Short Papers

Design and Control of an Exoskeleton for the Elderly and Patients

Kyoungchul Kong and Doyoung Jeon

Abstract—**Recently, the exoskeletal power assistive equipment, which is a kind of wearable robot, has been widely developed to help human body motion. The exoskeleton for elderly people and patients, however, has some limitations due to the weight and volume of the equipment. In this paper, a tendon-driven exoskeletal power assistive device, exoskeleton for patients and the old by the Sogang University (EXPOS), is proposed as a feasible solution. In case of EXPOS, the caster walker carries heavy items such as motors, drivers, controllers, and batteries so that the weight and volume of the wearable exoskeleton are minimized. The tendon-connecting motors and pulleys of hip and knee generate the assistive power according to the requirement of the users. In this paper, the design concepts of the EXPOS, sensing techniques, and control methods are discussed.**

Index Terms—**Caster walker, exoskeleton, tendon-driven mechanism, wearable robot.**

I. Introduction

The exoskeletal power assistive device is a type of wearable robot that uses the synchronization of the human and the robot. In this area, there has been much research ranging from the rehabilitation equipment for muscle disease patients to the power-amplifying devices for the soldiers who carry heavy military equipment [2]–[4]. As society now has more elderly than ever, it will encounter the lack of young people who support them physically and financially. Robotic research will contribute to solve some of the problems of the aging society. The wearable robot may be a solution that helps elderly people to live without the physical assistance of young people. Also, the wearable robot can help the rehabilitation of patients who have nervous and muscular diseases. Out of every one million people in the United States, approximately one thousand people will be diagnised with multiple sclerosis annually, which is a muscular disease [5].

Our aim in designing the exoskeletal device was to minimize the weight and volume of the wearable robot so that the elderly and patients can use it conveniently. When it is difficult for the elderly and patients to keep their balance while walking, they may want to hold on to something. For this reason, a caster walker is introduced for holding and locating the heavy parts such as motors, drivers, controllers, and batteries. The wearable equipment consists of pulleys and tendon so that the weight becomes less than 3 kg.

Servo motors are used for the hybrid assistive leg (HAL) [6]–[8], and a hydraulic driving unit is used for the Berkeley lower extremity exoskeleton (BLEEX) [2]. The power-assisted suits for the nurses are actuated by pneumatic actuators [9]. The series elastic actuator (SEA) is used for an exoskeleton for the knee and the ankle [10], [11].

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Fig. 1. Picture of the EXPOS.

Two control methods are usually applied for the exoskeleton systems: 1) the phase-sequence method for the HAL [6] and 2) the neural network theory [12], [13]. In this paper, the torque mode control using the fuzzy method is applied, and its experimental results are discussed.

II. Design Concepts of the Expos

In this paper, a smart caster walker and wearable exoskeleton are introduced (Fig. 1). For the elderly and patients, the wearable exoskeleton should be as light as possible for convenience, and the caster walker needs to be heavy enough to keep the body in balance when the user holds it. Although the exoskeleton for patients and the old by Sogang University (EXPOS) works on flat surfaces, it is usually suitable for use within the living space of the elderly and the patients.

A double-layered wire is used to transfer the power. As the motor in the caster walker rotates, the pulleys of the wearable exoskeleton rotate by the wire as shown in Fig. 2. The wire connecting the hip and knee joints has springs to maintain proper tension. When the spring constant k is small, the assistive torque is not transferred properly. When it is large, the efficiency decreases due to the friction of the pulleys. Hence the stiffness of the spring has to be carefully chosen.

