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The Efficacy of State of the Art Overground Gait Rehabilitation Robotics: A Bird's Eye View

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Abstract

To date, rehabilitation robotics has come a long way effectively aiding the rehabilitation process of the patients suffering from paraplegia or hemiplegia due to spinal cord injury (SCI) or stroke respectively, through partial or even full functional recovery of the affected limb. The increased therapeutic outcome primarily results from a combination of increased patient independence and as well as reduced physical burden on the therapist. Especially for the case of gait rehabilitation following SCI or stroke, the rehab robots have the potential to significantly increase the independence of the patient during the rehabilitation process without the patient's safety being compromised. An intensive gait-oriented rehabilitation therapy is often effective irrespective of the type of rehabilitation paradigm. However, eventually overground gait training, in comparison with body-weight supported treadmill training (BWSTT), has the potential of higher therapeutic outcome due its associated biomechanics being very close to that of the natural gait. Recognizing the apparent superiority of the overground gait training paradigms, a through literature survey on all the major overground robotic gait rehabilitation approaches was carried out and is presented in this paper. The survey includes an in-depth comparative study amongst these robotic approaches in terms of gait rehabilitation efficacy.

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Keywords: CP, SCI, BWS, Exoskeleton, Locomotion, Paralysis, Physical therapy, Rehabilitation robotics, Treadmill, Overground, Gait training.

1. Introduction

Spinal cord injuries (SCIs), stroke and even cardiovascular disease (CVD) often lead to gait disability leading to the condition of paraplegia or hemiplegia [1]. Such disability often causes distress to the daily life of the affected person and his or her family in various ways. Consequently, patients with disability may face with difficulties in pursuing their normal life. Therefore, it is vital for them to go through rehabilitation training at a stage as early as possible, as there is always a chance that they may regain the ability of some functional movements and enhance the quality of their life [2].

In recent years, there has been an increasing amount of literature in the field of rehabilitation robotics. There are many types of rehabilitation robots that have been developed just relatively recently, of which, the gait rehabilitation robots constitutes a large portion. The gait rehabilitation robots can be divided into two categories, viz. body-weight supported treadmill training (BWSTT) and overground gait training. BWSTT is usually an obvious choice for the patients with acute conditions due to the severity of the condition demanding stringent requirement for safety, which is usually relatively easily ensured in BWSTT. After a while, an overground training is needed in order to have a better walking education. Subjects with sub-acute motor incomplete SCI reached a higher level of independent walking after overground training, compared to BSWTT. Furthermore, BWSTT is said to be non-ecological training as patients cannot move freely and will only have to perform their gait re-education at a controlled speed of the treadmill. Besides, patients are not be able to walk independently as BWSTT is usually delivers fixed gate pattern.

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BWSTT does not cater for individual patient's gait pattern and requires as all of them undergo the same gait training [3]. These drawbacks has led to the alternative path of gait re-education, i.e. overground training.

A brief survey of the existing robotic overground gait training solutions is conducted in this work. The primary objective of the survey is to present the reader with a comparative evaluation of the various robotic solutions in terms of therapeutic outcome and other relevant features. Depending on the way the patient is secured within the device, the overground rehabilitation robots are first classified into two major categories, viz. with BWS and with exoskeletal support. An in-depth comparative evaluation amongst the existing approaches is discussed in the Discussions Section followed by Concluding Remarks.

2. Robotic Overground Gait Training Modalities

The overground gait training robots are, in essence, mobile robot platforms specially designed and equipped to facilitate the gait training. Patients are usually secured with body-weight support system (BWS), attached firmly to the robot frame. The approach results in a much reduction in the physical constraints on the patients, thereby allowing them to move freely by having the mobile robot simply following them. The approach has the potential to stimulate the re-learning of the functional motor pattern of overground walking in an optimal manner while increasing patient's motivation, which constitutes a crucial element in the subject's re-education [4]. With a view to combine benefits of the orthotic support (e.g. increased safety, reduced joint degrees-of-freedom etc.), that might be useful for certain patient group, more complex exoskeletons have also been used in conjunction with the over-ground gait training.

2.1. Overground Gait Training Robots With Body-Weight Support

The overground gait training robots with BWS constitutes major part of the recent development in rehabilitation robotics. In this approach, the patient's safety is fully ensured using an overhead harness, i.e. the BWS [5]. An appraisal of the recent developments within this modality of the rehab robots is carried out in this subsection.

2.1.1. SoloWalk

The SoloWalk [6] (Figure 1) is one of the BWS rehabilitation robots that is aimed towards helping individuals suffering from spastic quadriplegia to cerebral palsy (CP). SoloWalk is powered by geared DC motors for its omnidirectional wheels while a harness system, attached to a pair of underarm bars, for the BWS is designed to lift the patients and prevent them from falling. Between the frame and the harness is a force sensor that measures interaction force generated by the patient's intention of movement. The torso harness is design to reduce the pressure occurring at the shoulder while the patient is suspended from the device.

