Brief Biomechanical Analysis on the Walking of Spinal Cord Injury Patients with a Lower Limb Exoskeleton Robot

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***Abstract*— This paper presents a brief biomechanical analysis on the walking behavior of spinal cord injury (SCI) patients. It is known that SCI patients who have serious injuries to their spines cannot walk, and hence, several walking assistance lower limb exoskeleton robots have been proposed whose assistance abilities are shown to be well customized. However, these robots are not yet fully helpful to all SCI patients for several reasons. To overcome these problems, an exact analysis and evaluation of the restored walking function while the exoskeleton is worn is important. In this work, walking behavior of SCI patients wearing the rehabilitation of brain injuries (ROBIN) lower-limb walking assistant exoskeleton was analyzed in comparison to that of normal unassisted walking. The analysis method and results presented herein can be used by other researchers to improve their robots.**

Keywords*— *ROBIN; SCI Patients; Lower Limb Exoskeleton; Walking Assistant

I. INTRODUCTION

Because outdoor activities are becoming popular, the number of spinal cord injured (SCI) patients is continually increasing. When the spinal cord is injured, a person experiences paralysis, palsy, numbness, and so on. Serious damage to the spine can result in a permanent and complete loss of sensory-motor functions. There are no known methods to recover or cure damage to the spine at this time. To help SCI patients with ambulation for daily activities, several walking assistant exoskeleton robots have been introduced. HAL[1,2], ReWalk, and eLegs[3] are well–known, commercialized or nearly commercialized, exoskeleton-type robots. In addition, several related studies on other lower-limb exoskeletons have also been published. ROBIN series robots[4–6], developed by the Korea Institute of Industrial Technology, is currently being evaluated in the Hospital of Chung-nam University. Recently, several research papers related to the Vanderbilt exoskeleton, which was developed by Vanderbilt University in U.S.A., have been actively published.

All these lower-limb exoskeleton robots for SCI patients share several common features. The first feature is that they offer limited walking function compared to that of an uninjured human. The lack of degrees of freedom for the lower limbs of an exoskeleton, the use of assistive devices (e.g., crutches, canes, and parallel bars), and different physical parameters such as center of mass and inertia, lead to differences in the walking behavior between normal and SCI patients. The second feature is that these robots, except for the Vanderbilt exoskeleton, are operated by the detection of intent from users. User intent detection is an essential function for walking assistant exoskeleton robots to be used in the daily lives of SCI patients. Hence, published papers about these robots are mainly focused on their user intent detection methods and the efficiency of the methods.

Previously mentioned research has shown that these robots can be well operated by the intent of users and that their lower limbs can be moved in a pre-defined gait pattern. However, there are no results from evaluations or analysis on the quality of walking of the SCI patient. When we conducted experiments on the walking of SCI patients with ROBIN-P1, the SCI patients expressed problems such as feelings of the lack of safety and stability, feelings of discomfort, difficulty in walking long distances, and pain in the wrist, elbow, and shoulder, which prevented the patient from being able to walk for more than thirty minutes. For SCI patients to be able to use these robots in their daily lives at home not only the rehabilitation center or hospital, the previously mentioned problems must be solved. We can expect that the causes of these problems are the defects in the mechanical design, the lack of required functions, changed behavior mechanisms of walking caused by wearing an exoskeleton frame and using assistive devices, and so on. Regardless of the cause of the problems, to find the exact causes, an analysis or evaluation process for the walking behavior of SCI patients with lower limb exoskeletons is required. It is commonly known that in the rehabilitation process, an exact evaluation of the functions of a patient after functional recovery, replacement or surgery is very important to recover the affected functions successfully. According to Daponte[10], the general scheme of the rehabilitation process can be represented as shown in Fig. 1. Walking assistance for SCI patients with lower limb exoskeleton robots could be considered as a functional replacement process. In this functional replacement process, evaluation after replacement is an important factor for