For the convenience of wearing and divesting the device, the disconnectable power transmission is shown in Fig. 3. When power assistance is not necessary, a user may disconnect the device as shown in Fig. 3(b) and move freely while wearing the exoskeleton. For the safety of the device, the mechanical angle stoppers for joints are installed to prevent excessive motion, and an emergency switch is

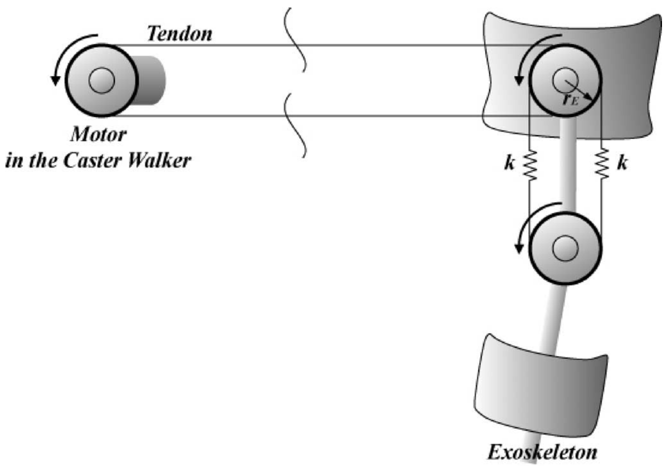
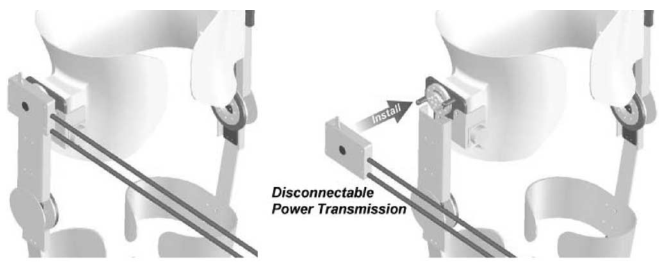


Fig. 2. Schematic plot of the tendon-driven mechanism.



(a) (b)

Fig. 3. Disconnectable power transmission unit. (a) Installed. (b) Removed.

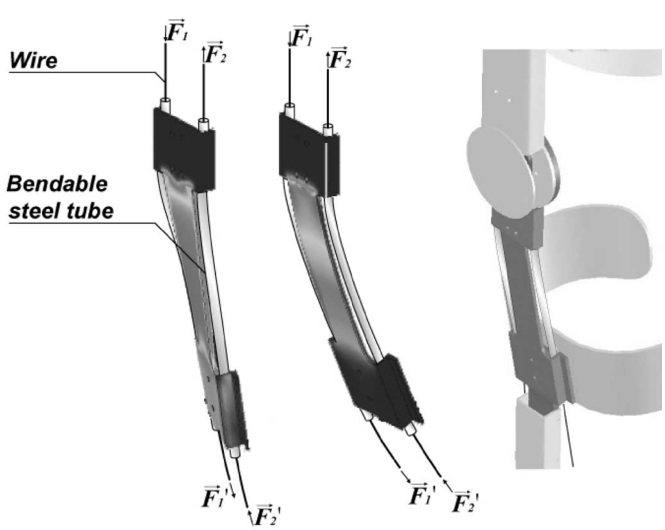


Fig. 4. Flexible frame for flexibility.

installed on the caster walker in order to protect the user in the event of malfunction.

The natural motion of human walk consists of motion on the transverse and frontal plane as well as on the sagittal plane [14]. To guarantee the natural motion of a user wearing an exoskeleton, a flexible frame of engineering plastic is applied as shown in Fig. 4. To transfer the power to the knee joint, the wires pass through the flexible frame and may lose

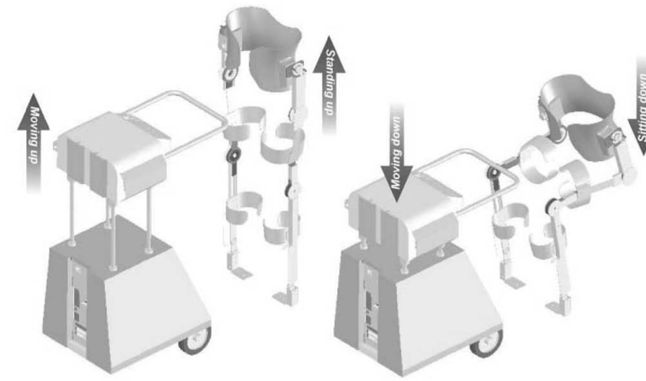


Fig. 5. Up–down mechanism for the handle of the caster walker.

