Robot-Assisted Gait Rehabilitation: From Exoskeletons to Gait Systems

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***Abstract*—In recent years, robotic technologies have been applied to build assistive robots, such as robotic exoskeletons and rehabilitation robots. Based on the clinical considerations, new trends of rehabilitation, like over-ground rehabilitation robots and home-based mobile rehabilitation robots, have emerged by combining both the knowledge from the exoskeleton and the rehabilitation robots. In this article, we review some of the important assistive and rehabilitation robots, in terms of their hardware, actuation, sensory and controls systems. The paper ends with a discussion on the future trends of the rehabilitation robots, especially on clinical-based considerations.**

Keywords-exoskeleton; rehabilitation; clinical; robots; gait

I. INTRODUCTION

Robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into human environments and vigorously engaged in its new challenges. Interacting, assisting, serving, and exploring with humans, the emerging robots will increasingly touch mankind and impact on their lives.

One of the recent developments in robotics research is concerned with the design of robots for the mechanization of physical therapy, referred to as robotic rehabilitation. These robots replace the physical training efforts of a therapist, which in many cases proved to be laborious and repetitive. Thus, in the general clinical setting of these robotic systems, a therapist shall still be responsible for the non-physical interaction and observation of the patient by maintaining a supervisory role of the training, while the robot carries out the actual physical interaction with the patient. Several groups are currently developing robots for “arm training,” [1-4] as well as for “gait training” [5-8], while the latter is the focus of this article.

From a robotic perspective, wearable robots are mechatronic systems worn by a subject in such a way that the physical interface permits a direct transfer of mechanical power and exchange of information. A wearable robot is designed to match the shape and functions of the human body. Initially, the primary applications of these robotic mechanisms were tele-operation and power amplification. Recent years, the works on exoskeletons have been extended and applied to rehabilitation and assistive devices for the disabled and the elderly. One important and specific feature of wearable robotics is the intrinsic interactions between human and robot.

Robotic systems for assistance and rehabilitation focus on providing missing movements and sensing to the user, providing a safer environment that make regaining movement-related function easier and faster. Eventually, robotic rehabilitation not only provides consistent and efficient therapy without exhaustion, it also has the potential to enhance the therapy beyond the abilities of the practitioner.

Nevertheless, the rehabilitation robotics or assistive robotics is the clinical-based engineering works. The ultimate goal is to transfer the engineering robotics technology into hospital or clinics use. Before we discuss what we can offer from engineering point of view, we must know what our “customers”' needs are. As a result a, the article begins with an introduction of the clinical point of view on rehabilitations robotics. Then we move on to a summary of some of the most widely known exoskeletons and assistive gait systems developed by various research institutes to addressing current technologies and design challenges. The robots are presented according to three categories: performance-augmenting exoskeletons, treadmill-based rehabilitation robots, and over-ground rehabilitation robots .Finally, the research experience of transferring the works on performance-augmenting exoskeletons and treadmill-based rehabilitation robots to the over-ground rehabilitation robots *NaTUre-gaits* (Natural and Tunable Rehabilitation Gait System) developed by the NTU (Nanyang Technological University) team in collaboration with TTSH (Tan Tock Seng Hospital).

II. CLINICAL CONSIDERATIONS

Based on recent years of experience working in the rehabilitation robot in collaboration with clinicians, we will discuss the future of the rehabilitation robot from the combined view of clinicians and engineers. The article will investigate the issue form three aspects as proposed in [9]: firstly, the goal of the rehabilitation robot; secondly, the barrier for engineering robot to be accepted by clinicians; lastly, how robotic rehabilitation would look like in the future.

The rehabilitation robots are suggested to perform the tasks which are difficult, laborious, or impossible for the therapist to do. Taking over-ground walking training for example, it requires at least three therapists to assist the patient to walk. At the same time, the therapies posture is not ergonomic and will resulted in fatigue easily. In addition, it is not safe for the patient as well, since support by the therapist might not holding firm if the therapist is exhausted. The walking motion during the rehabilitation is created totally based on therapists' experience, which is different from one therapist to another. Overall, the development of the rehabilitation robots should be "need to have" instead of "nice to have".

Although researches in robotic rehabilitation are intensive, however there are few robots are accepted and deployed for clinical use. It is not due to they cannot provide the function but simply hard and troublesome to use. Imaging if a machine took you half an hour to set up, it is not going to be accepted by the clinical communities, partially due to limited time a therapists have. We must avoid focusing too much on functionality while the usability is ignored. Since rehabilitation robots and assistive robots requires a lot of interactions between the human and the robots, usability and safety has risen to a state as equal to functionality.

