Development and Preliminary Testing of a Novel Wheelchair Integrated Exercise/ Rehabilitation System

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Abstract— **The people with spinal cord injuries (SCI) or post stroke hemiplegia are easily exposed to secondary problems due to limited mobility. A new wheelchair integrated lower limb exercise/rehabilitation system is proposed to help their daily living and rehabilitation. The system consists of three main modules: 1) an electric wheelchair, 2) a lifter which raises and supports the subject's body weight, and 3) a lower limb exoskeleton. This paper describes the concept of the entire system and configurations of the prototype. In the design of the lower limb exoskeleton, the ergonomic joint mechanisms are introduced to assist the natural daily motions based on the biomechanics of each hip, knee and ankle joint.**

I. INTRODUCTION

The people with quadriplegia (e.g. C5 level SCI) spend most of their time in beds and wheelchairs. Therefore, they are easily exposed to secondary problems such as degeneration of cardiovascular system, muscle and joint contracture, and bed sores. Stroke is the leading cause of adult disability in the world [1]. The most common neurological impairment caused by stroke is hemiparesis which reduces the patient's control on voluntary movements. Even after some clinical rehabilitation routines, a part of stroke survivors live with difficulty in performing the essential motions (e.g. standing up and walking) in the daily activities [1]. Despite of the substantial necessities, the amount of their exercise and physical training is practically limited due to considerable amount of required man power in the conventional rehabilitation approach. In order to resolve such limitation of the manual training and to improve the patients' quality of life, advanced robotic technologies have been applied.

Robot-aided rehabilitation has following advantages: 1) it can significantly reduce the physical therapist's load during the training so that the patients can train a sufficient amount of repetitive motions, and 2) it enables a quantitative analysis and evaluation on the user's performance. The most common type of the rehabilitation robot for walking is a lower limb exoskeleton linked to a treadmill and a body weight support (BWS) system [3]. Lokomat [4] (Hocoma Inc., Switzerland) is a commercialized robotic orthosis which can perform partial BWS with a synchronized treadmill and a patient lifter. ALEX (Active leg exoskeleton) [7] is a motorized orthotic device which has linear actuators at hip and knee joints. In this system, a force-field controller is applied to realize the assist-as-needed paradigm. LOPES (Lower extremity powered exoskeleton) [8] is a lower limb exoskeleton which selects its operation mode depending on the required amount of assistance to perform an interactive gait training. PAM (Pelvic assist manipulator) and POGO (pneumatically operated gait orthosis) are actuated by pneumatic actuators to assist pelvic and leg motions with inherent compliance [9]. Also, the robotic exoskeletons can be utilized to assist the daily motions of physically impaired people. The Rewalk [10], eLEGS [11] are exoskeletons for paraplegics' walking assistance. In those systems, the robotic legs help the user's joint motions while the body balance is maintained by the forearm crutches. SUBAR [12]-[13] is a lower limb exoskeleton system with a smart caster walker. In this device, the user can keep the body balance by leaning the upper body on the caster walker during the motions.

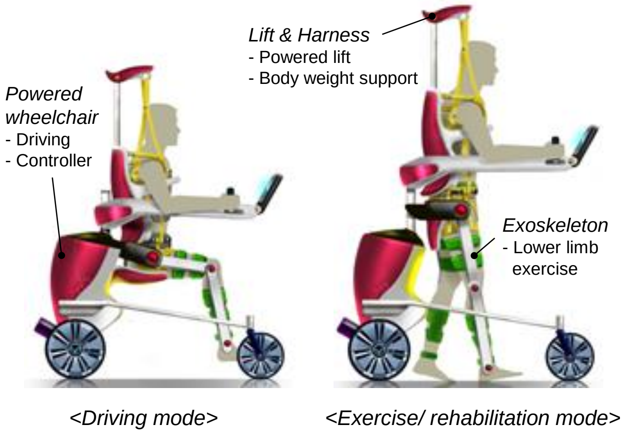

Figure 1. Conceptual sketch of the wheelchair integrated lower limb exercise/rehabilitation system for severely disabled people

