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Hannes Bleuler

Emerging Robotics Devices for Therapeutic Rehabilitation of the Lower Extremity

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Abstract—Application of robotics in rehabilitation provides various opportunities to improve the quality of daily life of disabled people. **Therapy rehabilitation is categorized as cardiopulmonary, neurological and musculoskeletal.** This paper focus on rehabilitation robots used for musculoskeletal therapy which assists in strengthening and restoring functionality and improving coordination in the musculoskeletal system. The development of therapy rehabilitation robots in the form of passive and active is reviewed in this paper with regards to the 21st century. Therapy rehabilitation robots are mainly discussed based on different actuation systems, degree of intelligence and virtual reality based rehabilitation robots. The main focus of this paper is to address the impact of the developments in the field of rehabilitation, limitations and challenges faced by current researchers.

I. INTRODUCTION

THE growth of people with reduced functional capabilities due to aging or disability has forced researchers to focus on methods of rehabilitation to allow patients to regain prior functional abilities. Although rehabilitation can be differentiated as physical, cognitive, emotional and social rehabilitation [1], the focus of this paper will be only on physical rehabilitation. In the case of patients who suffered from a stroke, after three months, one third of the surviving patients do not regain independent walking ability and those ambulatory, walk in a typical asymmetric manner. At the same time their walking velocity and endurance are markedly reduced [2]. Therefore the goal of physical rehabilitation is to facilitate restoration of patient's prior role and task performance with the assistance of physiotherapists of gait rehabilitation devices.

However, manual assisted training is labor intensive and therefore training duration is usually limited by personnel shortage and/or exhaustion of therapist. Manually assisted movement training lacks the repeatability and the patient's performance is monitored only by observation. With the advancement of technology, assistive devices have been developed to overcome the aforementioned limitations. Utilizing robotics to model machines for rehabilitation increases the number of training sessions, reduces personnel cost by assigning one therapist to train two or more patients.

Rehabilitation robots can aid in rehabilitation as assistive or therapy robotics devices. The goal of assistive devices is to assist the disabled patients in performing activities of daily living due to the inability of relearning. In contrast therapy rehabilitation robots mimic the task of clinicians in aiding the patients to perform activities and regain functionality. The therapy rehabilitation robots can be further distinguished as active, passive or hybrid depending on the performance level of the robotics design. Passive rehabilitation robots can only exert resistance force against human movement while active rehabilitation robots utilize a control system for actuators that are capable of supplying energy to assist voluntary movement while preventing harmful movements to the patient's joints. The latter rehabilitation robots can be either incorporated with intelligent systems or perform depending on the clinicians inputs to the system. Hybrid rehabilitation robots are a combination of passive and active rehabilitation robotics.

Most active rehabilitation devices contain an actuation system and a degree of intelligence. The actuation systems provide feedback to patients performing rehabilitation exercises in terms of vibro-tactile, electro- tactile and kinesthetic feedback. Tactile feedback provides a touching sensation either by means of a vibration (vibro) or small electrical current (electro). Functional electrical stimulation (FES) falls under the category of electro-tactile and is a rapidly developing area used to restore the lost functions of the nervous system by means of electrical stimulation.

Kinesthetic feedback is initiated by means of a single or multiple point force exertion. It is controlled by pneumatic, hydraulic or electrical motors to aid patients in performing exercises for rehabilitation purposes. Recent research integrates virtual reality with rehabilitation robots which incorporate a virtual environment in which the patients perform the rehabilitation tasks. VR enables the patients to not only immerse in a virtual environment but also sense the forces of the objects present in this environment.

This paper will review therapy rehabilitation robotics developed of the 21st century with a main focus scrutinizing the current rehabilitation robots for the development of an active rehabilitation robotics device using micro scale sensors and actuators. This project is a further expansion of the research on human motion analysis carried out by the Intelligent Systems for Sportsman Screening Services (ISSS) Research Group at Monash University, Sunway campus [3],[4],[5].