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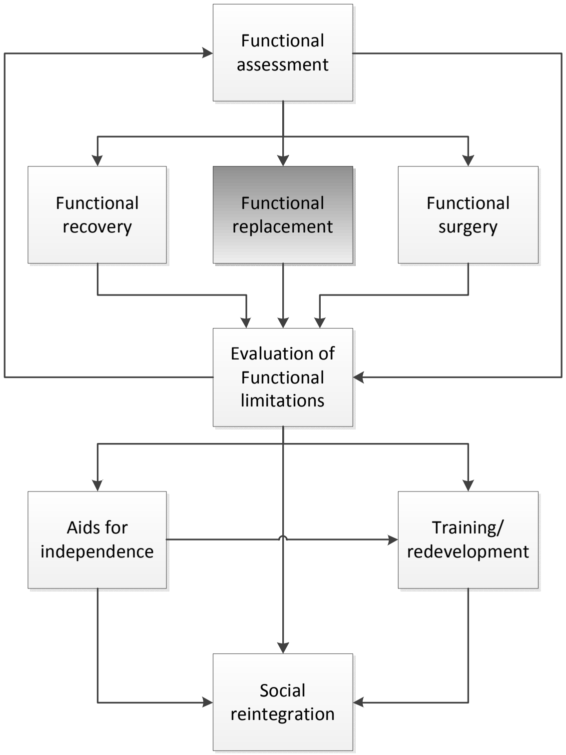

Fig. 1. *rehabilitation Process(Daponte [10])*

successful function recovery. Previously mentioned studies only conducted experiments to check whether the function of the replacement device satisfied the desired functions (e.g., intent detection or control of each joint on the pattern of gait). To achieve successful rehabilitation, further processes of evaluation are needed.

In this paper, we present the results of a brief biomechanical analysis that was conducted for a complete paraplegic SCI patient with a ROBIN lower limb exoskeleton robot. A general walking analysis method using the Vicon motion capture system that has the function of automatic walking analysis and manual analysis on the other factors are used.

Section 2 of our paper introduces the ROBIN lower limb exoskeleton robot and the method it uses to detect intent. Section 3 explains the environment of the experiment and shows the results. In Section 4, we discuss the results of the analysis. Finally, Section 5 contains our conclusions.

II. INTRODUCTION OF THE LOWER LIMB EXOSKELETON ROBOT ROBIN

In this section, we introduce the walking assistant exoskeleton robot, ROBIN, which was used to conduct the experiments. The research team from the Korea Institute of Industrial Technology developed the ROBIN series of exoskeleton robots to help with rehabilitation and enhance the quality of life of paraplegic patients.

The first prototype of ROBIN, ROBIN-P1, has the functions of sit-to-stand transfer, standing, walking, and stand-to-sit transfer to help with ambulation in the daily lives of paraplegic patients. For these function, the robot has 6 degrees of freedom (DOF) on the sagittal plane. A DC motor is attached at the hip and knee joint of each leg to provide assistive torque to the legs of a user. Ankle joints on each leg are passive joints with springs that follow compliantly with relation to the ground and bottom of the foot. Between the joints, there are links parallel to each segment of the lower limbs. An upper link extends from above the hip joint to the trunk of the body to cover the relative movement between the pelvis and the trunk and to restrict unwanted movement of the trunk of SCI patients.

As mentioned earlier, for the lower limb exoskeleton robots of SCI patients, assistive devices are needed to operate the robots safely. For the use of ROBIN, one pair of crutches is appropriate. These crutches help to facilitate the following functions: maintaining balance while walking, standing up, and sitting down, and detecting the intent of a user. To detect the intent of a user, ROBIN uses ground reaction force sensors and an inertial measurement unit attached to the body of the robot and the crutches. More specific information about ROBIN is available in previously published papers[5,6].

