward velocity was reduced by wearing the device while the other velocity profiles with and without the device showed no meaningful changes. Unlike treadmill based devices, the developed device turned out to support any locomotion in any direction while walking. This device can have potential to improve the mobility of the neurologically challenged by providing natural gait patterns, and these findings call attention to the possible further studies on extensive human sensorimotor learning system.

Keywords—robotic device; gait rehabilitation; admittance control; omni-directional mobility; body weight support

I. INTRODUCTION

Neurological impairments after stroke have tendencies of causing hemiparesis or partial paralysis which can deprive patients of ability to perform activities of daily living (ADL) like walking. Stroke survivors typically show significantly reduced gait speed, shortened step length and loss of balance in their gait patterns and often experience falls [1]. With the proven fact that repetitive and persistent stimulation could restore and reorganize defective motor functions caused by neurological disorders, strong need for therapeutic interventions has been arisen [2]. By reducing biomechanical inefficiency and improving unstable walking patterns through properly intervened process, independent walking and ADL could be re-achieved [3, 4]. Satisfactory rehabilitation outcome is strongly associated with high degree of goal oriented motivation and tasks [5]. Appropriate sensory inputs through proper instruction, explanation, feedback and participation are essential to promote learning skills of the neurologically challenged [6, 7]. Although non-ambulatory hemiparetic patients were able to improve their walking ability through the conventional rehabilitation processes [8, 9], the conventional rehabilitation procedures require excessive laboring effort of therapists in assisting walking of severely affected subjects, setting the paretic limb and controlling trunk movements. As the therapists often have to support the body-weight of the patient, the quality of the gait rehabilitation is limited due to physical exhaustion of the therapist. Therefore the availability, duration, and frequency of training sessions are often limited. Moreover, the walking performance of patients is not able to be quantified through the conventional rehabilitation which makes training programs rely on therapists’ qualitative judgment. Consequently, trial-and-error approaches were called in search of more appropriate rehabilitative processes.

Robotic assisted gait rehabilitation devices have begun to attract attention as an alternative of the conventional gait rehabilitation since they have facilitated or replaced the physical training effort of the therapists and have allowed more intensive and repetitive motions and increase training motivation by providing objectives and quantifiable measures of subject performance or by using interactive biofeedback [10]. Treadmill based devices are the most prevalent robotic rehabilitation method and Lokomat(Hocoma AG) is the most clinically tested system and one of the firsts of its type [11], and LokoHelp(LokoHelp Group), ALEX, LOPES, RGR also...
correspond to the this type of devices. However, this type of system provides only forward movement with pre-determined path. Constraining the patients to a fixed platform and a predetermined gait pattern is not natural and leads to less satisfactory functional outcomes. Additionally, the lack of cycle-to-cycle variation in the kinematics and sensorimotor feedback may cause habituation to sensory input, and reduce sensory responses to weight-bearing locomotion and ultimately impair motor learning [12]. In addition, the over-head harness body weight support(BWS) system allows only unrestricted movement in the vertical direction but restricts pelvic rotation, pelvic lateral movement which may be useful for balancing and generating desired gait patterns [13]. Pelvis allows force transfers from the lower extremities to the trunk, contributing to the forward progression of the body and to trunk vertical support [14]. The pelvic also moves laterally shifting body weight to each limb to maintain balance. These motions are important for energy efficient walking as well. Veneman claimed that the fixation of the pelvis severely affects gait dynamics by shortening step width and reducing coronal trunk rotation, and by lengthening step length and sagittal trunk rotation [15]. Therefore, the fixation of pelvis should be avoided if any natural gait is possible during the gait rehabilitation. Additionally, there still lies ambiguity on the assumption that walking on a treadmill could represent an actual gait on the over-ground in terms of body mass shifting, body mass acceleration and sensorimotor feedback such as proprioceptive input. Walking on treadmill indicated significantly greater cadence, smaller stride length and stride time as well as reductions in the majority of joint angles, moments, powers and pelvic rotation excursion compared with over-ground walking [16, 17]. Most of all, the over-ground walking is considered as the most natural gait pattern with actual foot contact, so the over-ground walking rehabilitation devices are recommended for increasing gait performance as well as having natural gait patterns.