Figure 1: SoloWalk [5]

The SoloWalk is supposed to largely reduce the therapist's physical workload. Users are supposed to be able to walk freely with the assistance of the device while the robot simply follows the patient's motion. Therapists monitor the therapy and a remote control is used to initiate patient's movement or therapist can also follows patient desired walking path.

2.1.2. Andago

The assistive rehabilitation robot called Andago (Figure 2) has recently been commercialized by a Swiss company Hocoma [7]. Andago is targeted towards helping patients having neurological damage such as strokes and SCIs as they need further assistance and therapy.

Figure 2: Andago [6]

Patient is secured with the BWS system attached firmly overhead to the mobile robot base. The man-machine interaction during therapy session leads to a condition where either therapist or the robot itself can change the condition by altering control parameters through the progress [8]. This device essentially equips the patient with an independent gait assistance. It is certainly a state of the art implementation of robotics into clinical practice.

In a case study, a female stroke patient producing initiated step for only 50% during her first four therapy session [9]. Following three weeks, the clinical observation validates that she has able to walk independently and has pass through her difficulties and ailments with success.

2.1.3. KineAssist

The KineAssist (Figure 3) consists of an omnidirectional base, harness joining at the pelvic, force-torque (FT) sensor that acts for the admittance controller, and an active BWS [10]. The robot provides stability of the unloading body-weight and allows the pelvic movement without any restriction. The mobile base is omnidirectional; equipped with forward-backward, lateral as well as rotational movement during its operation. Stroke patients usually overuse their pelvic movements and tend to have abnormal walking behavior as well as to avoid them from falling down.

Figure 3: KineAssist [11]

The development of this device has met the clinician's need as it involves an intense, specific locomotion system and walking training with BWS. Hence, provides patients with a lot of benefits that can ease clinician's work [11]. To facilitate an effective rehabilitation process, the KineAssist implements seven modes of operation that can be used throughout the rehabilitation therapy.

2.1.4. WHERE-I

WHERE-I (Figure 4) is a mobile manipulator that includes an electrically operated BWS mechanism, a robotic arm, two linear potentiometers and a safety system with an ultrasonic sensor which acts as a safety sensor [12]. To make the user/patient comfortable, the whole system is designed to be very low which is below the shoulder level. Using two potentiometer, patient's intention is easily calculated, which is then used to steer the base. This system using an electrical BWS mechanism as its support system. In order to have a stable control algorithm the RBF neural network is used for the mobile manipulator [13].

Figure 4: WHERE-I [12]

The amount of the emptied weight, aka the percent BWS, can be controlled by altering stature of the controller. Every sensor measures the body development from every side. Their signs are utilized to derive the strolling speed and the objective course of the user. WHERE-I has a distinction between the positions of influenced and unaffected appendage of almost 5% when 40% of the body weight is emptied.

2.1.5. WHERE-II

WHERE-II (Figure 5) can bolster the dispersed control plan on each pneumatic actuator. Henceforth, the more compelling recovery execution is relied upon contrasted with what might be acquired by a concentrated control plan. WHERE-II has about a 2% contrast and its relearning walk example is more like an ordinary step design contrasted with that of WHERE-I [12].

The most critical component in this framework is the individual BWS system on the left and right sides of the user. The stride instances of the left and right sides are, to some degree, diverse and are dictated by the nature of the disability. The BWS consists of a powerful pneumatic actuator that that enables a steady constrain body-weight emptying.

The framework is configured in such a way that the rotational hub of the human body is situated hanging in the balance between the driving wheels. This enables the framework to acknowledge three-level of-opportunity movement helpfully. Then again, the WHERE-II framework in crisis circumstances does not take any forward development charges and subsequently, security is guaranteed.

Figure 5: WHERE-II [12]

2.2. Overground Gait Training Robots with Exoskeletal Support

In addition to being benefitted from the attractive features of orthoses/exoskeletons, this category of the overground gait training robots makes use of the orthotic or exoskeletal support (instead of BWS), to enhance patient safety. These orthoses permit contact at several main parts of the lower limb and hence can control or guide different joints or segments of the limb. Some of the exoskeleton robots are categorized as *performance-augmenting exoskeleton* [14]. These types of robots are wearable and assist patients with their daily routine. Exoskeleton is much complex compared to the over-ground mobile robots. In order for the exoskeleton to be functional, they are designed with keeping user friendliness, mobility and the most importantly safety of the patient as the top priorities.

