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An Advanced Rehabilitation Robotic System for Augmenting Healthcare

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***Abstract*—Emerging technologies such as rehabilitation robots (RehaBot) for retraining upper and lower limb functions have shown to carry tremendous potential to improve rehabilitation outcomes. Hstar Technologies is developing a revolutionary rehabilitation robot system enhancing healthcare quality for patients with neurological and muscular injuries or functional impairments. The design of RehaBot is a safe and robust system that can be run at a rehabilitation hospital under the direct monitoring and interactive supervision control and at a remote site via telepresence operation control. RehaBot has a wearable robotic structure design like exoskeleton, which employs a unique robotic actuation - Series Elastic Actuator. These electric actuators provide robotic structural compliance, safety, flexibility, and required strength for upper extremity dexterous manipulation rehabilitation training. RehaBot also features a novel non-treadmill paddle platform capable of haptics feedback locomotion rehabilitation training. In this paper, we concern mainly about the motor incomplete patient and rehabilitation applications.**

I. Introduction

There are approximately 250,000 persons with spinal cord injury (SCI) in the U.S. alone, and 10,000 more individuals sustain a SCI every year [1-3]. Because the average age at the time of injury is 32, specialized care is essentially life-long. Over 50% of people with SCI have incomplete injuries. A significant percentage of individuals with motor incomplete SCI can regain motor function to at least some extent with potential for recovering the ability to walk again. This is a major goal of rehabilitation interventions in individuals with SCI. Unfortunately, traditional interventions only lead to relatively modest motor gains [4]. There is an urgent need for developing new and more effective approaches to improve rehabilitation outcomes in individuals with a SCI. Our early investigation was primarily focused on military combat casualty care, such as SCI patients and TBI (Traumatic Brain Injury) patients. This system can be applicable for other rehabilitation training scenarios as well.

Clinicians and researchers have started to explore the use of robotic systems to deliver rehabilitation interventions [5-7]. Robots appear to be an ideal choice to achieve the objective of facilitating the performance of movements that are highly-repeatable. The specificity of the movement patterns and the intensity of training are key aspects of gait rehabilitation protocols in individuals with SCI. Such protocols are known to be associated with neural adaptations leading to regaining motor functions [8]. Robots could relieve physical therapists from the burden of heavy, labor-intensive training techniques and focus on the quality of treatment.

While rehabilitation robotics has been met with a great deal of enthusiasm by the research and clinical communities, recent literature has questioned whether currently available robotic systems are adequate to maximize gait training outcomes [4,9]. Several studies have suggested that the modality of training achieved with currently available systems is not “ecologically” correct [6,10,11], i.e. that the way the task is implemented by the robotic system does not mimic satisfactorily gait in real-life conditions. For instance, studies have shown that the patterns of muscle activity recorded during robotic-assisted gait training are different from patterns recorded during over-ground walking [12]. Besides, it has been questioned whether systems should in fact allow one to train multiple ambulatory functions (e.g. stair climbing, ramp ascending/descending, walking on uneven terrain) as opposed to only level walking on the smooth surface of a treadmill.

To address the above-mentioned limitations of currently available systems, we develop a robotic system that has the ability of enabling training of different ambulatory tasks (e.g. level walking, ramp ascending/descending, stair ascending/ descending). We achieve this goal by relying on the use of footplates that will be used to guide the lower limbs according to trajectories corresponding to the different ambulatory tasks of interest [13]. To achieve “ecological” therapy, we also develop robotic components to train subjects in the use of the upper limbs while undergoing

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robotic-assisted gait training. This is particularly relevant in individuals with SCI.

To develop an integrated rehabilitation robotic system, a compliance based actuation with built-in safety mechanism into the robot control is desirable. We apply compliant Series Elastic Actuator (SEA) technology [14] to achieve a safe, reconfigurable and desirable impedance control capacity. The above features of our RehaBot system distinguish our rehabilitation system from the existing rehabilitation robotic system commercialized or reported in research laboratories.

II. Rehabilitation Robotic System

A. Overview

We are developing an advanced rehabilitation robot (**RehaBot**) system that releases physical therapists from labor intensive and repetitive training workload and enhances healthcare quality for patients with neurological and muscular injuries or functional impairments. This system can be run at a hospital under the direct monitoring and interactive supervision control and at a remote site via telepresence operation control. The delivery of this system would reduce hospitals costs and ameliorate the problem posed by the shortage of capable physical therapists. This RehaBot system can be applied for upper limb rehabilitation and lower limb rehabilitation separately. However, an integrated RehaBot system will be able to run upper limb and lower limp rehabilitation simultaneously when a system configuration is selected appropriately, which has not been completed so far.