proper tension due to the deformation of the frame. Thus, a bendable but uncontractable tube is used to keep the tension of wires as shown in Fig. 4. Even though the tube and the frame are deformed, the length is maintained and the wires keep the tension. When the friction inside the tube is ignored, F_1 and F_1' in Fig. 4 have the same magnitude in different directions.

As shown in Fig. 1, the EXPOS has four active joints; one degree of freedom for each of the hip and the knee joints. It has more degrees of freedom by flexible frame for bending and twisting as shown in Fig. 4 and two degrees of freedom for each ankle joint.

As the hip and the knee joints require torque in both directions [15], they are actively assisted by controlling four servo motor controls on the caster walker. However, as the ankle joint requires the torque mostly only in one direction, the ankle joint is passively assisted by using shock absorbers. In other words, the shock absorbers reduce the impact and the spring inside them accumulates energy. The spring force helps the walking by dissipating energy. The appropriate power of the shock absorber is selected through experimental results by comparing the rms values of the EMG signals.

The caster walker has a handle bar which can be lifted up and down by pneumatic actuators as shown in Fig. 5. As the height of the handle bar is synchronized with the up–down motion of a user, sitting down and standing up actions are conveniently performed. Also, the distance between the caster walker and the user is maintained as they are constrained by the wires.

The caster walker has to be heavy enough to support a user but the elderly and patients do not have enough strength to push the heavy caster walker. For this reason, the caster walker has four wheels actuated by motors. In other words, the caster walker may lead the motion of a user.

III. Sensing Technique

Potentiometers are installed at the pulleys of the wearable part in order to measure the angle and calculate the joint velocity for each joint. Pressure sensors are installed at the thigh braces and the shoes to estimate the requirement of the person who wears the exoskeleton. Fig. 6 shows how the pressure sensor measures the muscle movement [1]. When the brain orders a joint to move, an electric signal is transferred to the muscle through the neuron. The muscle then contracts or relaxes to generate the muscular power and it pushes the air bladder which is tightly attached on the muscle and wrapped by braces. The pressure sensor measures the pressure change of the air bladder. As the muscle contracts before the joint action, the sensor signal precedes the joint movement.

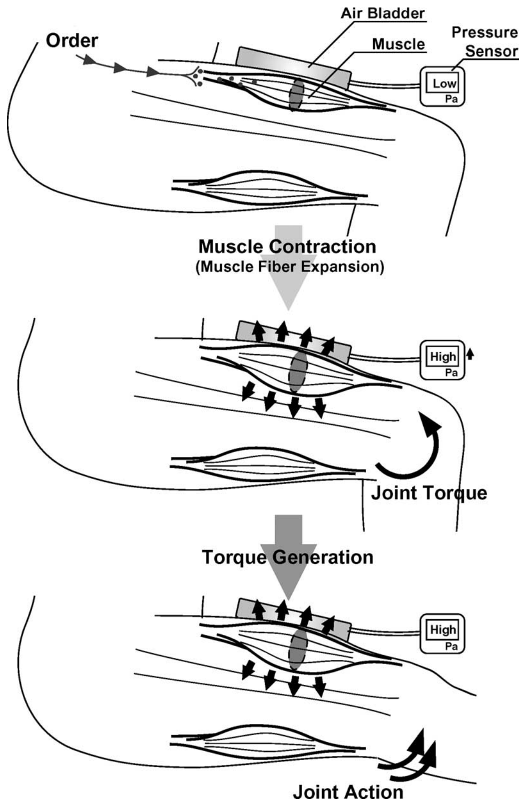


Fig. 6. Principle of pressure sensor.

