Kinematic Comparison of Gait Rehabilitation with Exoskeleton and End-Effector Devices

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Abstract Recently, various gait rehabilitation robots have been used as therapy in clinical fields for stroke, spinal cord injuries, and several neurological disorders. We investigated the kinematic differences with joint trajectories of two types of gait rehabilitation robots, i.e., exoskeleton and end-effector devices. Furthermore, we compared the end-effector device's stair climbing and descending motions to actual motions. The exoskeleton device shows larger hip and knee angle than the end-effector device during gait. However, exoskeleton ankle joint was restricted in dorsiflexed position. The end-effector device's stair climbing motion was similar to actual stair motion, although there was a delayed and lower maximum flexion. Compared with the actual motion, the stair descending motion had a lower maximum flexion angle for both hip and knee joints in the end-effector device. In addition, the end-effector device's ankle trajectory was aligned with the dorsiflexion angle, while descending to the bottom stair.

1 Introduction

Gait rehabilitation is a tough task for patients and therapists. Particularly, therapists need to take physical efforts for patients with severe conditions who have difficulty in walking independently. Nowadays, several gait rehabilitation systems are launched in the market for reducing these physical efforts and enlarging the time and

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This work was supported by the R&D Program of MOTIE/KEIT [10045164, Development of an overground gait rehabilitation robot technology with a success rate over 90 % in gait intention detection based on biosignal interface for various gait rehabilitation of stroke patients].

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J. González-Vargas et al. (eds.), *Wearable Robotics: Challenges and Trends*,
Biosystems & Biorobotics 16, DOI 10.1007/978-3-319-46532-6_35

number of gait rehabilitation interventions. These systems consist of a balance support module including body weight support, a robot module, and other modules such as virtual reality module for improving motivations.

Gait rehabilitation robots could be mainly divided into two types: exoskeleton and end-effector robotic devices [1]. The exoskeleton-type device has an external structural mechanism with joints and links in correspondence with a human body. However, the end-effector-based device has footplates that are mounted on the robot [2]. The end-effector-based robot does not need to be accurately aligned with the joints. The exoskeleton-based robot operates via smaller end-effector forces [3]. Robot-assisted gait training provides versatile control, but the expensive robot devices lead to efficiency debates in comparison with other conventional training techniques [2]. Some studies show significantly higher rates of independent walking during end-effector-based training compared with exoskeleton-based training [4]. The end-effector-based robot presents new features including climbing up and down the stairs [5].

The purpose of this study was kinematic comparison of gait trajectory of body joints, i.e., hip, knee, and ankle joints, provided by gait rehabilitation robots: exoskeleton-based and end-effector-based robots. In addition, we analyzed the up and down stair climbing motions for the end-effector-based robot. The analyzed data could be used to optimize intervention as well as for designing overground wearable robotic devices.

2 Materials and Methods

2.1 Robot Systems: Exoskeleton and End-Effector Devices

In this study, we used two types of gait rehabilitation robots as shown in Fig. 1. One is Lokomat robotic gait orthosis (Hocoma AG) system that consists of a treadmill, a dynamic unloading system, and two light-weight robotic actuators that attach to the subject's legs. The hip and knee joints are actuated by small DC motors and linear ball screw assemblies [6]. These motors do not require a high torque.

Fig. 1 Gait rehabilitation robot systems (*left* Lokomat, *right* G-EO system)

The other is G-EO System Evolution (RehaTechnology). This device allows securing the subjects with a harness while they stand on the footplates of the machine. The footplates have three degrees of freedom each, allowing control of the length and height of the steps and footplate angles [7].

2.2 *Procedure and Instrumentation*

One healthy male subject with no known neurological injuries or gait disorders participated in this study. All experimental procedures and risks were fully explained prior to his participation.

The subject walked at a comfortable pace (2.2 km/h) using the Lokomat, and a physical therapist who has used the Lokomat for over three years adjusted the step length of the Lokomat until the subject felt comfortable with the gait pattern. As with standard clinical practice, the Lokomat was operated in the position control mode with 100 % guidance force. A foot lifter was used in this study for blocking the foot drop during gait.

The G-EO system could adjust the ankle dorsiflexion angle at initial contact and the plantar flexion at toe off. Thus, we adjusted the gait speed, step length, and ankle angle of the G-EO until the subject felt comfortable with the gait pattern.