The new trends of rehabilitation robots now focus on the home-based rehabilitation. According to therapist point of view, the neurological injury episode should not be just confined within the several months after injury but a long time disease need to get treatment and exercise. The transportation cost and the limited facilities in the hospital make it impossible for the patients to get trained every day. Following this criteria, we can imagine that the future rehabilitation robots will emphasize on home-use and portability.

To summarize, the rehabilitation robots should be designed to assist therapies to perform the task, which is hard or impossible for the therapist to do and at the same time provide the best rehabilitation intervention to patient based on the therapist directive. At the same time, the new rehabilitation robots design should shift on to easy-to-use, portability and home-based function

III. DESIGN CONSIDERATIONS IN EXOSKELETONS AND REHABILITATION ROBOTS

Although robotic exoskeletons and rehabilitation robots are designed for different intentions and can be categorized into performance-augmenting exoskeletons, rehabilitation robots, mobile medical exoskeletons; they, are both wearable, have robot human interaction, help human to support body or external weight, as a result they face some common design problems and challenges. An introduction of robotic exoskeleton design considerations from the view of human lower limb biomechanics, human machine physical interfacing, human machine physical interaction, actuation system design are presented later. Table I has listed some important design factors in design exoskeletons.

A. *Human lower limb biomechanics*

Understanding the biomechanics of human lower limb functions in walking is essential in designing exoskeleton and gait systems. This article will investigate from the perspective of kinematics and functionality of hip, knee, and ankle joints. A comparison for different robotic exoskeleton mechanisms is given.

Joint level kinematics includes kinematic structure of the joint, degree of freedoms (DOFs), and range of motion (ROM). Conventional robotic joint are usually designed to model human joints. However, they cannot exactly replicate the human joint kinematics due to the complex nature of the human joints. Over-simplified exoskeleton joint design will cause low kinematic compatibility resulting unwanted interaction forces between human and exoskeleton. However, too complex joint design may add design cost and complexity or even reduce the reliability of the system. Meanwhile the lower limb is a highly kinematic redundant system, regarding to system level kinematics, which makes it not feasible to design an exoskeleton perfectly matches each joint. Even a possible kinematic equivalent design will also cause undesired constrained force to human if there is misalignment in joint axis between the human and the robot. The first ergonomic design criteria was introduced by Schiele and van der Helm [10]. As a result, the investigation into functional significance of joints during walking is of great importance to eliminate the joint with little impact for walking. Overall, the design of exoskeleton design should be kinematical compatible while still can provide satisfactory functionality.

a) *Hip joint*

Hip joint is different from other joint since it provides three dimensional motions and it is usually modeled as a ball-socket joint. The sagittal plane motion is most important during walking in which hip flexion prepares the clearance for swinging while transition from hip flexion to extension facilitate limb advancement during swing phase and also provide propulsion force in stance phase [11]. Motion in frontal and transverse plane motion is subtle; however transverse plane motion is essential in changing direction during walking. Torque required in sagittal plane is between -80 to 60 Nm, and it is important to note that the required hip torque in frontal plane is also very large created by body weight in single support phase.

b) *Knee joint*

Knee joint is a complex joint with a large range of motion in the sagittal plane and relative small angles in transverse and frontal plane. Usually, it is modeled as a one dimensional rotary joint in sagittal plane, whose motion is used for progression in stance phase and clearance preparation and limb advancement in swing phase[11]. Since the knee joint is the connection between thigh and shank, knee is the key determinant of limb stability in walking. The highest knee toque is approximate 60Nm which occurs at the in early stance to do weight acceptance. Attention has to be paid into the knee joint design is that the knee joint is not a perfect rotary joint but also have translational motion in sagittal plane which is modeled as a four bar linkage [12].

c) *Ankle joint and foot*

Ankle and foot is the most complex joint system of the lower limb totally having 33 joints. However, only three joint plays significant role of walking: ankle joint which provides rotational mobility in sagittal plane, subtalar joint which provides rotational motion in frontal plane, and at last, transverse tarsal joint which enable rotational motion in transverse plane. The largest torque occurs in the sagittal plane during heel pushing which provide propulsion force for limb advancement and the magnitude is up to 120 Nm.