III. EXPERIMENT ENVIRONMENTS AND RESULTS

A. *Experiment Environment Settings*

The principle method of walking analysis is the comparison between affected walking and normal walking on the basis of several biomechanical factors and parameters. To refine the biomechanical parameters for the walking of an uninjured human, biomechanical data are needed. The process for obtaining this data is well known and corrected. The types of biomechanical data are anthropometric, kinematic, ground reaction forces, dynamic, and electromyography data. In this paper, we only focus on anthropometric and kinematic data. It seems that analysis of the others biomechanical data such as dynamics and electromyography data are not useful for the analysis of a robotic walking aid.

To capture the data in the movement of an SCI patient, the Vicon system was used. Vicon system is a well-known IR camera-based motion capture system and its effectiveness for walking analysis has been verified in many published studies. Our experiment was conducted in walking analysis room at Chung-nam University. In this experiment room, there were eight IR cameras, and four force plates. Data from the cameras and force plates were concurrently recorded and analyzed by the Nexus software of the Vicon system at a frequency of 100 Hz. For capturing body motion, generally, 35 IR markers are attached to the body of the subject. In the case of an exoskeleton wearer, the same method is used; however, some modification is needed. Because currently known lower limb exoskeleton robots do not have a pelvic structure, it is difficult to place the four markers that are normally attached to the pelvis of a human. This creates two problems. We attached four markers on the part of the link above the hip joint nearest to the pelvis to minimize error. Nevertheless, this placement selection can cause differences and errors in the process of transforming the captured marker position to joint angles and the position of center of mass (COM). The Vicon system contains the model of a human body. This body model is derived from the empirical knowledge on human anatomy to estimate anthropometric data. The length, width, and depth of subject's body segments and total weight are used to estimate anthropometric data. When the user wears the ROBIN robot, this model is not suitable to estimate accurate anthropometric data. Hence, the position of the center of mass is not accurate and is therefore unsuitable for comparison to the normal case. However, the comparison of the tendency of movement can be used to observe how the COM moves in the case of an SCI patient and to then evaluate the stability of the movement.

To guarantee the safety of the SCI patient during the experiment, several safety devices, such as a parallel bar on each side of the patient and an overhead safety line, were installed to prevent the patient from falling to the ground. A medical doctor as well as a physical therapist participated in this experiment to ensure the safety of the subject.

B. *Method and Subject*

The experiment was conducted with a completely paraplegic SCI patient who was injured at the eleventh thoracic vertebra (T11) and an uninjured person. One might ask why the uninjured person participated to capture his walking motion in this experiment. The analysis of normal walking is widely known; however, the conditions of the present experiment could be different from those of previous experiments or analyses. To compare walking under the same conditions, we conducted another walking analysis on an uninjured subject. The SCI patient wore ROBIN and walked several times. He was familiar with the use of ROBIN, had been trained in its use, and had used it for a year. He was also familiarized with the development process of ROBIN. To reduce the effects of fatigue from walking, the subject was made to rest at least 20 min after each trial. All the participating subjects had been informed about the specific procedures and objectives of this experiment, and they gave their consent. This experiment was conducted under the authorization of the Institutional Review Board of Chung-nam University. For analysis, 20 walking trials were conducted and recorded for each subject.

C. *Data Process*

Captured walking data are processed in two steps. The first step is automatic processing by the NEXUS program of the Vicon system. This program analyzes the walking of a human and outputs the relevant temporal and spatial parameters. The second step is done using raw data from the Vicon system. The raw data consist of positions of the markers, angles of each joint in three dimensions, angular velocity, position of the COM, etc. The raw data from one walking trail commonly include 7 or 8 strides. We divided this raw data into 7 or 8 pieces, each containing one stride, to normalize and average data from one walking cycle. To divide a complete data set into individual strides, each stride was classified by the tendency of ground reaction forces. One stride generally refers to the period from the initial contact with the ground of one leg to the next initial contact of that same leg. When one leg contacts the ground, the ground reaction force increases. Conversely, when the leg is in the swing phase, the ground reaction force reduces to zero.