Figure 6: WalkTrainer [19]

2.2.1. WalkTrainer

The WalkTrainer (Figure 6) is a mobile device allowing overground gait training with physiological locomotion for paralysed patients. The device is composed of a walking frame, pelvic orthosis, a body weight support, two leg orthoses and a real-time controlled electro-stimulation. The device actively assists patients in their movements by correcting their manner of moving and by controlling their equilibrium [15]. The tackle based BWS framework is connected to the casing. The vertical DOF is controlled by two engines (static and element emptying). The static engine controls the preload of a spring (0%–100% of the body weight) and the second engine modifies progressively the vertical removals amid stride. All other DOF of the BWS framework are sans let, either by a latent system or basically by the associating straps [16].

2.2.2. NaTUre-gaits

The NaTUre-gaits (Figure 7), or Natural Tunable Rehabilitation Gait framework, is developed taking into couple of principles into account [17], viz. (a) to accomplish a moderately typical strolling motion, the hip and knee flexion are vital, and (b) in the event

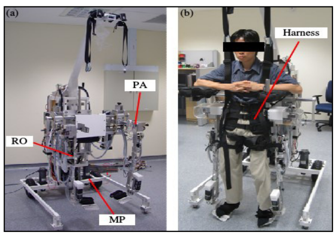

Figure 7: NaTUre-gaits [17]

that the forward impetus is to be given by foot alone (not by abdominal area with grasp or other strolling helps), the plantar flexion of the lower leg is required.

The overground strolling requires discontinuous ground contact. Amid the get in touch with, it is important to give smooth effect between the foot and the ground at introductory heel contact. After this, foot-ground contact conditions are expected to keep out the foot dragging inside the entire position stage. Moreover, prerequisites of single and twofold foot position stages are given when coordinate both the privilege and left foot. At last, foot leeway prerequisite are given in the swing stage. These are the issues particularly vital to subjects over a course of restoration procedure. In the event that the movement catch test information to be utilized for the direction, the joint edges are scaled up or down to meet those obliges. For instance, one basic approach to stay away from ground sway issue is to expand the hip and knee joint, in order to abbreviate the vertical length at the position phase [18].

2.2.3. H2

H2 is a light weight lower appendage exoskeleton intended for rehabilitation, mostly designed for stroke patients taking after neurological put-down. It can also be utilized for stride walk remuneration as a part of patients who have loss of motion of the lower appendages taking after spinal rope wounds. It is considered for overground stride preparing in a clinical situation as a respective wearable gadget with six degrees of freedom (DoF), in which hip, knee and lower leg are controlled joints. The exoskeleton configuration ought to be ergonomic, agreeable, and lightweight, with a solid structure, versatile to various clients and because of security.

Figure 8: H2 [23]

Since different fragments of the gadget can be utilized independently, H2 offers promising method for utilizing one-sided Hip-Knee-Ankle, Knee-Ankle or just Ankle forms of the gadget, redoing treatment conventions to every patient's particular needs. H2 is implement to correct patient's gait pattern as it helps the paretic leg to be fully utilize by the patients, with the same bodyweight amount shifted on both legs. This behavior will prevent patients from having shorter foot stance of the paretic leg. This will enhance the gait performance and recovery process will become smoother.

H2 is equipped with mobile application. Patients also give a positive feedback towards using this device during therapy session. This device is user friendly and really helps a lot in knee flexion. [19].

2.2.4. ReWalk

This exoskeleton robot is a wearable robot which can be used to assist paralyzed patient to get their gait re-education (Figure 9) [20]. ReWalk is a device that offers patient to move by manipulating their own centre of gravity. It helps patient to perform routine ambulatory and regain their normal gait pattern.

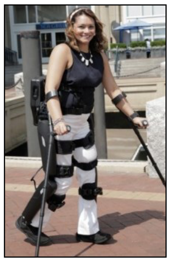

Figure 9: ReWalk [16]

The robot comes with a battery that is worn by the patient to move from one place to another. Crutches are used as additional assistance for the patient. It is equipped with the sensor at the torso level to sense the posture of the patient and thus command the robot to switch the mode appropriate for the posture. In addition to level walking ReWalk can also assist in climbing stairs. Besides, there are four additional modes of operation for the device, i.e. sit-stand, stand-sit, up steps, and down strides.

2.2.5. HAL

The Hybrid Assistive Limb or HAL is the first ever cyborg-type robot that has been invented to support human body. HAL is an assistive gadget that can mimic motor organs and contribute in helping and improving human movement. It is designed specifically for administrator's lower appendage during its early invention and has eventually been into a wider scope. Each version of the HAL comes with improved features facilitating better assistance.