B. *Human machine physical interface*

The physical interface design is important since it responses for transmission of mechanical power from robotic exoskeleton to human. Improper design of the physical interface between human and the robotic exoskeleton may not provide enough support to human or even result in severe injuries. The contact method, contact intensity, and the contact areas on the body should be considered in the design. Several requirements must be satisfied in order to make the physical interface function properly: first, they must fix the robotic exoskeleton to the human preventing the loss of alignment between the two; second, they should maximize the force transmitted to increase the effectiveness of support; third, they should be comfortable and user-friendly.

The physical interfaces can be classified into two categories according to its function: fix the user to the robotic exoskeleton; provide body weight support. When the interface is designed to maximize the force transmission, the physical interface should be rigid. A fully rigid circle support is hard to adapt to the morphology of human's lower limb, as a result, a textile strap is used to tighten the lower limb to the robotic exoskeleton with a half circle brace. At the same time, the compression increases the soft tissue impedance which reduces the probability of misalignment between the body and the robotic exoskeleton.

C. *Human machine interaction*

Human and robotic exoskeletons are two different dynamic systems which require the cooperation with each other to achieve a common goal. The human machine interface can generally be divided into two parts: the method to control the exoskeleton; the way by which the human intension is passed to the exoskeleton.

Either for performance-augmenting exoskeletons or rehabilitation robots, the control strategy is designed based on the principle that the robots won't hinder human motion and the robot can act according to human's intension. The other important aspect is the control method must ensure the safety of the user. The simplest control method is position control by controlling each joint to track pre-defined trajectories. However, this control method reduces the adaptability of the system. In order to implement higher level control, Different sensors are needed to acquire system and environment information.

Design human intention transferring method should base on the two principles: the method must be robust which means the method must be able to transfer human intension correctly; the number of sensor used should be minimized to reduce system cost.

D. *Actuation system design*

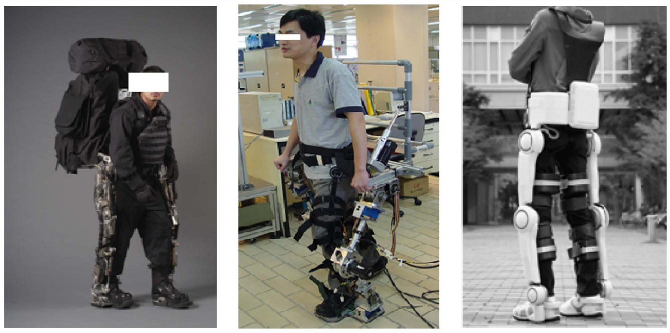
Actuation system consists of three parts: power source, actuator, actuation mechanism. Due to the mobility necessity of exoskeletons (except treadmill-based rehabilitation robots), the design of a light weight, energy efficient and powerful source is another challenge. Battery is a common power source. However, it has a low specific energy (energy per unit mass). Due to this low specific energy, batteries are used in the robotic systems have to be large and heavy, unless the operation time is short or the robotic system requires little power.

Since the relative high torque requirement during walking, the actuator combined with actuation mechanism must be able to output sufficient torque. DC motors combined with gears is the most common design, however it suffers from several drawback: first, the gear box has output torque limit, to withstand high torque, the size of the gear becomes large and task up too much space. Second, gears always have backlash problem, and the error can be amplified to be very large due to the length of the lower limb. Harmonic drive may be a better solution with high torque output and a compact size but the gear ratio only has limited selections. Hydraulic actuators is another solution to power the system, however such an exoskeleton design demands a great deal of power, requiring a heavy power supply to achieve system autonomy. This approach leads to a noisy device that has a very low payload to system weight ratio. Further, this type of exoskeleton is heavy and, if failure were to occur, could cause significant harm to the wearer. Another challenge regarding of the actuation system design is to determine the required joint toque on which the motor is selected. Oversized motor will be inefficient while an undersized motor cannot provide enough assistance.

IV. CURRENT EXOSKELETON DESIGNS

A. *Performance-augmenting exoskeletons*

The robotic exoskeletons are developed to augment the performance of the able-bodied person are usually named as performance-augmenting exoskeletons [8]. Some of the representative exoskeletons from this category include: BLEEX (Berkeley Lower Extremity Exoskeleton) [13], HAL-5 (Hybrid Assistive Limb) [14] and NTU-LEE(NTU Lower Extremity Exoskeleton) [15].