The existing robotic rehabilitation devices such as Lokomat, ALEX, and LOPES should be installed in specialized facilities (e.g. hospitals or clinical centers) due to their significant sizes and costs, which practically limit the daily access of individual users. On the other hand, the aforementioned robotic walking assistance systems (i.e. Rewalk, eLEGS and SUBAR) are not suitable for people with severe disabilities such as quadriplegia since they require upper limb functions to keep the body balance. In this paper, the authors propose a new design concept of the exoskeletal robotic system which enables the severely disabled people to independently perform automated physical rehabilitation trainings during the daily activities. Basic design concept of the device focuses on the BWS training capable mobile exoskeleton system. Specific target group is severely disabled people who can barely move their limbs such as C5 to L2 level SCI people and post stroke hemiplegia. Fig. 1 represents a conceptual sketch of the developed device. The system

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features an exoskeleton integrated with an electric wheelchair and a patient lifter.

The proposed robotic wheelchair has following advantages: 1) it can enable the people with quadriplegia to have a daily access to the sufficient amounts of lower limb exercises and rehabilitation training; 2) the user can utilize the device as transportation (i.e. an electric wheelchair) in the driving mode. This paper focuses on the device concept, hardware mechanisms and implementation of the system.

In what follows, hardware configurations and functions of each module are described in Section II, the detailed design of exoskeleton joint mechanisms are presented in Section III. In section IV, software architecture including the user interface and control algorithm is introduced. For the performance verification, a healthy subject performed the essential movements in daily activities with the developed system and its results are given in Section V.

II. HARDWARE CONFIGURATION

Fig. 2 presents the prototype of the developed device. The entire system consists of the electric wheelchair module, the lift module for the body weight lift and support, and the lower limb exoskeleton module. Mobile base is composed of four wheels, a seat, arm rests and a back rest like a normal wheelchair. Driving wheels are equipped on the front side and the control box is installed on the back of the wheelchair. Each driving wheel is powered by a DC motor and the steering mechanism is controlled by the velocity difference of two driving wheels. All electronic parts (e.g. control units and batteries) are installed in the control box.

Lift module contains a main-lift which assists the user's standing up motion and a sub-lift which controls the amount of BWS (body weight support) during any lower limb motion. The linear actuator of the main-lift raises the back rest against the base frame of the wheelchair so that the user can be pushed forward and upward during the standing up motion. Load cells are integrated in the sub-lift to provide a feedback signal to maintain the amount of BWS during the walking motion. Safety equipment (i.e. safety bar, arm supports, and harness) is also installed in the lift module to maintain the user's trunk balance.

Figure 2. Prototype of the wheelchair integrated lower limb exercise/ rehabilitation system

The exoskeleton module assists the user's lower limb joint motions. Fig. 3 represents the degree-of-freedom (DOF) configuration of the device prototype which follows the natural human limb kinematics. For each leg, 6 DOF is considered: 3 DOF in hip, 1 DOF in knee, and 2 DOF in ankle joints (see axes of rotations in Fig. 3). The hip, knee and ankle joint motions on the sagittal plane (i.e. flexion and extension) are selected as active DOFs based on the biomechanics properties of the human walking [14]. At the distal end of the right arm rest, a joystick is installed as a user interface to let the patient control the device. Also, a touch screen panel is placed on the top of the control box to allow therapist to monitor and control the system.

The overall functions of the exercise/rehabilitation mode can be described as follows: 1) as the system captures user's intents to do exercise, the lift module helps the user to stand up, 2) as the walking or any predefined motion is initiated by the user, the exoskeleton mobilizes the his/her lower limb motion, and 3) the sub-lift controls the amount of BWS during the training motions by monitoring the lifting force measured by the load cells.