Several over-ground rehabilitation devices were developed and commercialized. KineAssist(Kinea Design LLC), WalkTrainer(Swortec SA), and NaTUre-gait(Univ. Nanyang Tech) are widely used as over-ground walking devices [18]. The KineAssist is a mobile gait training robotic system with complex actuated trunk and pelvic support mechanisms. It enables more realistic over-ground training and allows patients to move the device under their own control rather than the device move the patients through predetermined movement path.

However it does not have biofeedback of the gait parameters such as kinematics and muscle activities, so that it cannot quantify the effectiveness of rehabilitation during the intervention though.

It’s no wonder that there has been growing needs to develop more affordable and effective neuro-rehabilitation robotic system which can benefit the broad spectrum of patients. The novel gait training system should not only be able to relieve the therapists’ mechanical work, but also be able to move to any direction under the users’ own control to avoid the inhibition of sensorimotor input. The BWS system should be able to provide comfortable unloading, and BWS combined with omni-directional mobility should be able to support natural pelvic motion while walking. In addition, the wearable motion capture system should be able to sense joint position and/or muscle activation, and provide assistance only as much as needed during defined periods of the gait cycle. The wearable motion capture system will provide therapists with biofeedback to diagnose and assess the motor deficiency and to evaluate the efficacy of the therapy.

II. DESIGN DESCRIPTION

The overall system has been developed and the prototype of the device was shown in Fig.1. This system includes an omni-directional platform, the human-machine interface with the FT sensor, and active BWS system, and EMG and IMU sensor based biofeedback system. With this system, the patients can move in any direction without being constrained in one plane of movements, and the body weight can be supported by the active BWS system so that the therapist can facilitate the gait rehabilitation more effectively and practically with less laboring efforts. The specific description will be followed below.

A. Omni-directional Mobile Platform

The motivation for using the omni-directional mobile platform is from the fundamental biomechanics principles. The pelvic forward-backward, side-to-side (lateral), rotational, and vertical movements are strategically adapted during normal walking. Moreover, the pelvic rotation, and lateral movement are the major factors of the determinants of gait and minimize the energy consumption during walking by smoothing out the vertical displacement of CoM [19]. Constraining these motions leads to abnormal muscle activation and gait kinematics causing abnormal walking patterns. Therefore, there are strong needs to support pelvic motion without being constrained in any direction of movement since the patients have to practice normal and realistic gait in a natural way to be recovered from motor deflection. The concept for omni-directional platform can help the patients to practice gait in the proper and natural manner. The design were proposed by Yu using an active split offset castor(ASOC) unit consisted of two coaxial conventional wheels [20]. This system has a number of advantages which include use of simple structure, high energy efficiency, and robust mobility on uneven terrain. We have applied this concept to our device, and it is believed that the over-ground walking with omni-directional mobility could perform natural locomotion in environments congested with static and/or dynamic obstacles and narrow aisles.

Fig. 1. Proposed Design of the Gait Rehabilitation Device
With this design, the 3 DoFs of pelvic motions can be supported; the forward-backward, side-to-side (lateral) and rotational movement (Fig. 2). Consider a platform that is carried by active split offset castors units that move on a plane, the central point of the platform \( V_{cx}, V_{cy} \), and its' angular velocity, \( \Omega \) can be defined by velocities of each wheels, \( V_{11}, V_{12}, V_{21}, \) and \( V_{22} \) (Fig. 2). Therefore, the three DoFs of central point can be controlled by the velocities of each wheel. The specific equations were presented in [20].

B. Body Weight Support System

Biomechanical demands of a walking task can be controlled by modulating walking speed and supporting the load caused by body weight. The neurological damages on brain motor function lead the patients to suffer from the loss of BWS ability with variety of motor defections [21]. In this sense, BWS system has come to play an important role in the gait rehabilitation, particularly for individuals who have suffered a stroke or spinal cord injury. Therefore, the unloading certain percentage of the body weight allows neurologically challenged patients with weak muscles to practice gait training more efficiently. In this study, we proposed an active BWS system that provides active support of the body weight to the desired percentage and move the pelvis and trunk vertically to perform the natural like gait pattern. The users’ body weight can be actively obtained via the vertical axis of the FT sensor, and the constant unloading weight can be comfortably imposed by linear actuator and pelvic harness via PID controller during dynamic walking (Fig.3).