(a) (b) (c)

Figure 1. Performance-augmenting exoskeletons:(a) BLEEX [16],(b) NTU-LEE [15],(c) HAL-5 [17],

The BLEEX exoskeleton was developed at the University of California [16]. The skeleton focuses on helping solider to increase performance. NTU-LEE developed by Low of the Nanyang Technological University [15] has similar function as BLEEX; however different control methods were

TABLE I. BIOMECHNICAL PROPERTIES OF HUMAN LOWER

		Purpose	**Performance-augmenting exoskeletons**			**Rehabilitation Robots**					**Mobile Medical Exoskeletons**				
	Joints	**Biological Limb**	***BLEEX***	***HAL-5***	***NTU-LEE***	***Locomat***	***NaTUre-gaits***	***WalkTrainer***	***ALEX***	***LOPES***	***eLEGS***	***MIT Medical Exoskeleton***	***ReWalker***	***REX***	***Honda Leg***
DOF	Pelvis	6	N/A	N/A	N/A	N/A	5	N/A	3	N/A	N/A	N/A	N/A	N/A	N/A
	Hip	3	3	3	2	1	1	3	2	2	1	2	2	3	2
	Knee	2	1	1	1	1	1	1	1	1	1	1	1	1	1
	Ankle & Foot	4	4	1	1	N/A	3	3	1	N/A	1	1	N/A	2	3
ROM(deg)	Hip	140/15[a] 40/30-35[b] 15-30/60[c]	121/10[a] 16/16[b] 35/35[c]	NA	140/15[a] 40/30-35[b] 15-30/60[c]	N/A	50/15	N/A	40/40[a]	60/30 15/15	N/A	N/A	N/A	N/A	N/A
	Knee	120-140/0-10[a]	121/0[a]	N/A		N/A	80/0	N/A	45-60/0	90/0	N/A	N/A	N/A	N/A	N/A
	Ankle & Foot	40-50/20[a] 30-35/15-20	45/45[a] 20/20	N/A	140/15[a]	N/A	10/20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Torque (Nm)	Hip	140/120[a]	150/120[a]	N/A	118	N/A	31[a]	N/A	50[a]	65 30	N/A	N/A	N/A	N/A	N/A
	Knee	140/15[a]	100/120[a]	N/A	118	N/A	35.2[a]	N/A	50[a]	65	N/A	N/A	N/A	N/A	N/A
	Ankle & Foot	165[a]	200/150[a]	N/A	118	N/A	132[a]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

a. Flexion/Extension b. Adduction/Abduction c. Internal/External d. Inversion/Eversion implemented into the systems. Different from the previous design, HAL [17] does not have the function of carrying weight at the backpack. The system was developed at the University of Tsukuba by Sankai.

1) *Kinematic structure*

a) *Exoskeleton architecture*

As this type of exoskeleton aims at augmentation, there should not be collision between the robot and users when performing a task. At same time, the structure cannot protrude out which otherwise will limit the mobility and maneuverability of the system. As a result, an anthropomorphic design which matches exactly to human leg is usually preferred compare to non-anthropomorphic design which usually cause collision between human and robot and may force human into unreachable configurations[16]. All the three exoskeletons presented here choose a almost anthropomorphic design which means they are kinematical similar to human's leg but with reduced unnecessary DOFs to achieve more compact and power efficient design.

b) *Degrees of freedom*

The first challenge in hip joint design is the offset of joint rotation axis in abduction and adduction. BLEEX solves the problem by moving the rotational axis to the rear of the hip. MIT exoskeleton [18] which is not motioned in this paper due to it is a quasi-passive design offers a cam design in which the robotic joint rotation center moves to align with the anatomical joint. The hip transverse rotational axis also suffers the same problem. However, due to the small relative motion to each other, BLEEX's hip joint design still have a offset in transverse rotational axis between human and robot to simplify the design. HAL-5 also includes 3 DOFs but no detailed design was reported.

All the three exoskeletons knee joint design is one DOF, which allows knee flexion/extension. The internal/external rotation is eliminated because its unimportance in walking.

The ankle joint design varies a lot between the 3 exoskeletons. BLEEX has the most complicated design with 4 DOFs including ankle flexion/extension, inversion/eversion, internal/external rotation and one DOF at the foot, which allowing exoskeleton foot flexing with human foot. Among the 4DOFs, only flexion/extension is powered and the rotational axes of ankle abduction/adduction and rotation don't align with human's rotational axis in order to simplify the design. HAL-5 has 1 DOF in the saggital plane which is passive without powering.

c) *Range of motion*

Since all the anthropomorphic exoskeleton design is close to human kinematics, as a result, the range of motion is determined by investigating the joint range of motion as shown in BLEEX[16]. It is also pointed out in BLEEX that the ranges of motion of exoskeleton should be slightly less than that of the human to achieve a better maneuverability [16].However, based on different application like MIT knee exoskeleton which is designed to assist people running, has a knee flexion up to 135 degrees [19] .

d) *Active DOFs*

In the joint design, BLEEX[13] chosen to actuated the joint which requires substantial power while leaves other kinematic important joints passive actuated by loading with them stiff elastic components to increase kinematic compliance between the human and the robot. HAL-5 and NTU-LEE also followed this criterion.