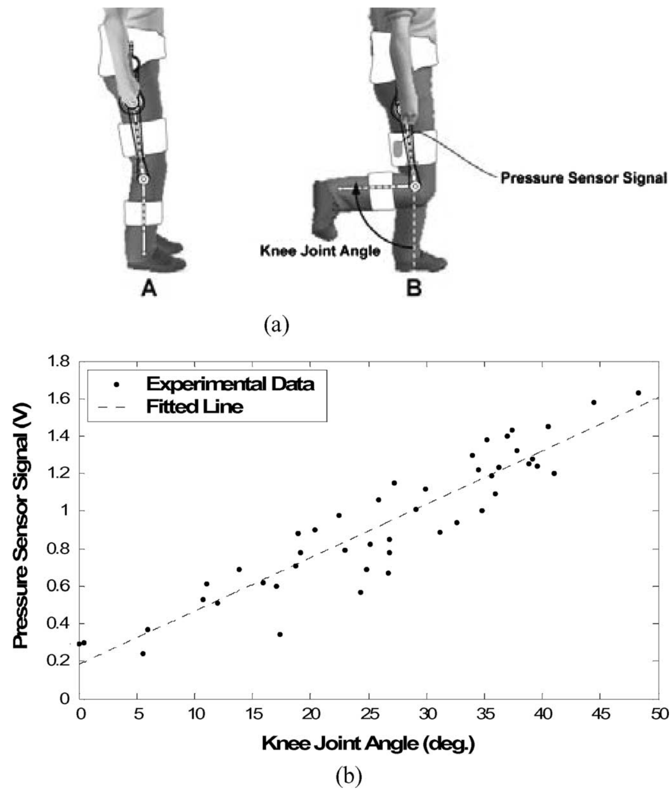


Fig. 8. Proportionality between the pressure sensor signal and the joint angle. (a) Experimental condition. (b) Experimental data and fitted line.

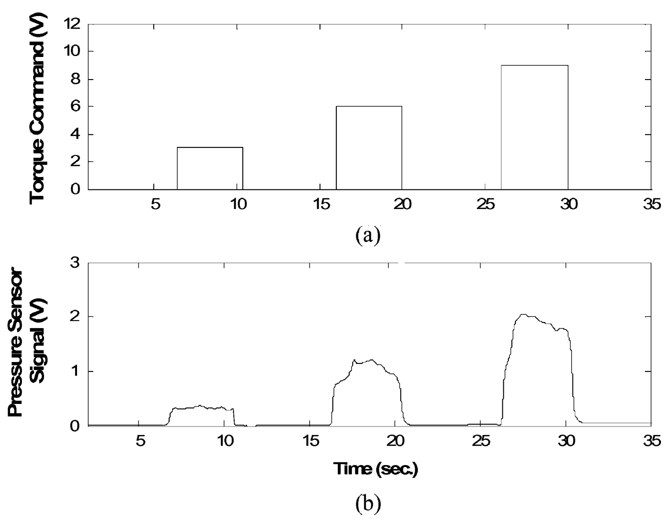


Fig. 7. Comparison of the pressure signal at thigh and applied torque. (a) Input voltages to apply torque. (b) Pressure sensor signal by resisting the torque.

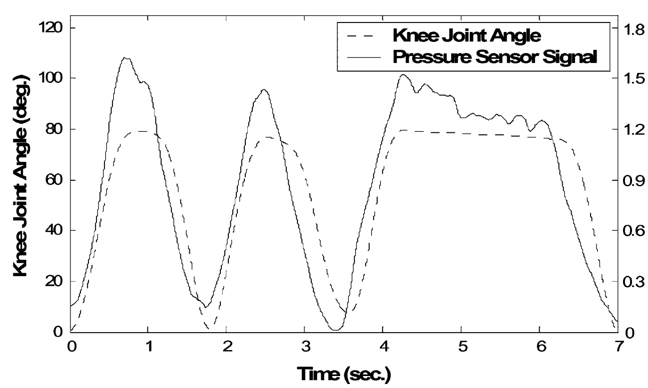


Fig. 9. Comparison of the knee joint angle and the pressure sensor signal.