The hip, knee, and ankle range of motion in sagittal plane data during gait, stair climbing, and descending were captured using a flexible goniometer (SG Series; Biometrics Ltd) connected to a wireless transceiver (Delsys Trigno).

The stair climbing and descending motions were performed on real stairs that consists of total 12 stairs, which had a step height of 17 cm. We used foot-switches under each heel for detecting the gait cycle and start points of stair climbing and descending motions. The start points of stair climbing and descending motions were set to the timing of heel rise to perform each motion, respectively. To comparison of gait motion with robot devices, we added Winter's gait data [8].

3 Results and Discussion

3.1 *Comparison of Gait Motion Trajectory*

Generally, Lokomat shows greater hip joint trajectory than G-EO during gait. In late stance phase, G-EO kept the hip flexed and showed the lower hip flexion in swing phase compared with Lokomat. The knee joint trajectory of G-EO was kept flexed throughout gait. At initial contact, G-EO shows greater knee flexion and smaller swing phase than Lokomat. The Lokomat ankle trajectory was small and limited compared with G-EO because a foot lifter is applied to the ankle of the Lokomat. The foot lifter consists of a loop that is fastened around the ball of the foot to prevent the

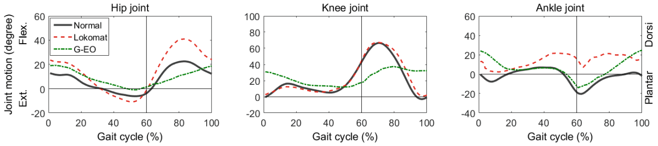


Fig. 2 Hip, knee, and ankle trajectories during gait. The *vertical line* represents toe-off. Normal data means Winter's [8] gait data

patient's foot drop in the treadmill while walking. Therefore, the Lokomat ankle trajectory was limited to perform only the plantar flexion (Fig. 2).

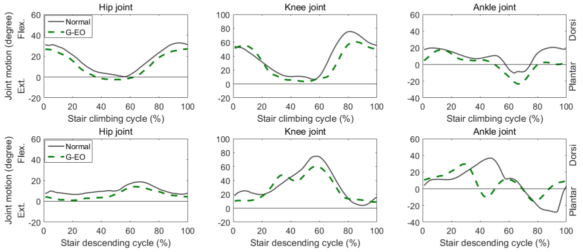
3.2 Comparison of Stair Climbing and Descending Motion

G-EO's stair climbing motion shows similar trajectories to the real stair climbing motion. However, the G-EO indicated a delayed and lower hip flexion compared with the real stair motion. These trends of delayed and lower maximum flexion are displayed similarly for the knee joint. The ankle trajectory of the G-EO shows larger plantar flexion when the foot is lifted until it is laid on the stair while climbing each stair.

The stair descending trajectory of the G-EO presents lower maximum hip flexion compared to the real stair descending motion. These trends were also observed for a knee joint. The ankle joint trajectory showed maximum plantar flexion while descending the bottom stair, but the G-EO showed increased dorsiflexed ankle trajectory during the stair descending motion (Fig. 3).

The two types of wearable robotic devices can have similar concepts of general stationary gait rehabilitation robots, such as Lokomat and G-EO. A wearable robotic device has an external mechanism, like ReWalk [9] and Robin-H [10], that corresponds with the human joints. Additionally, a wearable device has foot and ankle posture control with respect to the body trunk. The robot gait training is repeat the training in the context of the best obtained by limiting the degree of freedom confined to the artificial within the hardware and software framework of the patients. For the patients who can endure end-effector driven movements with

Fig. 3 Hip, knee, and ankle trajectories during stair climbing and descending (*Normal* actual stair climbing and descending motions)



trunk control, weight bearing and shifting, the end-effector devices allow dexterous ankle movements for the subjects with some motivation of self-determined hip and knee movements. An exoskeleton device effectively blocks foot drop using a foot lifter in the case of severe patients. In view of gait adaptation, exoskeleton device is much better than with end-effector device. However, an end-effector-based device is more effective to encourage a user's motivation.

4 Conclusion

In this study, we confirm the kinematic difference characteristics of the training motion of two types of gait rehabilitation robotic devices. Even though the analysis results are restricted to two devices, the results represent distinguished points for joint kinematics, such as ankle and other joints. For developing overground wearable robotic devices, the kinematic analysis results could be applicable. Further studies are required to evaluate not only the kinematics but also the kinetics of gait rehabilitation robots.

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