2) *Human machine physical interfacing*

BLEEX only has two rigid attachments between the robot and human since it doesn't transfer any force to human while only help human carrying weight. However, in HAL-5, the exoskeleton is attached to the human by two rigid brace on each leg to transfer power from the exoskeleton to the human. However, no discussion was found out on the point of attachment which would provide the most comfortability and transmission efficiency.

3) *Human machine physical interaction*

The exoskeleton needs either to follow the human's motion as in BLEEX and NTU-LEE to help human to transfer heavy load, or provide joint torque to human in HAL-5. Different control methods are presented in the exoskeleton. HAL use EMG (electromyography) signal to transfer human intention into the exoskeleton. This method is very intuitive since human muscle power is trigged by EMG signals. Later, they employed a robust method that is use user's foot pressure as the indicator of user's intension to control the HAL [20]. While, in NTU-LEE, a ZMP method was employed to trigger the motion of the exoskeleton which based on the human's intention of balancing. BLEEX demonstrated a very novel control method which estimates human motion not by measuring the state of human or the interaction force between human and the robot but the dynamic state of the exoskeleton [21]. Later they improve the algorithm to a hybrid control method which increases the robustness of the algorithm [22].

4) *Actuation system*

Energy autonomous is the one of the most important part in exoskeleton design since it is essential to allow the user to go anywhere he desires. BLEEX has put a lot of effort in achieving energy autonomous. To reduce the size and improve the efficiency of the system, hydraulic actuators were selected based on its high specific power that is ration of actuator power t actuator weight [13]. At the same time, a lot of effort was put into the design of the hybrid hydraulic/electric portable power supply [23]. In HAL-5 electric motor and harmonic drive was used to achieve an energy autonomous system.

B. ***Rehabilitation robots***

Another class of the robot related to exoskeleton is rehabilitation robot which is designed to provide therapy to the patient who suffers from neurological disorder such as stroke, Parkinson Disease, or Cerebral Palsy. Being able to deliver automated gait therapy to the physically impaired patient, these devices are designed to replace classic therapy which is labor-intensive and requires effort form two or three therapies. The rehabilitation robots can be divided into two sub-categories based on the training environment: treadmill-based rehabilitation robots, over-ground rehabilitation robots.

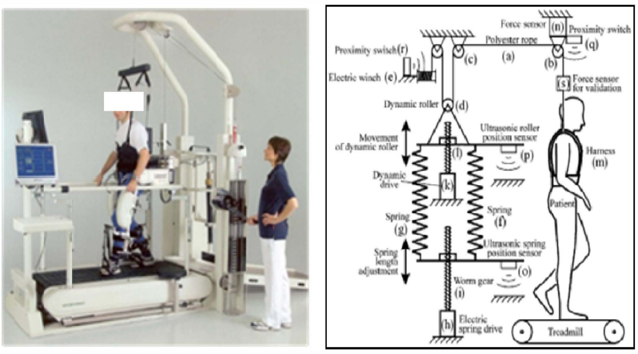
There are some similarities between performance-augmenting exoskeleton and rehabilitation robots since they provide the same functionality of assisting human walking. However, the human-augmenting exoskeleton is designed from the point to reduce human power expenditure of walking; as a result the metabolic cost is the measurement of the system performance. While for rehabilitation robots, they are designed for the view of clinicians, which require the robot not only assist the patient to walk but also act as the role of therapist. . Despite the design challenges to meet the requirements of the clinicians, some of the issues faced in performance-augmenting exoskeleton such as energy autonomous don't present in rehabilitation robots design.

1) Treadmill-based rehabilitation robots

a) Lokomat

Lokomat [24] is a novel mechatronic body weight support (BWS) system that developed to provide precise body weight unloading for patients with neurological or other impairments during treadmill training. To maximize the therapeutic outcome of human gait rehabilitation, a passive elastic spring element used to take over the unloading body weight. The novel mechatronic design provides an active BWS, instead of traditional fixed BWS. In addition, a robotic exoskeleton system support hip and knee movement in the sagittal plane, while the ankle joint is not support. The system provides continuous torques limited at hip of 50Nm and at knee of 30Nm. DC motor and ball screw mechanism are chosen to build a linear actuator to drive the exoskeleton leg [25].