D. *Result*

The walking of the paraplegic patient was analyzed on the basis of three factors. The first f was a kinematic factor, i.e., the angles of each joint on the sagittal plane. It is known that ROBIN only has two active joints in each leg. A kinematic factor comparison was done for these active hip and knee joints. The result is shown in Fig. 2. There were three representative differences between the walking of the uninjured person and the SCI patients. In the case of the SCI patient, the amount of movement in the joint was larger than that in the case of the uninjured subject. It seemed that the limited freedom of the pelvis in the sagittal and coronal planes caused this large movement to increase foot clearance in the swing phase. The sub-walking phases were also different. Normally, the portion of each walking sub-phase in a single stride are in the order: loading response (including initial contact, 0–10%), mid-stance (10–30%), terminal stance (30–50%), pre-swing (50–60%), initial swing (60–73%), mid-swing (73–87%), and terminal swing (87–100%). At near 50% of the stride, as shown in Fig. 2, the sub-phase of normal walking begins the pre-swing phase; in contrast, the SCI patient is still at the end of the mid-stance phase at 50% of the stride. In this figure, we notice that the stance phases (from the loading response to the terminal stance) are longer in the case of the SCI patient. The cause of this phenomenon could be that the patient had difficulty maintaining his balance, and it required more time to move the crutches to the anterior position. The effect of this first cause is normally seen in elderly persons. The final difference was observed in the early stage of a stride, the initial contact phase, when the shape of each joint was different between the SCI and uninjured patients. For the walking of an SCI patient, it seems that early initial contact occurred, yet the joints of the stance leg were not fully extended. There are two possible causes for this. The first is that there was insufficient

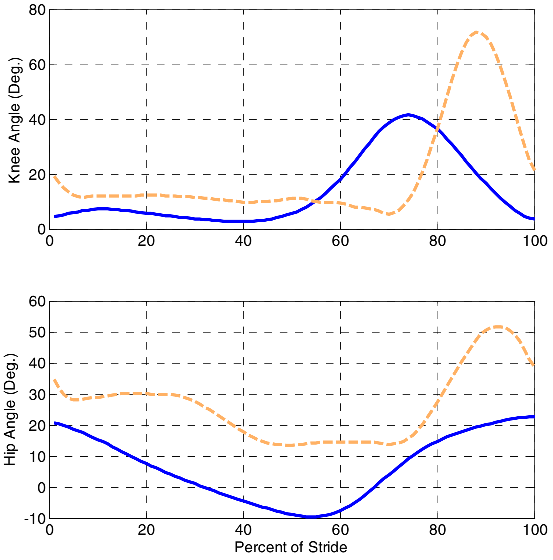

Fig. 2. *Joint angle comparisions between the uninjured and SCI patients. The solid line denotes hip and knee joints angle trajectory for one stride of the uninjured subject while the dotted lines denotes that of the SCI patient.*

interaction between the patient and the robot. The second is that the patient found it difficult to maintain his balance on one leg, as a result of which he unintentionally moved his COM toward the swing leg.

The second analysis performed was on the trajectory of the COM. Normally, the COM is located in front of the pelvis or umbilicus when a human is standing. It moves during the changing of the posture or moving of the body. In a normal walking stride, along the x axis, which is aligned in the direction from the posterior to the anterior, the COM moves forward linearly (Fig. 3). In the case of an SCI patient, however, the shape of the trajectory of the COM along the x axis resembles collapsing stairs. The forward movement of the COM of the SCI patient is not as clear, and the trajectory shape is considerably jagged. We believe that the cause of this phenomenon is that the balance of the body is not stable. Considering the y axis, the trajectory of the COM in the y direction is also different. This difference arises from using crutches. The crutches are moved forward for a double support or stance. At that time, the COM is located near the rear leg of the user; however, in the case of the uninjured subject, the COM is located between the two legs. This difference changes the position of the COM in the y direction in the initial contact phase, as shown in Fig. 3. The second difference is that in the case of SCI patient, there are high-frequency movements in the trajectory. This phenomenon also arises from the instabilities in the walking of the SCI patient.