III. DESIGN OF THE EXOSKELETON JOINT MECHANISM

Human legs contain three joints (i.e. hip, knee and ankle) as shown in Fig. 3. The hip joint can be modeled as a ball-socket joint which has three independent DOFs (i.e. flexion/extension abduction/adduction, and internal/external rotations). The kinematics of knee joint can be described as a hinge joint (i.e. flexion/extension) with the varying center of rotation (COR) whereas the ankle joint has two independent

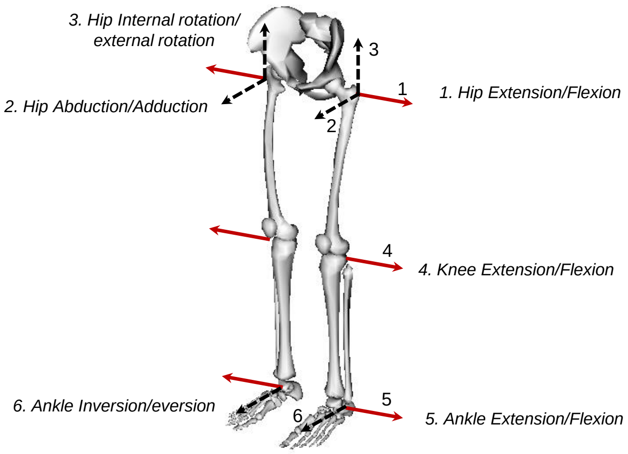


Figure 3. Joint configuration of the exoskeleton corresponding to the human lower limb DOFs

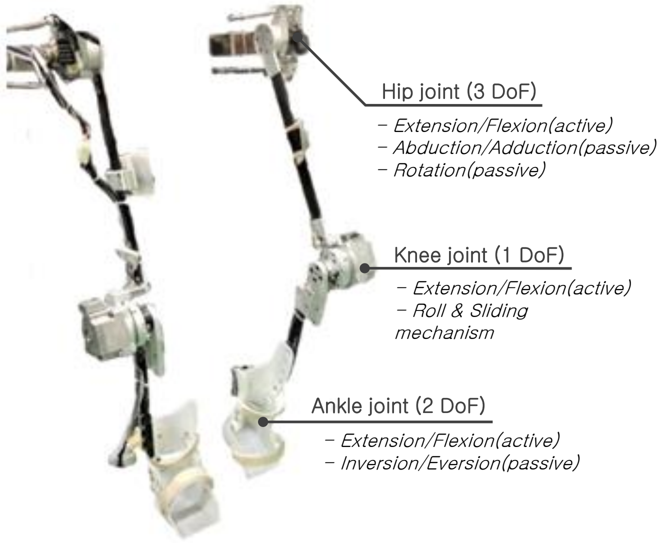


Figure 4. Prototype of the 12 DOF lower limb exoskeleton

DOFs (i.e. flexion/ extension and inversion/eversion).

From the human joint configuration, the exoskeleton is designed to have six DOFs per each leg (see Fig. 4). In order to determine the actuating DOFs among them, biomechanics data (e.g. required torque, angular velocity and range of motion) of human walking and standing up motions is evaluated [14]. Since the most of joint actions during these motions occur on the sagittal plane, each flexion/extension DOF is decided to be actuated.

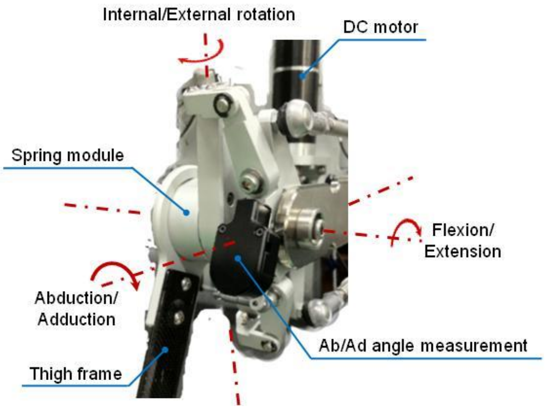
Each joint actuator is chosen based on the required torque for standing up and walking motion in maximum speed of 3km/h and 80Kg weight [14]-[15]. The overall structure of the exoskeleton is designed to follow the natural human leg kinematics. In order to minimize volume of the device, an anthropometric design is incorporated. It also has an advantage in the control issue by making the robot dynamics similar to the human limb dynamics.