Regularly, patient training in Lokomat is performed with a fixed gait pattern as the robot followed the predefined joint angle trajectories. However, this method doesn't take into account of peculiarities of each patient. Considering the patients who have residue voluntary locomotion abilities, assist as needed approach was proposed which states that the robotic intervention needs to be specifically tailored to the requirements posed on each subject and minimized to only the situations in which the subject really requires it [26]. Gait pattern adaptation algorithms were implemented in Lokomat to realize the assist as needed approach [27].

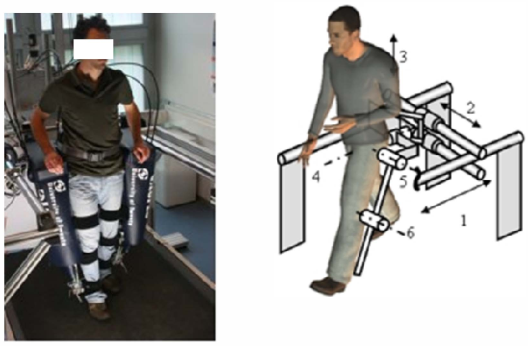


(a) (b)

Figure 2. (a) Lokomat system with patients [28] (b) Sketch of the mechanical setup [24]

b) LOPES

LOPES [29] contributed a more flexible actuator for the design of the exoskeleton. It has a two part： first is a 2-D pelvic control system; the other is the exoskeleton leg with four actuated DOFs which assist hip flexion/extension, adduction/abduction, knee flexion/extension and ankle flexion/extension. Bidirectional mechanical interaction is allowed between the robot and the training subject. Two control models are proposed as "patient-in-charge" and "robot-in-charge". However, the position measurements are not accurate enough for the inverse dynamical gait analysis which still needs improve.

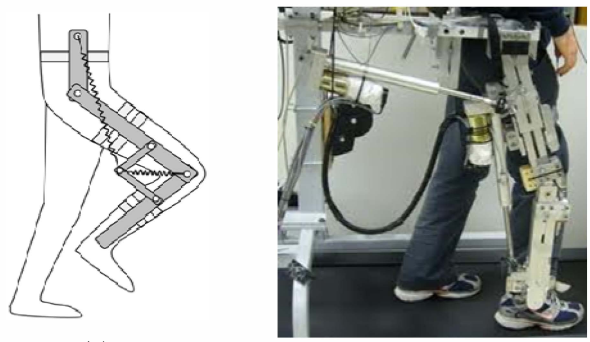


(a) (b)

Figure 3. LOPES (a) Subject's leg strapped to LOPES exoskeleton (b) schematic overview of degrees of freedom [29]

c) ALEX

A pure mechanical leg orthosis was developed in the University of Delaware. It aims to reduce the effect of gravity on the patient's leg through a mechanism added with spring which makes the system gravity-balanced in every configuration [30]. Another treadmill-based rehabilitation robot was developed by the same group called ALEX [31]. The system are actuated the hip and knee joints in sagittal plane while hip abduction/adduction and ankle. A force field controller is applied into the system which can display the force file acting on the foot to represent the physiological foot trajectory during overground locomotion.



(a) (b)

Figure 4. (a) Gravity-balanced Mechanism[30] (b) Active Leg Exoskeleton (ALEX) [31]

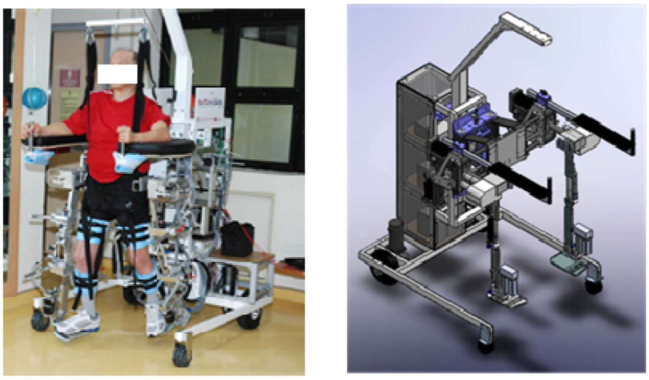
2) Over-ground rehabilitation robots

Over-ground rehabilitation robots have the similar function as treadmill-based rehabilitation robots while the over-ground rehabilitation robots addressing the ability of over-ground gait training.

a) NaTUre-gaits

The developed robotic system is named as *NaTUre-gaits* [5], as a Natural and Tunable rehabilitation gait system. The overall objective of this research is to develop and initiate an overground training incorporated with pelvic control and active assistance to lower limb so as to improve walking capabilities of a subject in rehabilitation mobility progressing stages.