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II. HISTORICAL DEVELOPMENT OF REHABILITATION ROBOTICS

Since the early 1960's clinicians have been using continuous passive motion (CPM) machines to aid rehabilitation process following surgery [6]. CPM is a rehabilitation technique that involves progressive passive range of motion (PROM) to an extremity through an externally applied force [7].

The CPM technique was used for further developments of active rehabilitation robots. In [8], a group of occupational therapists and engineers has programmed a commercially available robot to perform fundamental exercise routines with the patient, collect patient data and generate reports. A programmable, force controlled, albeit single axis device named BioDex was introduced by R. Krukowski in the mid 1980s [9]. The publication of the first multi-axis robotic system was in 1988. This was an intelligent robotics system consisting of two double link planar robots with force sensors, for continuous passive motion [10]. WARD (walking assistance and rehabilitation device) was proposed in 1996, based on a pneumatic actuator system to relieve patient's body weight [11].

Therapy rehabilitation robotics initially focused on kinesthetic feedback and later expanded in to FES and VR based therapy systems. FES is used to restore walking by artificial stimulation of electrical currents to neuronal tissue. Although the concept of FES was introduced by Moe and Post [12], the first application of FES for walking was implemented by Liberson and colleagues in 1961 for drop foot [13]. In 1963, Kantrowitz [14] implemented a system with surface electrical stimulation on both quadriceps and great gluteal muscles of a completely plegic patient to stand. A research group in Ljubljana included FES into regular physiotherapy programs in 1983 [15]. It has been found that during rehabilitation programs about 60% of patients can receive FES as means of therapy, (due certain criteria that needs to be satisfied [16,17]), 25% receive FES in order to improve or perform certain functions and only about 10% are provided with FES orthotics at the conclusion of rehabilitation [18]. An important research was carried out by Kralj and colleagues [19] using four channels of surface stimulation placed over quadriceps muscles and peroneal nerves. Activation and deactivation of stimulation of the muscle and nerves in an alternating manner resulted in simultaneous hip and knee flexion and dorsiflexion. The Parastep-I system which received approval from the United States' Food and Drug Administration (FDA) used Karlj's technique to allow patients with complete or incomplete paraplegia, to walk.

FES was also widely used as foot drop stimulators to overcome weakness of the tibialis anterior muscle. The first commercialized implantable foot drop stimulator was developed by Rancho Los Amigos Medical Centre and Medtronic Inc [20].

Although the birth of VR dates more than a few decades back, the application of VR for lower extremity rehabilitation was initiated recently. In 1999, Rutger's ankle

was introduced by Girone and his colleagues which addressed the shortcomings of existing rehabilitation devices [21]. This resulted on the development of a virtual reality based rehabilitation exercise which involved the piloting of an airplane through 3D hoops, in the year 2001[22].

With the development of therapy robots, the need for intelligent systems arose. Applying intelligence to rehabilitation initiated from designing and implementing intelligent wheelchairs and later expanded into the development of therapy robots. In the late 1980's an intelligent system for the rehabilitation of joints was proposed. This system automatically calculates the reaction occurrence at human joints which aid physical therapists to avoid patient discomfort due to forces applied by the device [10].

III. CURRENT TECHNOLOGY

The current rehabilitation robots was identified and divided as represented in table 1. VR technology is also integrated for some rehabilitation processes for increased improvements of patient performances.

TABLE I
CURRENT TECHNOLOGY OF REHABILITATION ROBOTS

| Actuator Systems | | Virtual Reality Based Rehabilitation | Intelligent Systems |
|------------------|-----------------|--------------------------------------|---------------------|
| Kinesthetic | Tactile | | |
| Pneumatic | Vibro-tactile | Audio feedback | Simple algorithms |
| Electric | Electro-tactile | Visual feedback | AI |
| Elastic | | Haptic feedback | |

A. Actuation systems

1) Kinesthetic rehabilitation robots:

Most developed rehabilitation robots are in the form of exoskeletons which allow humans to overcome certain limitations of the body. Although many robotic exoskeletons are used by military personnel, promising exoskeletons are being used in the 21st century for physical rehabilitation. The most popular rehabilitation robot used in current days is the LOPES (Lower extremity powered exoskeleton) designed to help patients regain lost motor control [23]. Gait trainer GT-I [24], the Lokomat [25] and Autoambulator are other current developments utilized in gait training which are mostly performed on even ground. GT-I developed by Hesse et al. applies the principle of movable footplates which are controlled by a planetary gear system, simulating foot motion during stance and swing phases. Lokomat is a robotics exoskeleton used during treadmill walking to aid patients in moving the hip and knee. Two robotics arms are used in AutoAmbulator to assist patients to step on a treadmill with supported body weight. The limitation of these devices is the restriction of training only on even ground. Therefore the same group who designed GT-I introduced HapticWalker which was the first gait rehabilitation device that did not restrict training of walking to even ground [26]. The detailed description of the above devices is reviewed in [26].

Most available kinesthetic rehabilitation robots are controlled by electrical motors to drive the actuator [27]. But in recent years the pneumatic control of rehabilitation robots

was introduced and was considered advantageous in comparison to electric motors due to its cost factor and higher power to weight ratio. PAM (pelvic assist manipulator) and POGO (pneumatically operated gait orthosis) are actuators which are pneumatically controlled. Other proposed actuation systems are namely elastic actuation systems [28],[29],[30] motorized mobile platforms (treadmills), artificial pneumatic muscles [31], [32] and gravity balancing. Some of the aforementioned devices only aid patients to perform a predetermined movement and are categorized as passive rehabilitation robots. The Active Leg Exoskeleton (ALEX) [33] and the powered leg orthosis proposed in [34] are examples of active rehabilitation robots which overcome the restriction of passive robots by allowing voluntarily movement of patient's impaired leg and restricting movements that are harmful.

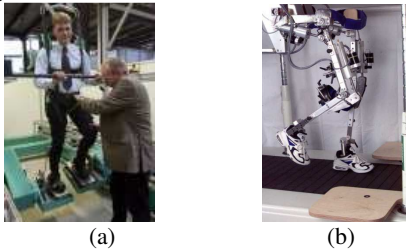


Fig. 1 Force-feedback assistive devices a) HapticWalker, and b) Lokomat

The Northeastern University in Boston proposed a new approach (AKROD) for active rehabilitation devices [35],[36]. Electro-Rheological Fluid (ERF) was used to provide controllable and tunable resistive torque to motion on a healing joint which aids in regaining muscle strength. ERF has the property to change rheological properties such as viscosity in the presence of an electric field. This property enables the usage of ERF for rehabilitation devices to control and vary the damper component of the device.



Fig. 2 AKROD device using ERF control system

2) Tactile feedback systems:

Vibro-tactile feedback systems are widely used in sports to offer corrective feedback to the athlete when performing actions that are differing from that of the coach. In [48] a student's performance is tracked using Vicon motion capture system and compared with the performance of a teacher. A suit consisting of sensors was worn by the student which generated real time feedback commands. Student's joints moving in error received tactile feedback proportional to the error percentage calculated with comparison to the movements of the coach. This research paper states that an accelerated learning rate of up to 23% was observed in comparison to no tactile feedback. This concept used to train a student's performance can also be applied in rehabilitation where the patient's performance can be compared with reference to normal gait.

FES is another technique used in the field of rehabilitation to evoke involuntary muscle contractions of patients who have undergone stroke or spinal cord injury [37]. In recent years many FES based rehabilitation robots have been commercialized for therapeutic use or permanent orthotic systems. Although FES can be mainly divided as surface FES and implantable FES, FES-assisted walking therapy mostly involves surface electrodes on lower limbs to induce greater muscle force, joint range of motion and load bearing in the legs [20]. Kralj's surface FES technique described in section II is widely being used in the present day for paraplegic gait.

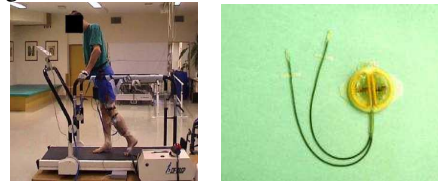


Fig. 3 FES based assistive device for rehabilitation

Fully implanted FES systems offer long term usage, improved convenience, and the ability to stimulate deep muscles such as hip flexors [19] in comparison with surface stimulation. Currently available fully implanted systems for gait rehabilitation such as the system proposed by Kobotics and Praxis FES are described in [20].