C. Human-machine interface

The interface between the device and the user is pelvic support harness combined with the six DoFs of FT sensor. The interface is critical for the robotic assisted gait devices. Given that the robotic rehabilitation devices always interact with the user, the design has to take into account the user’s gait characteristics. The user generally has physical contact with the harness system for support. A key requirement is that the interface should be able to adapt the users’ intention for different levels of physical and mental functionality. It also should provide a natural feeling for the user and be easy for the user to learn and to use. In case the user and device have direct physical interaction at the CoM of the body which is the pelvis, the force and torque of the CoM can be assumed to represent the walking movement. This force and torque signals contain the user’s intention as well as gait information of the user. However, using force signals directly to generate motion can result in unstable motion due to the fluctuation of the signals. This study suggested an admittance control method which is consisted of virtual mass and damper parameters to provide natural and intuitive interaction between user and device [22]. As can be seen in the Fig 4, the force and torque of the CoM of the body is translated through pelvic support harness and detected by force/torque sensor. The detected force and torque were translated into velocities through the admittance control system. The mass-damper model acts as a low pass filter so that the high frequency noise due to shock and vibration from the system can be reduced. Damping parameter will return output of the FT signal to equilibrium as quickly as possible without oscillating. The user interacts with the system and the one only feel this virtual model, thus the user will have a different feel of the system by tuning the model parameters.

With \( F \) as the user input force in the respective directions (forward-backward, lateral and rotational movement) and \( V \) as the system response in the same direction, the transfer function of the system is defined in (1).

\[
G(s) = \frac{V(s)}{F(s)} = \frac{1}{Ms + B}
\]

where \( M \) is the mass, and \( B \) is the damping parameter. The time response of the system for a step input is (2).

\[
v(t) = \frac{F}{B}(1 - e^{-\frac{t}{\tau}})
\]

where \( \tau \) is the time constant defined by \( \tau = M / B \). A linear 3 DoFs mass-damper model for the over-ground device system is defined in (3).

\[
\begin{bmatrix}
M_{x} & 0 & 0 \\
0 & M_{y} & 0 \\
0 & 0 & J_{z}
\end{bmatrix}
\begin{bmatrix}
\dot{V}_{x} \\
\dot{V}_{y} \\
\dot{\omega}
\end{bmatrix}
+
\begin{bmatrix}
B_{x} & 0 & 0 \\
0 & B_{y} & 0 \\
0 & 0 & B_{z}
\end{bmatrix}
\begin{bmatrix}
V_{x} \\
V_{y} \\
\omega
\end{bmatrix}
=
\begin{bmatrix}
F_{x} \\
F_{y} \\
M_{z}
\end{bmatrix}
\]

where \( M_{x}, M_{y} \) and \( B_{x}, B_{y} \) are mass and damper and \( J_{z} \) is moment of inertia and \( B_{z} \) is damping in vertical axis.

![Fig. 3. The Active Body Weight Support System](image-url)
B. Gait Experiment with the Device

A. Experiment without the Device

Young subjects (age: 27.25 years, height: 172.25 cm, and weight: 62.63 kg) were participated in this study. All subjects were instructed to walk naturally with their preferred speed on the 10m distance walkway in the gait lab. 4 markers were attached on the landmarks of the pelvis; left and right anterior-superior iliac spine, and left and right posterior-superior iliac spine. 8 high speed optical cameras (Vicon, Oxford, UK) captured the 3D position of the reflective markers with sampling rate of 100Hz. All subjects were instructed to walk more than 3 successful trials. The raw kinematic data were pre-processed through the customized software (Nexus, Oxford, UK) provided by Vicon motion capture system. The 3D marker information were low-pass filtered using a 4th order Butterworth filter with cutoff frequency of 6Hz and this pre-processed data were extracted into Matlab program to calculate positions of the CoM such as forward-backward, lateral, and rotational movements during gait. The velocities of CoM were obtained by differentiating the positions with respect to time.

B. Gait Experiment with the Device

A subject who has age of 29 years, height of 171.5 cm, and weight of 72 kg was participated in this experiment. The subject was asked to wear harness and be tightly attached to the device system. We instructed the subject to walk on 10 m walkway with preferred gait speed. The mass and damper parameters have been selected as aforementioned. The detected force and torque of the CoM were translated into velocities through the admittance control model. The forward-backward, lateral, and rotational velocities obtained from admittance control were analyzed in this study.