Fig. 1 illustrates the top level system framework for RehaBot. The framework is designed to:

- Ensure human-robot safety at all levels of control and to provide mechanisms for safety and failure monitoring and reporting;
- Enable task-level control of the robot through direct human-robot interface, tele-consultation, progressive rehabilitation, and direct training;
- Enable remote communication between an operator (a physician or therapist) and a patient through telepresence;
- Provide reconfigurable rehabilitation procedures for upper and lower limb training via virtual reality environments;
- Provide tools for local and remote monitoring, scheduling, and administration of RehaBot resources.

Shown in Fig. 1, there are two major operation modes of RehaBot system: 1) direct rehabilitation operation and 2) rehabilitation with telepresence remote supervision. To implement this framework, we designed a layered control system as described in the next section.

B. Upper Limb Rehabilitation Robot System Design

Development of an upper limb wearable exoskeleton rehabilitation robot system for neurological and muscular function recovery and retraining of dexterous manipulation skills requires: 1) safe actuation mechanism, 2) sufficient motion control, 3) correct joint structure, 4) selection of a sensory package for training measurement, and 5) effective patient-robot interaction.

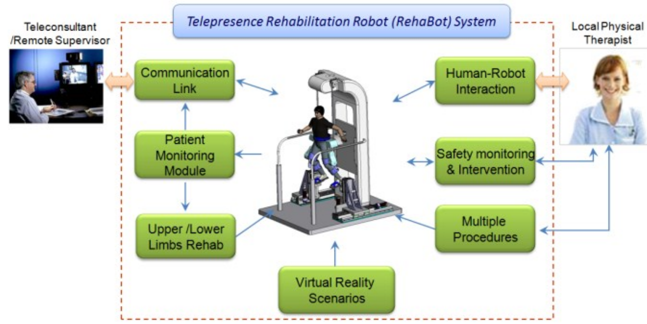

Fig. 1: Block diagram of a system framework of the RehaBot system.

Structural Specification: In the upper limb rehab robot system design, there are total 7 DOF active / passive control joints: 2 DOF active shoulder joint, 1 DOF for active elbow joint, 1 DOF for active upper arm rotation, 1 DOF for forearm supination/pronation, and 2 DOF for active force controlled wrist.

System Design: We designed the full RehaBot upper limb system including a wearable exoskeleton arm and wrist end-effector. Our core technology in this design is applying the SEA actuation to each joint of the arm, providing compliance, safety, and adequate power for patient motion and strength training.

Fig. 2 shows our design of this upper limb rehabilitation training mechanism. In this design, we adopted the wearable exoskeleton robotic system for upper limb rehab training including motion retraining and manipulation skill training.

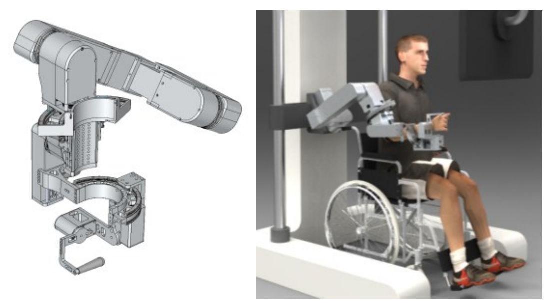

Fig. 2: The RehaBot upper limb design. (Left) 7 DOFs upper limb device and (Right) Illustration of a wearable exoskeleton arm with patient.

Throughout the upper limb rehabilitation device, we employed SEA's in the 3 joints surrounding the shoulder and the elbow joint, 3-SEA DOFs and 4 low-inertia direct drives.

C. Lower Limb Ambulatory Rehabilitation System Design

The design of a lower limb rehabilitation robotic training system includes SEA actuators, non-treadmill paddle system and haptic feedback technologies. The Hstar's RehaBot lower body extremity mechanism is an exoskeleton based concept. Fig. 4 shows the concept design of lower extremity ambulatory rehabilitation robot system. The RehaBot lower body system consists of a foot mechanism (4 DOF-All Active) and an active pelvis System (6 DOF-4 Active, 2 Passive)

Foot Mechanism: The Foot Mechanism is primarily a 4 DOF serial link Cartesian manipulator which drives the foot and causes the ankle to plantar and dorsi flex during the gait cycle. The main purpose of the Foot Mechanism is to create a virtual terrain for the patient. This terrain can be controlled to provide different reaction forces to the user or can be driven by the user in passive mode. Fig. 4 and 5 show the screenshots of the 4 DOF foot pedal system design for ambulatory gait training.