The pressure signal at the thigh tends to be in proportion to the joint torque. Fig. 7(b) represents the pressure signal at the thigh when a person stands resisting the torque applied by motors as shown in Fig. 7(a). As the measured signal shows uniform values without noise, the complicated filter which causes the phase delay is not required.

When a person stands [see Fig. 8(a)], the pressure signal during the lifting up of the thigh is proportional to the knee joint angle [Fig. 8(b)]. This shows that the pressure sensor is useful to detect and estimate the motion.

To compensate for the time delay of motors and tendons, the sensor signal should precede the joint movement. Fig. 9 shows the knee joint angle measured by potentiometers and pressure sensor signal under the same conditions as in Fig. 8. As the pressure signal precedes the joint angle by approximately 0.3 s, the pressure sensors can be used to detect the motion of the users and the dynamic delay of the motor system can be compensated for.

The difference between the pressure sensor measurements on opposite sides of the brace may be used to estimate the torques of the hip and the knee joints. The torques of the hip and the knee joints can be estimated as follows:

$$\hat{\tau}_{\mathrm{assist}} = k_0(P_{\mathrm{front}} - sP_{\mathrm{rear}} - \mathrm{bias}) \tag{1}$$

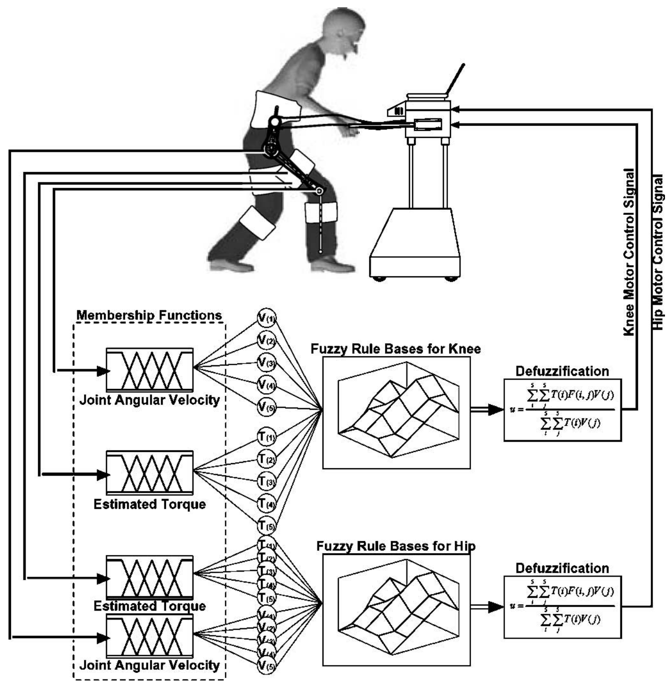


Fig. 10. Schematic plot of the overall control system.