Foot drop stimulators are a class of FES devices which is designed to treat foot drop. This abnormality occurs due to weakness in toe and ankle dorsiflexions which causes the inability to raise the forefoot during swing phase. As a result, individuals with foot drop scuff their toes along the ground or bend their knees to lift their foot higher than usual to avoid the scuffing, which causes a "steppage" gait. Foot drop stimulators have been developed to artificially activate the dorsiflexor muscles during the swing phase of gait [38],[39].

Researchers have also recently combined FES with cycling in a treatment protocol that aims to generate active movement of paralyzed muscles [41], [42].

B. Virtual Reality in rehabilitation

The incorporation of VR systems is a breakthrough for gait rehabilitation due to its numerous underlying strengths. Among these are that VR provides the opportunity for ecological validity, stimulus control and consistency, real-time performance feedback, independent practice, a safe testing and training environment [43]. An important factor for rehabilitation is the motivation of the patient to perform tasks assigned. Studies have proved that the technology of VR which allows the patients to emerge in a virtual environment maintains their motivation and increases progress [44], [45]. Systems have been proposed which have integrated VR in to available gait training devices for patients recovering from stroke, spinal cord injury, Parkinson's disease etc.

VR is also used in conjunction with Haptics to allow patients to not only see the virtual environment but also sense the objects although not present in the real world. Therefore using haptics enable researchers to develop VR based exercises which aid in the rehabilitation of the

impaired joints. Most of the currently developed rehabilitation exercise systems are focused on hand rehabilitation which allows patients to perform exercises in a virtual environment [43],[46],[47]. This will not be discussed in detail, because the scope of this review paper only focuses on the lower extremity.

Haptics is utilized in [48 – 49] to analyze the movement of a human in a virtual environment and apply a real time corrective vibro tactile feedback in terms of erroneous motions or collision in the virtual environment.

C. Integration of Intelligence for active robots

Assistive devices discussed above can precisely measure the characteristic of a patient's movement and provide necessary feedback to assist movements that the individual cannot perform alone. Determination of the amount of the magnitude of feedback requires the machines to possess a certain degree of intelligence. Most developers of therapeutic robots use simple control algorithms for the feedback system to reduce receiving noisy signals [27],[50],[51].

Yet, researches have proposed complex algorithms based on artificial intelligence such as artificial neural networks (ANN) based PI-gain to provide optimal force assistance [52], fuzzy inference systems (FIS) to ensure safety and correct errors of foot drop stimulator system [53] and to determine the amount of mechanical force required to match correct gait phase [54], hybrid systems for paraplegic gait [55] and knee rehabilitation [56] etc. Using computational intelligence led to advancement in gait rehabilitation due to its numerous advantages such as increased accuracy, safety, increase training effect etc.

Utilizing feedback systems in rehabilitation relies on accurate timings on when to trigger the feedback signal. The timing can be easily determined by differentiating between gait phases. Walking gait consists of two main divisions, stance and swing phase, in which stance phase is when the foot is in contact with the ground and the swing phase is when there is no contact between the foot and the ground. Stance and swing phase can be further divided in to eight phases, namely initial contact, loading response, mid stance, terminal stance, pre swing, initial swing, mid swing and terminal swing.

The stance and swing phase of a gait can easily be differentiated by placing two force sensitive resistors (FSRs) at the heel and the toe off the patient. Yet, due to the complexity of the gait cycle more sensors and algorithms are required for accurate differentiation of gait phases. This requirement has led researches to propose sensory systems with the integration of gait phase detection algorithms [40].

Accelerometers and magnetometers were used in [57] for continuous identification of gait phase fusing simple and complementary methods: morph-mathematics, cyclogram analysis, wavelet transform, qualitative analysis and cross correlation. A combination of foot pressure and joint angles information was also proposed to define gait phase detection algorithms [54], [58].