A. Hip Joint Design

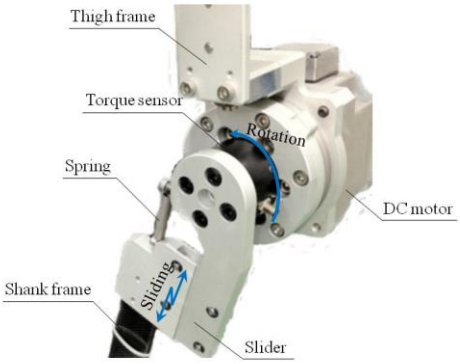
Human hip joint is a three DOFs ball-socket joint [16]. The axis of rotation for each DOF is aligned to penetrate the femoral head. In the exoskeleton design, only the axis of flexion/extension DOF is aligned to the real human DOF (see Fig. 5(a)). The other two passive DOFs are located near the human hip joint in a universal joint configuration.

The actuator in the active hip DOF is separated from the exoskeleton since it requires considerable power. In order to drive the hip flexion/extension DOFs, a high-power electric motor is installed at the back side of torso frame and power is transmitted through a four-bar linkage mechanism. At the axis, a torque sensor is installed to measure the interaction force between human and robot.

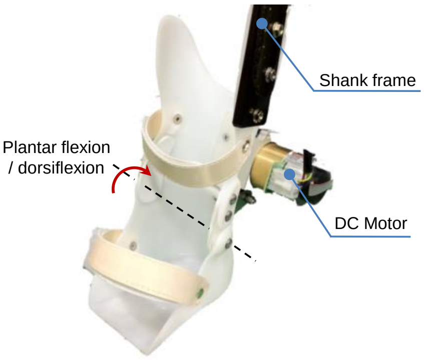
Two passive DOF were designed to have limited joint range of motion (ROM) to ensure wearer's safety (abduction 5deg., adduction 5deg., internal rotation 8deg., external rotation 8deg.). Within the passive DOFs, elastic springs are installed to keep them in the direction of origin angles to enhance the joint stability. At each axes of passive DOF, a potentiometer is installed to measure the angular position.



(a) Hip joint configuration



(b) Knee joint configuration



(c) Ankle joint configuration

Figure. 5 Detail view of the exoskeleton joint mechanism

B. Knee Joint Design

Human knee joint performs flexion/extension motion. As the COR varies along the flexion angle, the joint kinematics contains combinations of rolling and sliding motions (anterior-posterior translation) [17]. This complex joint motion can be approximated by a four-bar linkage model. From the kinematic analysis on the linkage model, the path of COR forms J-shaped curve around the femoral condyles.

In the linkage model, an additional sliding mechanism is utilized to realize the anterior-posterior translation during knee flexion (see Fig. 5(b)). As a result, the exoskeleton's shank frame extends its length along the additional sliding mechanism as the knee flexes. The stroke of the sliding mechanism is computed from the four bar linkage model of human knee motion [17]. The knee joint is driven by a flat type electric motor and a torque sensor is installed to capture the interactive torque between human subject and robot.

C. *Ankle Joint Design*

Human ankle joint consists of two independent DOFs, flexion/extension in the tibiotalar joint and inversion/eversion in the subtalar joint. In the exoskeleton design, the axis of flexion/extension is aligned with the tibiotalar joint axis: i.e. the normal axis to the transverse plane is 8 degree tilted in the lateral direction and the normal axis to the frontal plane is 6 degree tilted in the posterior direction [18].

According to the biomechanics data, human ankle joint requires most torque to support the subject's body weight [14]. In this design, a small size electric motor is selected for the ankle actuation since the user's body weight can be fully supported by the lift module. The passive inversion/eversion DOF is equipped with an elastic spring to keep its direction in the origin angle. Also for the natural motion of metatarsophalangeal joint, the rigid frame under the toe region is removed (see Fig. 5(c)).