It is important to highlight some conceptual specifications of the gait system developed. First of all, the research is aimed to design a device that can be applied to rehabilitation training progress of therapy for reducing manpower and increasing efficiency. The gait system is not to totally replace the conventional manual training with therapists, but serves as an assistive platform to reduce the physical and work burden of a therapist and thus enhance the quality of the rehabilitation training extended to the patient. Secondly, although the robotic device provides a gait training platform for a wide range of patient groups, the design consideration in its first version caters for those patients, who have lost their trunk control. Finally, the proposed robotic system can be served as a useful platform for clinical-engineering research, progress comparisons, and quantitative outcome evaluation of rehabilitation progress.



(a) (b)

Figure 5. (a) A SCI subject walks with *Nature-gaits* (b) Schematic View of *NaTUre-gaits*

b) WalkTrainer

WalkTrainer [32] is an impressive robotic system providing the over-ground walking with the consideration of the pelvic motion. This device also makes efforts to combine the robotic rehabilitation with electro-stimulation. The use of *WalkTrainer* shows flexibility and diversity potential applications. Pelvic control is one of the major objectives for *WalkTrainer.*

Figure 6. *WalkTrainer* [32]

C. Mobile medical exoskeletons

A new kind of rehabilitation and assistive robots called mobile medical exoskeletons emerge which are portable and can be used at home. It functions both in the way of assistive device and rehabilitation device. Different from the performance-augmenting exoskeletons which are used by healthy human, this kind of device is designed for person with gait disability. Also compared to rehabilitation robots where usually exists a body weight support system to keep balance and help to support body weight, the mobile medical exoskeletons requires the patient to balance themselves which means the patient must have a healthy upper body.

With a similar structure as performance-augmenting exoskeletons, the article wants to emphasize the design of the human robot interfacing as it is the essential to the safety and stability of the system. Since hip, knee and ankle are weight-bearing joints，it will collapse if there is not enough muscle force provided. As a result, the mobile medical exoskeleton should provide enough external joint moment to compensate the lack of force in these joints and also body weight support to minimize the weight loaded on these joints. So a good human robot physical interfacing design is very important. The details of the designed will be presented later in the article.

The article will investigate this new kind of rehabilitation exoskeleton by presenting four of the most well-known designs from the perspective of both the mechanical design and control method applied. Table II prepares the general performance between three mobile medical exoskeletons.

a) eLEGS

The *eLEGS* [33] is a system designed and built at Berkeley Bionics. Its architecture is almost anthropomorphic which means it is kinematically similar to a human's, but does not include all of the degrees of freedom (DOF) of human legs. It is the market version of the MIT mobile medical robots which is still under the development of more functions [7, 34]. The system uses hydraulic cylinders to power the hip and knee extension and flexion. In order to minimize the power requirement of the system while prevents unnatural posture, the hip adduction and abduction, ankle dorsi-plantar flexion are passively controlled by being loaded with very stiff elastic component or spring. The computer and the battery are attached at the back of the system. The exoskeleton interfaces with the patient through a torso brace and straps, an upper strap, a knee brace. Crutches or a cart are needed to support the device and the patient preventing falling. The system has a total weight of 20kg.

The system utilizes several sensors for control including force sensors at the heel and toe to detect the phase change during walking by measuring the contact force between the foot and the ground [7, 34]. The actuated knee and hip joint angles are measured by a potential meter and a digital encoder. An accelerometer/gyroscope at the torso is used to detect the posture of the patient to control the hydraulic actuator.

(a) (b) (c)

Figure 7. *(a) eLEGS [33]* (b) ReWalk [35] (c) REX [36]

TABLE II. PRPERTIES OF MOBILE MEDICAL EXOSKELETONS

	eLEGS	***ReWalk***	***REX***
Maximum Speed:	0.89m/sec	0.83m/sec	0.05m/s
Weight	20kg	15 kg	39kg
Battery life	Over 6 hours	2 hours 40 minutes	2 hours
Other support	Crutches needed	Crutches needed	No
Who can use			
E-Legs	Those who can self-transfer from a wheelchair to a chair and are between 5'2″ – 6'4″ tall and weigh 220 lbs or less.		
ReWalk	ReWalk Exoskeleton is suitable for lower-limb mobility impaired adults who have functioning hands, arms and shoulders, as well as the ability to stand (healthy skeleton and cardio-vascular system).		
Rex	People with weakened muscles and by some people with disabilities due to stroke and/or spinal cord injury.		
Motion			
E-Legs	Standing up from a chair, walking, climbing up and down stairs		
ReWalk	Standing up from a chair, walking, climbing up and down stairs ascending/descending slopes		
Rex	Standing up from a chair, walking, climbing up and down stairs		