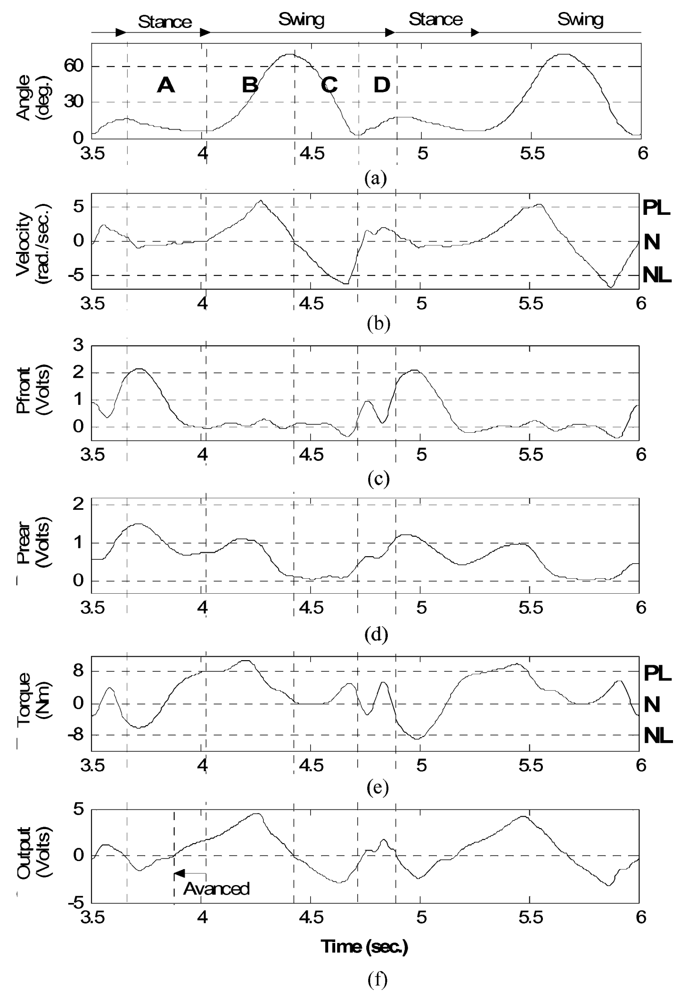


Fig. 11. Controller analysis. (a) Knee joint angle. (b) Knee joint angular velocity; PL, N, and NL mean positive large, normal, and negative large, respectively. (c) P_{front} : pressure signal in the front side of brace (on the Vastus Medialis muscle). (d) P_{rear} : pressure signal in the rear side of brace (on the biceps femoris muscle). (e) Estimated joint torque using (1); PL, N, and NL mean positive large, normal, and negative large, respectively. (f) Fuzzy controller output.

where k_0 is the scaling factor of the joint torque, s is a parameter used to adjust the sensor signals, P_{front} is the pressure signal in the front side of the brace, and P_{rear} is the pressure signal in the back side. The k_0 and s values depend on the users. Even the bias changes according to the tightness of braces. The parameters can be decided by some initial actions such as comfortable standing and sitting. When the wearable robot does not fit the user's legs, the sensors do not measure the muscle movement properly. Therefore, frames and braces of the EXPOS should be fitted for each individual.

IV. Control Method and Experiment

The movement of the muscle consists of three modes: active mode, passive mode, and free mode. Muscular power is generated by the muscle contraction in an active mode and by the muscle relaxation in a passive mode [14]. The muscle can be contracted or relaxed without generating the muscle power in the free mode [14]. The pressure signal cannot be exactly measured in the free mode, and consequently the exoskeleton may disturb the user's motion. The joint angular velocity is used to solve this problem during the free mode. When the sensor signal is small while the joint is moving, the motor is driven in the direction of the joint angular velocity in order to remove the resistance of the motors and the gears.

Fig. 10 shows the entire configuration of the control structure. In order to control the motor that drives the hip and the knee joints, each fuzzy membership function, fuzzy rules, and the defuzzification function are decided. A triangle function is used for fuzzy membership functions, and the interpolation is used for defuzzification.

Following rules are configured to set the fuzzy rules: 1) if the torque calculated using (1) is small and the absolute value of the joint velocity is large, the motor input depends on the joint velocity because the muscle is moving in the free mode, 2) if the calculated torque is large and the absolute value of joint velocity is small, the motor input depends on the calculated torque, and 3) if the calculated joint torque and joint velocity are in the same direction, the motor input is maximum.