IV. SOFTWARE ARCHITECTURE

The architecture of the overall control system is shown in the Fig. 6. The control system is composed of two main parts: Host computer and Real-time controller. The user or the therapist can interact with the system through system's user interface such as, joystick, touch screen, and emergency switch. The operator can control and/or monitor the system as follows:

- *Task selection*: The system executes the pre-defined tasks according to the command of therapist. The standing up, sitting down, walking, knee joint exercise, ankle joint exercise, stair climbing, and driving mode are implemented as pre-defined tasks.
- *Motion parameter adjustment*: User interface allows the therapist to easily adjust training parameters on the touch screen panel. For the gait training, stride length, gait speed, peak amplitude of joint angles, and the amount of BWS are adjustable parameters. In the knee and ankle joint exercise mode, joint ROM, cycle time, and number of repetition can be controlled.
- *Monitoring & Analysis*: Host computer graphically displays user's performance on the touch screen panel to let the therapist monitor and evaluate the patient's motor function based on quantitative data (e.g. exercise time, number of repetition, tracking error, assistive torque, and human-robot interaction force).
- *Start & Stop command*: User can always activate or deactivate the control command of the tasks by the joystick. In case of any abnormal motions, the system can be immediately stopped by an emergency stop button.

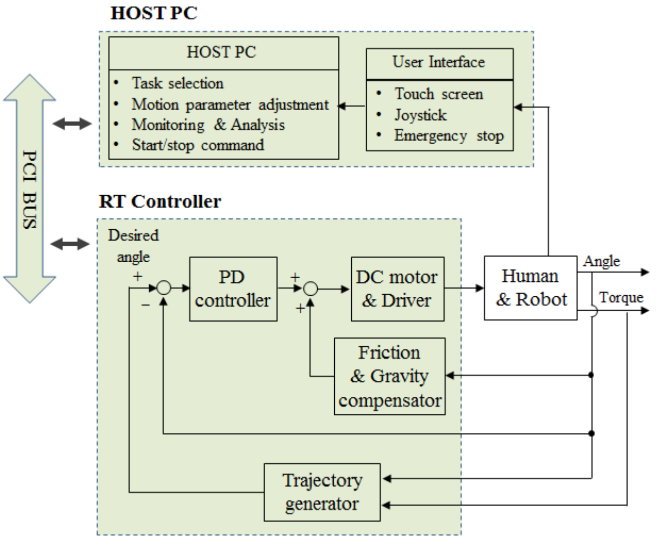


Figure 6. The arthitecture of the control system

Real-time controller collects data and processes it within a designed closed-loop feedback control structure. Real-time controller runs at 1 kHz sampling rate and communicates with the host computer through the PCI bus. As a preliminary controller, a joint position controller is implemented and has been tested. The position controller is tuned with high PD (proportional and derivative) gain for the robustness against disturbances. In addition, friction and gravity is compensated in a feed-forward manner to improve the tracking performance.

Exoskeleton joint trajectory is generated on-line according to the selected task and training parameter. Basic pattern of the trajectory of each task is pre-defined from human biomechanics data and experimental results. Gait pattern of the each hip, knee and ankle joint is derived from clinical gait analysis data [14]-[15]. In order to acquire the reference joint trajectories during other tasks (e.g. standing up, sitting down, stair climbing), a healthy person performed each motion without any control input (except the friction compensation control input) on the exoskeleton and recorded the joint kinematics.

V. EXPERIMENTAL RESULTS

To evaluate the performance of developed prototype, two healthy subjects were participated in the experiment. Each subject's information, such as height, weight, age, and sex was put into the computer (Subject A: 1.75 m height, 75 kgf weight, age of 27, male. Subject B: 1.70 m height, 60 kgf weight, age of 24, male). Prior to the experiments, the link lengths of the exoskeleton were adjusted to each subject's dimension. Following essential motions in the daily activities and functional exercises were performed and evaluated (see Fig. 7).