C. Results

The velocities from 19 strides without device, and 3 strides with the device were analyzed and shown in Fig 5. The results of the forward-backward velocity without the device were presented in Fig. 5(a). The forward-backward velocity without the device was 1.2 m/s at the initial contact (IC) and reduced to 0.9 m/s at the loading response (LR) phase. It was increased again during mid-stance (MS) to terminal stance (TS) when the opposite limb is forwarding. In sequence, the velocity was decreased during double support phase. Therefore, the velocity of forward movement showed W shape during gait showing the mean velocity around 1.0 m/s. The device did not alter the velocity profile of CoM but the mean velocity was relatively reduced to around 0.5 m/s. The results of the lateral velocity were presented in Fig. 5(b). The lateral velocity was -0.15 m/s at the IC and increased to 0.15 m/s at the TS phase. It was decreased again during swing phase. There was no meaningful change in lateral velocity profiles between with and without the device showing that the device can support forward-backward and lateral movements during the gait. The rotational movement also could be achieved by the device as can be seen in the Fig. 5(c). The excursion of rotational velocity profile had no meaningful changes compared with the profile of without the device.

IV. Discussion and Conclusion

This study has developed and testified a novel robotic over-ground gait rehabilitation device for stroke survivals. The developed device has the over-ground walking platform with omni-directional mobility, human machine interface with pelvic harness and FT sensor with admittance control method, and active body weight support system. These functions allow unrestricted pelvic motion during rehabilitation, and unload the body weight with providing stability during rehabilitation.

The omni-directional mobility overcome one of the major limitation of treadmill based rehabilitation device which the movements are constrained only in forward direction. Using this omni-directional mobility, a user can instantaneously move in any direction and any configuration. Especially, the developed device can support forward-backward and lateral movement as well as rotational movement during walking. Stoke survivals tend to overuse or exaggerate pelvic movements to compensate the abnormal gait pattern and avoid falling down during swing phase. Previous studies have proven that stroke survivals have increased anterior pelvic tilt, dropped contra-lateral pelvic in coronal plane and retracted side of pelvic in transversal plane [23]. In addition, Karen and his colleagues claimed that the pelvic lateral displacement was significantly increased for the stroke survivals to maintain deteriorated balance ability during walking [24]. Abnormal pelvic movements have triggered a strong need to support or to constrain the pelvic motion by putting the pelvic movement into the normal range of motion of gait.
In other words, the rehabilitation devices should be able to support the lateral movement but at the same time constrain pelvic motions in case the lateral displacement is highly exaggerated. The decision can be made through the information detected by FT sensor embedded on the pelvis. In addition, this human-machine interface system is less analytical and the users can actively interact with this system without constrained in pre-determined path and autonomous control, so that the device can be under the users’ own control. It will be expected to potentially increase their motivation of gait rehabilitation as well. Therefore, it is important to capture the users’ intention and translate useful information into the device, so that the omni-directional mobility can be acquired in accordance with the users’ intention. In this sense, this study experimentally investigated proper virtual mass and damper parameters of the admittance control system to evaluate the performance of the developed device. Although the forward-backward gait velocity was relatively reduce with the developed device, the other velocity profiles of with and without the developed device showed no meaningful changes confirming the feasibility of the device. However, when both the mass and damping were relatively high (\( M = 12 \text{ kg} \) and \( B = 140 \text{ Ns/m} \)), the device was too heavy to carry and the mean gait velocity was significantly reduced (0.3 m/s). On the contrary, for models with small mass (8 kg) and damping (80 Ns/m), the motion was extremely oscillatory because the response was too sensitive. However, when we selected 10 kg mass and 120 Ns/m damping, system showed optimized movements for a normal gait. The pelvic support body weight unloading system was mounted in this device to provide comfortable off-loading and natural up-down movement in gait rehabilitation. This unloading system can support the pelvic up-down movement, so that 4 DoFs of pelvic motions can be supported by this device.

Wearable motion capture systems will be integrated in the future. Current gait kinematics and muscle activation patterns information can only be obtained using expensive optical system and EMG sensors in the gait lab. Normally, gait test is done only before and after the rehabilitation therapy due to the complexity and cost. Since constant biofeedback during the rehabilitation process is critical to provide proper instruction of intervention, the real-time IMU and EMG sensors have to be integrated to this system to measure gait kinematics and muscle activation during or after the rehabilitation. Therefore, this study can call attention to the possible further studies on extensive human sensorimotor learning system and the developed device can benefit a large group of patients with improved outcome at reduced cost.

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