b) ReWalk

ReWalk[35] is a wearable robotic device which helps the paralyzed people to walk. It is actuated by DC motors at hip and knee joint only at the sagittal plane. The ankle joint is unactuated. Different attachment methods are observed form the placated videos according to the patients' condition. Battery and controllers are attached at the back f the user.

The system is designed with a remote controller which can be used to change the motion mode of the system such as ground walking or climbing stairs. There is a posture detection sensor at the torso to detect the upper body movement of the user and the information is used estimate the user's walking intension and drive ReWalk accordingly.

c) REX

Different from *eLEGS* and *ReWalk*, *REX* [36] is developed by REX Bionic doesn't require any extra support like crutches. The motions which it provides can be referred in ftable. The other interest part of the system is it doesn't use sensor to sense the intension of the user but use joystick for the user to control the exoskeleton.

D. Other systems

There are other exoskeletons or assistive devices which don't below to any of the categories motioned in this article such as Honda Leg [37]. The machine is worth motioning since it offers a novel mechanism which is a body weight support mechanism. It proposes a solution for the patient who cannot support his body weight to walk. Unfortunately, this design is only aimed at healthy person; however, the design concept will benefit other rehabilitation robots design.

Figure 8. Honda Leg [37]

V. CONCLUDING REMARKS

Research on performance-augmenting exoskeletons and rehabilitation robotics has been active in the past ten years. The knowledge using in performance-augmenting exoskeletons and treadmill-based rehabilitation robots is combined together to generate the new over-ground rehabilitation robots. The trend for developing a mobile home-based rehabilitation robots can see more combination of the knowledge form the two fields. This article reviews the different human-augmenting exoskeletons and rehabilitation robots. We can see how these knowledge is combined together to generate new rehabilitation tools to benefit the society. Several mobile home-based rehabilitation robots have already gone through the clinical trial. The eLEGS has been tested with three patients with incomplete paralysis and one complete paralysis [7]. It has also been reported that ReWalk has gone through the clinical trial since 2008 [35].

Again, we want to emphasize that the importance of the clinical consideration in the designing of rehabilitation robots. This is actually the driving force in the changes of the rehabilitation robots. Here we want to share experience on the development of *NaTUre-gaits* following the clinical considerations.

As mentioned earlier, several challenges exist in the rehabilitation of over-ground walking training such as it requires at least three therapists to assist the patient to walk and it is not good for therapist body since they have to work in an unnatural posture. In addition, it is not safe for the patient and the provided motion may not be accurate. *NaTUre-gaits* is developed to solve such problems with natural pelvic control and walking motion, which will require at least four therapists to achieve such rehabilitation intervention. Successful clinical trials and good feedbacks from the doctors, therapists, and patients proved it is a successful design and realized the goal whereby the robot acts as the role of the therapist, delivering the exercises to the patient.

The same problem faced in *NaTUre-gaits* is in the usability design to minimize the set-up time. Effort is being made to develop a quick adjusting mechanisms in attachments and harness to allow the patients to quickly secured on the harness and attachments. Even during the day of the clinical trial, we have discovered together with the therapist a fast way to get the patients from the wheel chair to stand onto *NaTUre-gaits.* Continuously efforts are being put on to make the machine easy to use. If the patients can be quickly set up on the machine, time can be optimized to let the patient to do more training.

The future trend of the rehabilitation robots is determined by the requirement of clinical. *NaTUre-gaits* is a good example to illustrate this. Compared to the treadmill-based rehabilitation robots, the wheeled mobile platform in *NaTUre-gaits* was designed to allow the patient to have a real over-ground walking feeling. The new trends of rehabilitation robots now focus on the home-based rehabilitation. According to therapist point of view, the neurological injury episode should not be just confined within the several months after injure but a long time disease need to get treatment and exercise. The transportation cost and the limited facilities in the hospital make it impossible for the patients to get trained every day. The mobility-based rehabilitation robots come out to meet the demand of the therapist.

Overall, the rehabilitation robots should be designed to assist therapies to perform the task, which is hard or impossible for the therapist to do and at the same time provide the best rehabilitation exercise to patient based on the therapist advice with easy- to-use designs.

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