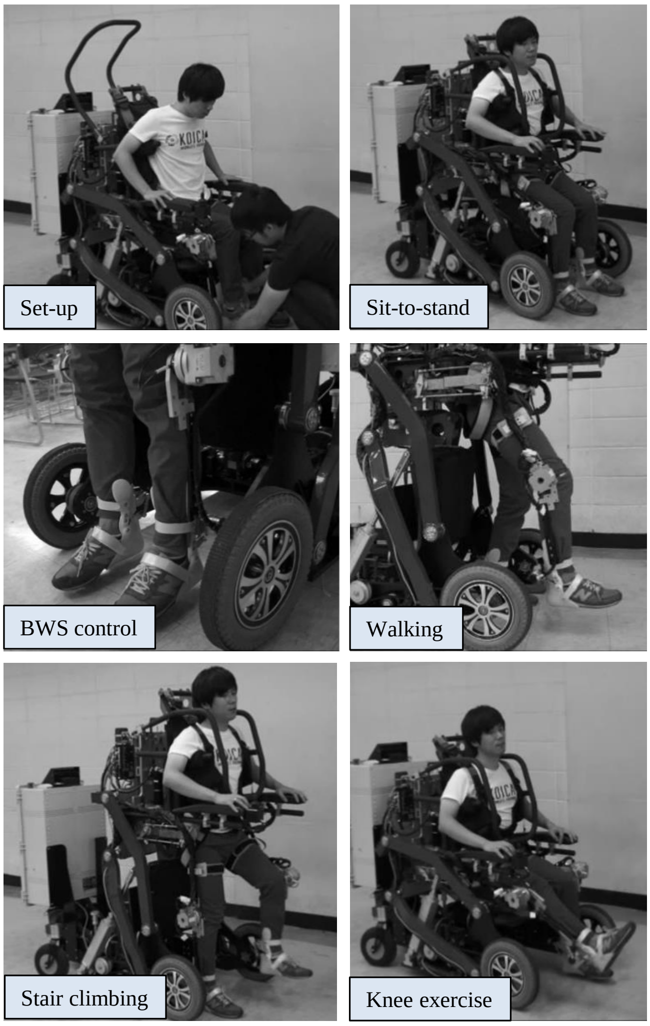


Figure 7. Funtional testing and evaluation of the developed system

- *Set-up*: The subject sits on the wheelchair seat and an assistant (or therapist) helps wearing the exoskeleton on the subject's leg. Harness and safety bar were fitted to the subject for safety.
- *Sit-to-stand*: Before the motion, subjects were asked to fully relax their upper and lower limb muscles as if they are quadriplegic. Both subjects successfully complete the standing up motion in 31 seconds. The subjects' feet were placed on the ground during the motion.
- *BWS control*: The assistant determines the amount of BWS while the subjects were in the standing posture. The lift module could lift up the subjects with 100% BWS so that the subjects' feet were placed to 80mm above the ground.
- *Walking*: A walking exercise with 100% BWS, 0.4m/s walking speed, and 0.85m stride length was tested. The joint tracking performance of position controller on each subject is plotted in Fig. 8. The ordinate represents the hip joint angle while the abscissa indicates the knee joint motion. As shown in

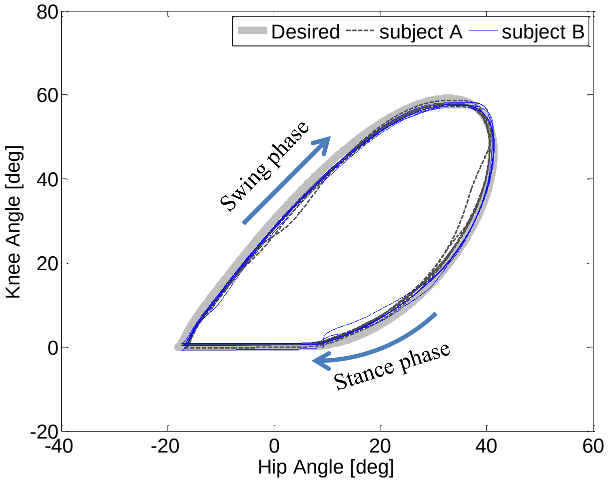


Figure 8. Hip vs. knee plot of the exoskeleton with the subjects at the walking experiments. Thick solid line represents desired joint angle, thin dotted line represents joint angle with the subject A, and thin solid line represents joint angle with the subject B.