Fig. 11 shows the data of right knee joint for two cycles during the normal gait. Fig. 11(a) and (b) shows the angular position and velocity, respectively. In Fig. 11(a), zero degree represents the full extension of the knee joint. Fig. 11(c) and (d), respectively, shows P_{front} and P_{rear} values that are used in (1). In the A position, the user's right leg performs stance motion and both P_{front} and P_{rear} show large values because both muscles contract to make the joints stiff and to maintain body balance. However, in the B position which represents swinging motion, the user lifts his calf, and only P_{rear} shows a large value because only the muscle in the rear side of the thigh actively generates the muscular power. Fig. 11(e) shows the estimated torque from P_{front} in Fig. 11(c) and P_{rear} in Fig. 11(d) as given in (1). Fig. 11(f) shows the fuzzy controller output combining the estimated joint torque in Fig. 11(e) and the joint angular velocity in Fig. 11(b). As the pressure sensor can measure the muscular movement in advance, the controller output is generated before the user's action such as swinging motion as marked with "Advanced" in Fig. 11(f). In the C position, the magnitude of the estimated joint torque in Fig. 11(e)

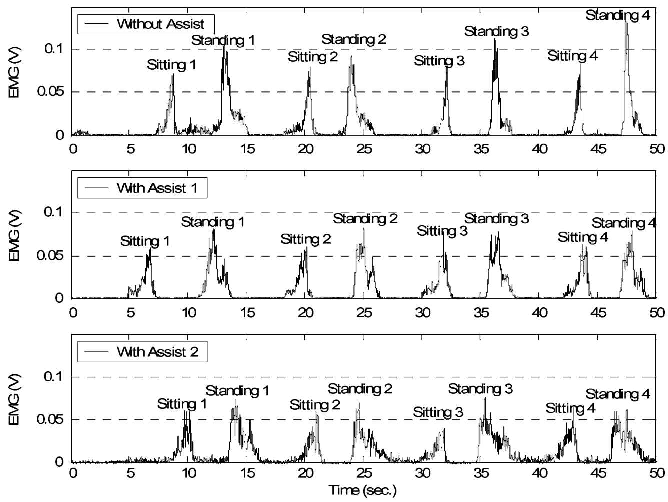


Fig. 12. Comparison of EMG signal with and without assistance.

TABLE I
PEAK VALUES OF EMG SIGNAL

	Without Assist (Peak[V])	With Assist (Peak[V])				Assistant Effect
		Exp. 1	Exp. 2	Exp. 3	Exp. 4	
Standing 1	0.118	0.081	0.071	0.084	0.075	-
Standing 2	0.093	0.083	0.072	0.092	0.078	-
Standing 3	0.113	0.072	0.074	0.079	0.082	-
Standing 4	0.135	0.079	0.079	0.071	0.082	-
Average	0.115	0.079	0.074	0.082	0.079	32.2%
	(=*a*)	0.078 (=*b*)				(=*c*)

The assistant effect, *c*, is calculated as follows, $c=100\times(a-b)/a$.

Fig. 13. Picture of the EXPOS with an elderly person.

is not very large, and the controller output is decided according to the joint angular velocity [see Fig. 11(b)] to remove the friction of motor systems.

As the EMG signal presents the scale of the muscular power [15], [16], an EMG sensor was used to quantitatively evaluate the assistant effect. The EMG signals with and without wearing the EXPOS for sitting and standing actions are compared. Fig. 12 shows the absolute values of EMG signals in experiments. The actions were repeated four times for 50 s. To evaluate the assistance effect, the peak values at the standing up motion were compared as the maximum torque is required for this motion. Table I represents the peak values for four sets of experiments. When the average values of peaks are compared, it is observed that 32% of muscular power was assisted with the EXPOS.

V. CONCLUSION

This paper proposes the tendon-driven exoskeletal assistive device, EXPOS, which consists of a wearable exoskeleton and caster walker to overcome the drawbacks of the exoskeleton for the elderly and the patients. Fig. 13 shows the EXPOS and a user. The user in Fig. 13 responded that the EXPOS helped him to walk, sit down, and stand up fairly well. Although there are many things to be improved in the design and control, the feasibility of the wearable exoskeleton for the elderly is demonstrated.

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