Finally, we analyzed the temporal and spatial parameters of walking (table 1). In the case of normal walking, the proportions of double and single stances in a stride were 19.8% and 40.6%, respectively. An inversion of these proportions occurred when the SCI patient walked with ROBIN. The double-stance period consumed about 60% of a stride. Generally, this period is short in normal walking. However, for elderly or weak persons, the time spent in this period increases to maintain balance. For SCI patients using ROBIN, the process of moving crutches for advancing occurs several times during this period. Cadence, which is the step rate per minute, is about one-fifth that of normal walking in the case of an SCI patient. Time spent in a double stance and a single step result in this slow walking rate. Further, the step length of the SCI patient was half that of normal walking. Although the range of motion of ROBIN was similar to that of a human, the SCI patient encountered instabilities and walked with a reduced step length. These difficulties resulted in a slow walking speed with the walking speed of the SCI patient being about 7% of the normal walking speed.

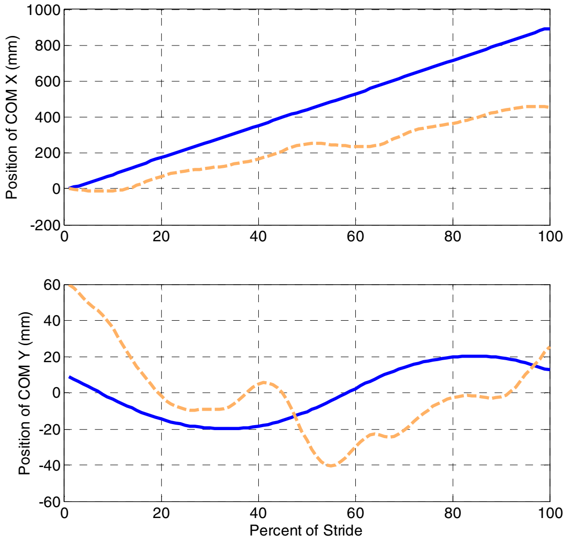

Fig. 3. *Comparision of the position of the COM between the uninjured and SCI patients. The solid line denotes COM trajectories during the stride of walking of an uninjured person, while the dotted lines denotes those of an SCI patient.*

IV. DISCUSSION

By comparing the walking of uninjured and SCI patients with ROBIN, we quantitatively and qualitatively evaluated the walking performance of ROBIN. There were three representative problems: insufficient interaction between the robot and the user, unstable movement, and an extremely slow walking speed. The causes of these problems could have been the limited degrees of freedom and functions and the influence of using crutches. Although the experiment was conducted with only ROBIN, this robot and other lower-limb exoskeletons for SCI patients share many similar features. These robots only have six degrees of freedoms on the sagittal plane from the foot to the trunk. As the pelvis lies between the thigh and the trunk, in the natural case there is one degree of freedom more than in the robot. Detecting user intent for these robots is a matter of recognizing a behavior pattern (which indicates a user’s intention), such as left step, right step, and final step, from a behavior set and a time cue (which indicate when a user wants to perform the action). This problem arises from the limitations of the body of the SCI patient. We believe that the previously mentioned problems could also occur with other robots.

V. CONCLUSION

In this paper, we presented a brief biomechanical analysis on the walking of a completely paraplegic SCI patient using ROBIN-P1. Although several studies related to walking assistant exoskeleton robots for SCI patients have shown acceptable results for the several functions of their robots, there are no analyses on the ability of SCI patients to walk using those robots. Analysis and evaluation are very important for improving the outcomes of functional replacement. For the analysis on the walking of an SCI patient, we conducted walking experiments with an SCI patient wearing a ROBIN lower-limb exoskeleton. Experiment data were captured and processed by the Vicon motion capture system. Three biomechanical parameters, namely, joint angles, positions of the COM, and temporal and spatial factors, were compared. In the comparison, we found several problems that made walking more difficult for the patient, and we inferred the causes of these problems. In the future, we plan to attempt the design of more patient-sensitive experiments and perform more specific analyses.

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