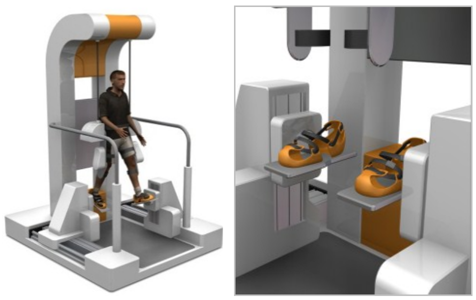

Fig. 3: The concept design of lower extremity ambulatory rehabilitation robot system.

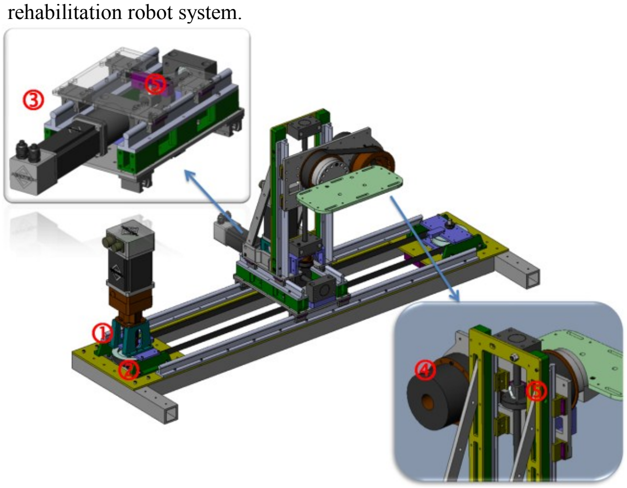

Fig. 4: Non - treadmill pedal system for lower-limb rehabilitation robot.

Active Pelvis System: The pelvic rehabilitation device consists of the following sub-assembly systems; a) Pelvic sub-assembly, b) Vertical DOF carriage assembly, c) Vertical support structure, and d) Frame assembly. The pelvic sub-assembly (Fig. 6 (right)) is a main assembly including a SEA-based hip flexion/extension DOF (❶), a passive hip abduction/adduction DOF (❷), a hip size adjust mechanism (❸), a compliant pelvic obliquity DOF (❹), a belt-driven hip rotation DOF (❺), and a passive knee joint.

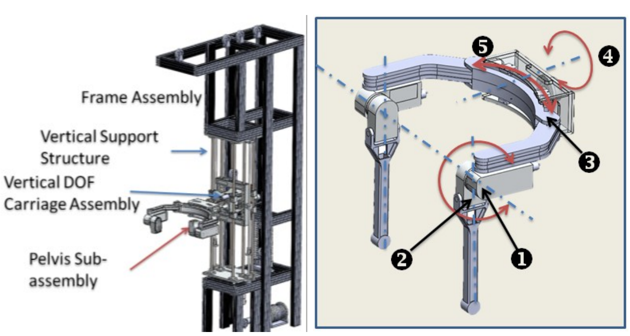

Fig. 6: (Left) Active pelvis system and (Right) pelvis sub-assembly.

D. Control System

The RehaBot system employs a layered patient-centered control system to provide reconfigurable progressive and direct rehabilitation training capabilities. The RehaBot control architecture runs on embedded PCs located on the robot. The layering scheme provides increasingly higher levels of abstraction from the physical robot hardware. The Robot-Sensory-Abstraction-Layer provides a unified representation and API that allows for the robot component hardware to be interchanged without significant changes to the control layers.

Gait Control: We implement gait control strategies relying upon information gathered using the motion tracking sensors. For patients with significant strength deficiencies, the gait control will be used to guide the patient's lower extremities and generate the desired walking pattern. This control modality is referred to as 'active control'. When patients improve sufficiently their ability to ambulate with weight support, the pelvis controller reduces support gradually according to how patients improve motor performance from session to session. With highly function patients, the gait control will turn into a partial active and partial reactive control.

Haptics Feedback for Advanced Robotic Performance and Safety: Haptic interfaces and force sensors are installed on the robot footplates to improve RehaBot rehabilitation capability and patient safety.

Feedback from Patient's Affective Status for Adaptive Robotic System Control: Patient affective data such as emotion and mental states will be used for robotic system parameter adaptation and optimization of the training process. Patient affective information will measure and track patient's engagement, and provide feedback for the system operation control. We develop an Affective Robot to improve patient's motivation.