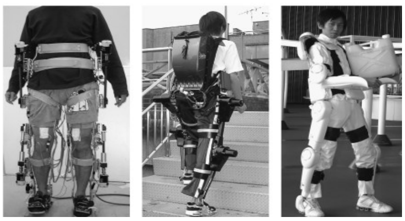

Figure 10: (a) HAL-1, (b) HAL-3 and (c) HAL-5 [21]

HAL is designed to pick up cerebral nerve signals and send it out to the muscle to construct a new loop of network. This robot can regenerate the nervous and musculoskeletal of paraplegia to move their leg again. HAL is mainly used in rehabilitation focusing on disable and elderly people. However, the invention can also be used for lifting heavy loads, entertainment and to support workers involved in demanding jobs such as rescuing people, and in construction field.

HAL-1, using DC engines and ball screws, was produced as the main model of HAL and it upgraded the wearer's strolling capacity by intensifying the wearer's own joint torque. Subsequent to building up a few models, HAL-3 was created towards more appropriate framework to be utilized as a part of genuine everyday life. These robot suits have a force unit on every hip and knee joint, and they bolster utilitarian movements of the lower appendages with various joints at the same time. After that, HAL-5, was produced for entire body support. It helps human movements including the wearer's abdominal area exercises, for example, conveying substantial burdens [22].

3. Discussion

3.1. Overground Vs Exoskeleton

A comparison between various features pertaining to overground gait training and exoskeleton based gait training is presented in Table 1, while Table 2 provides a summary of the features available in various solutions by various groups within the same two modalities.

Table 1: Comparison between overground and exoskeleton training

Overground	Exoskeleton
A comprehensive system	Much complex system
Using BWS support	Using hydraulic cylinder to power hip
Allows normal walking behaviour	Corrects leg movement
No inertial properties of the leg changes	Changes the inertial properties of the leg
Patients in severe injury to minor ailments	Patients must have healthy upper body
Patients are secure with harness	Will collapse if do not have enough muscle force
Cannot use to climb stairs	Can be used to climb stairs

Table 2: Summary of BWS and exoskeleton

Variables	Body Weight Support Overground Training (BWSOGT) Design					Exoskeleton Design				
	SoloWalk	Andago	KineAssist	WHERE-I	WHERE-II	Walk-Trainer	NaTUre-gaits	H2	ReWalk	HAL
Mechanism	Omnidirectional	Omni-directinal	Omni-directional	Steerable wheel	Steerable wheel	Sagittal & transverse plane	Sagittal plane	Sagittal plane	Sagittal plane	Sagittal plane
Fall prevention mechanism	√	√	√	√	√	√	√	√	√	√
Mobile base	√	√	√	√	√	√	√	X	X	X
Application	CP	SCI	Stroke	Elderly and disable people		SCI	SCI	Stroke	Paralyzed	Ageing or physical disabilities

3.2. Summary of reviewed rehabilitation robots

All of the robotic rehabilitation have their own part that contribute towards the enhancement of patient’s performance. Their contribution have led to a better life. Either BWSOGT or exoskeleton rehabilitation robotics both have desired aim and target that are focusing on patient safety and health. These robotic devices have proven that they have made the gait re-education become better from time to time. With the collaboration between clinician and engineers patient's need can be fulfilled.

All of the BWSOGT designed robots are equipped with fall prevention system where sensors are placed on desired place to ensure patient's safety as they are unstable in their walking behavior. BWSOGT is the element that supports patients using a harness either hanging harness or a pelvic harness.

The exoskeleton is design to help people with disability as well as ageing. Senior citizens may have self-ability that is been diminishing from time to time. By using the exoskeleton device, it may help patient with their physical ability. Some heavy task may also be ease with the help of exoskeleton device. This has proven that with a wearable exoskeleton many tasks can be done much easier.

4. CONCLUDING REMARKS

The current survey has made efforts to cover (in terms of their therapeutic outcome or efficacy) all the robotic overground gait training solutions that has been reported so far in standard literatures or even other media. Even though there has been a considerable amount of advancement achieved so far, it simply fair to conclude that the contemporary technology is still in its infancy and hence, there is still a long way to go in terms of bringing out a high degree of efficacy from the developments along this robotic therapeutic modality. Most importantly, the efficacy of any instance of such robotic modality is supposed to be validated by rather lengthy clinical trial, which seems to be still lacking with all the solutions so far. From engineering perspective, it is apparent there is still enormous room to make progress in terms of mechanical design, electromechanical and mechatronic design, and control systems; all of which potentially contributes towards a higher degree of efficacy of such therapeutic solution.

Considering the dire humanitarian need of such highly expensive robotic device around the world, there is still a lot of progress to be made in terms of multidisciplinary research to largely increase the availability of such technology.

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