The complexity of human gait has led some researches to believe that the comparison of sensor outputs to a threshold value does not accurately distinguish gait phases. Therefore the application of fuzzy logic for gait phase detection algorithms were introduced in [59], [60] and experimentally proven. Primary experiments carried out to control FES assisted devices were utilizing foot pressure measurements, joint angles or a combination of both. J.H.Choi et al. and Richard Lauer et al. proposed gait phase detection algorithms based on signals acquired from magnetic sensor array [61] and electromyography, respectively [62].

IV. LIMITATIONS OF ROBOTICS IN REHABILITATION AND CURRENT CHALLENGES

Application of robotics in physical rehabilitation has led to many innovations to aid physically disabled people to restore their daily life activities. The obvious advantages of utilizing machinery with or without integrated intelligence in comparison to manual therapy are time limitations, labor intensiveness, lack of repeatability and inaccuracies due to manual observations. In spite of these advantages some clinicians and patients are reluctant to try new approaches which lead to utilization of past techniques of rehabilitation. Therefore it is essential to educate people about the new technology and inform the importance and reliability of rehabilitation robots in industry.

A key issue addressed in rehabilitation robots is the comfort of patients and safety that is required due to the close interaction between the patient and the robot. Some systems have incorporated manual emergency stop buttons which shuts down the system in case of any difficulty faced by the patient. Manual switches may not be practical due to the slow motions and reflexes of the physically impaired. Hence automatic shutdowns due to exceeding pre-defined limits of angles or forces applied on human joints can be more acceptable. HapticWalker introduces an emergency shutdown system if the ankle dorsiflexion angle exceeds a prescribed limit [2]. Using electro-rheologic coupling can also increase safety of system by modulating slippage which limits potentially dangerous output torques [35],[36].

The adaptability of robots to the human limb in terms of lengths, range of motion and the number of degree of freedom (DoFs) is a significant matter in designing robots. A high number of DoFs allow the broad variety of movements with many anatomical joint axes involved [63].

It is also important that the actuators used for rehabilitation purposes are operated in an ideal force mode control. A force mode control is ideal when the actuator has zero impedance hence is completely back-drivable and the torque output is exactly proportional to the control input. This issue can be tackled by using rubber muscle actuators which requires a power source such as an air compressor. Kyoungchul et al. has proposed a system which includes a spring in between the motor and the human joint to satisfy the criteria of an ideal force mode control [64].

A survey carried out by M. Lee et al. addressed possible improvements of gait rehabilitation devices in a clinicians'

point of view [65]. The survey concluded that 58.62% of the respondents want to see the patients' records when they are being trained by the robot. These data is preferred to be viewed in both tabular and graphical formats by 68.75%. In the absence of the therapists, the system should also be able to provide patients with information such as their progress, and notify wrong movements.

FES assisted rehabilitation devices has experienced many technological advances throughout the years. However it is not yet proven as an effective procedure in terms of a large portion of the general population [21]. A major drawback in FES is that it tends to produce rapid fatigue in muscles due to the asynchronous recruitment of muscle fibers. In [66] a study was carried out to compare muscle fatigue resulting from high and low frequency stimulation. This study concluded that the muscle fatigue was less, and the peak torque occurred faster for high frequency stimulations.

Research has shown that using VR for rehabilitation is promising in terms of patients' motivation. Yet, the equipment required for VR based rehabilitation can be costly and this limits the usage of this technology in many clinics and rehabilitation centers.

V. CONCLUSION

The developments in therapeutic rehabilitation robots for lower extremity in the 21st century were reviewed in this paper. The technological advancements, limitations and challenges were also addressed. This review was carried out to gather information for the development of a robotic device for rehabilitation. The first phase of the project was to develop a gait phase detection system. A fuzzy logic based gait phase detection system was developed by using foot pressure and knee joint angle measurements. The second phase is to develop a rehabilitation device to rehabilitate patients with low knee flexion and extension. FES based system will be used to stimulate corresponding muscles to facilitate maximum knee flexion and extension during walking. The feedback system will be initially simulated and tested in a simulation environment before testing the prototype on humans.

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