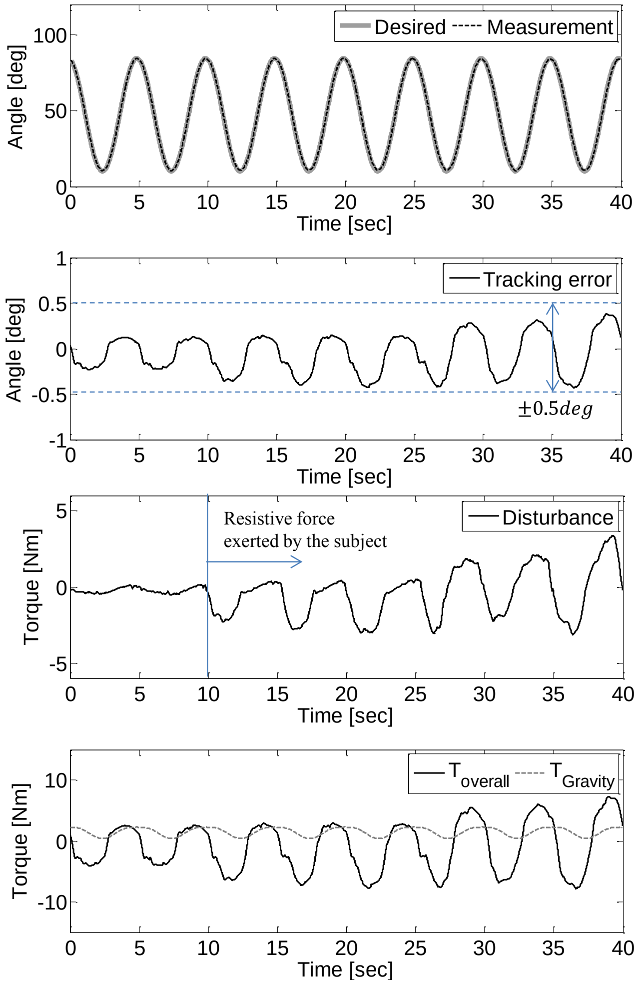


Figure 9. Joint controller tracking performance under knee joint exercise of the subject A. (a) desired and measurement joint angle, (b) tracking error of the joint angle, (c) measured disturbance at the joint, (d) assistive joint torque generate by actuator

the graph, the designed position controller enables the exoskeleton to track the desired joint trajectories regardless of subjects' height and weight.

- *Stair climbing*: The subjects performed stair climbing motion from the standing posture with the assumption that there is a 150 mm height virtual step in front of the subjects. Once the subject climbed a virtual step, then the exoskeleton hold the posture for 3 seconds. After that each joint angle were reversed back to the standing posture. This motion procedure was repeated five times for each leg.

- *Knee joint exercise*: In the sitting posture, the subjects followed the repetitive knee flexion and extension motion guided by the exoskeleton. During the motion, joint ROM was determined to 10~80 degrees of flexion with 5 seconds of cycle time. In order to verify the position controller's tracking performance against an external disturbance condition, each subject was asked resist the motion after two cycles of fully relaxed motion. In here, the generated interactive torque was measured by the torque sensor within the knee joint as the disturbance value. Fig. 9 represents the experimental results of subject A. Note that the magnitude of tracking error (see Fig. 9 (b)) stays within 0.41 degree even under the disturbance condition (35~40 seconds, maximum disturbance torque of 3.7 Nm) compare to the fully relaxed condition (0~5 seconds, maximum disturbance torque of 0.4 Nm).

VI. CONCLUSION

This paper introduces a novel robotic rehabilitation and assistance device for the severely disabled people to conduct automated rehabilitation trainings in daily activities. In order to realize a mobile BWS (body weight support) training system, a lower limb exoskeleton is integrated with a mobile platform (i.e. electric wheelchair) and a patient lifter. Based on the design concept, a prototype is fabricated and its performance is tested and evaluated through experiments. It is expected that the developed system can enable the people with quadriplegia to have a daily access to the sufficient amounts of lower limb exercises and rehabilitation trainings. The future works involve: 1) continuous system improvement in its performance and safety, and 2) actual implementation and clinical evaluation on the people with quadriplegia.

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