Telepresence and Remote Supervision: The RehaBot should support telepresence robot interface, teleconsultation and remote supervision so that a physician / therapist can instruct or control the robot for a task configuration remotely. In this way, a physician / therapist can supervise multiple robots at his/her training control console. These telepresence robot control modules include: supervisory control, telepresence perception, teleoperation with manual interaction, teleoperation with force feedback, teleconsultation, and remote monitoring.

E. Safety Monitoring and Intervention Modules

For an actively controlled robotic system, safety monitoring is very important. A robotic system can be designed for lasting long, but not without errors or component malfunctions. Safety monitoring becomes a real time safe guard so that acceptance of the robotic system in real world can be possible beyond the function level. As a packaged module, safety, system self-diagnosis, warning signals and intervention mechanisms should be designed together and work together collectively.

III. PROTOTYPING AND PERFORMANCE TESTING

We completed the prototyping and the testing of the RehaBot lower foot mechanism hardware system. We also finished the prototyping of the pelvis system and upper limb rehab device and are currently assembling devices for testing. Using an example human locomotion data, we performed a series of the performance tests for the RehaBot foot mechanism with or without load. Fig. 7 shows a simplified human leg model and a walking trajectory data generated.

A trajectory control algorithm was created for gait training. In Fig. 8, we show screenshots of a pedal trajectory we controlled using an example human locomotion data. These tests achieved;

- The belt-drive mechanism achieved the desired speed/torque requirements for the horizontal X-axis.
- The direct ball screw drive achieved the desired speed for the lateral Y-axis.
- The power-transfer from right-angle gearbox to belt-pulley system to drive ball screw achieved the desired speed/torque requirements for the vertical Z-axis.

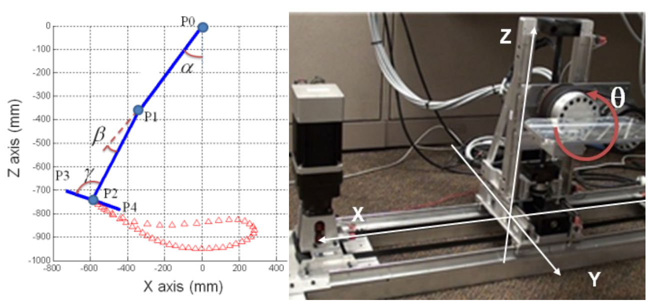

Fig. 7: (Left) A simplified human leg model and (Right) Coordination on pedal system.

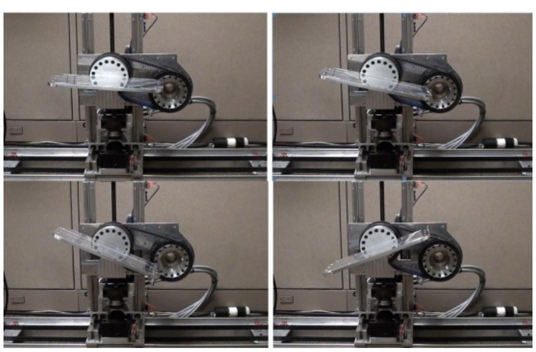
Fig. 8: Screenshots of the testing for foot pedal mechanism performance.

IV. CONCLUSION AND FUTURE WORK

The significance of developing an advanced medical robotic system like a RehaBot for augmenting healthcare capabilities is widely acknowledged. We have created an innovative design that is safe and feasible for hospital and medical center applications. The designed RehaBot system includes modular control software architecture that allows multiple operation control scenarios – direct operation control by means of human-robot interaction and telepresence control which works with a physical therapist directly or remotely via telepresence. The prototype system is a user friendly system and safe to use because of the series-elastic actuator based exoskeleton system and haptic feedback. The virtual reality scenarios will extend rehabilitation training procedures to many variable terrains and environments for more effective patient training. The real-time patient monitoring and performance measurement provides the progressive rehabilitation training and optimal performance. The exoskeleton part of RehaBot system design has a built-in safety mechanism and it will generate robust and effective rehabilitation training for TBI and SCI patients with neurological and musculo-skeletal functional impairment.

Through our preliminary systematic technology exploration we created the RehaBot system as a foundation for future enhancement. We will further develop and clinically validate RehaBot and its rehabilitation procedures. Finally, our RehaBot system when fully developed will significantly improve healthcare procedures and contribute groundbreaking technology to the medical care community as a whole.

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