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Standing Mobility Vehicle with Passive Exoskeleton Assisting Voluntary Postural Changes

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Abstract— **This study proposes a novel personal mobility vehicle for supporting and assisting people with disabled lower limbs. The developed mobile platform is capable of assisting voluntary postural transition between standing and sitting, called the Passively Assistive Limb (PAL) mechanism, in addition to high mobility with upright posture. The device consists of gas-spring-powered passive exoskeleton for postural support and two in-wheel motors for mobility support. The developed robot system allows a user to sit down on chairs and beds, and stand up through easy operations. In addition, a user can move the system in the standing posture without using their hands. In this paper, the development and assessments of the standing mobility vehicle are described.**

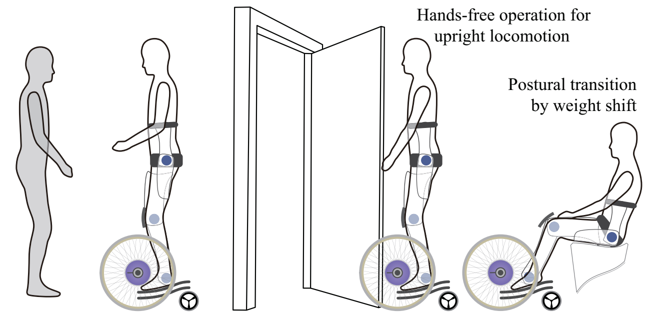

Fig. 1. Usage example of developed PMV

I. INTRODUCTION

There are a large number of wheelchair users with permanent disability in their lower limbs. For example, about 270,000 patients of spinal cord injury (SCI) in the U.S. have reduced motor function in the affected limb. Almost 40% of these patients have gotten the injury by traffic accidents, and the average age at injury is 41.0 years [1]. Many of them were injured in their younger years. However, apart from wheelchairs, there are not sufficient options that can substitute for the SCI patients' locomotion functions even though the function is essential for their social life. Robotic artificial legs [2][3] for prosthesis, a wearable robot suit [4] for rehabilitation, and a standing-style locomotion system for persons with SCI [5] have been developed so far. However, these robotic systems have not been developed to the extent where they can be used for assisting the daily locomotion of patients with disabled lower limbs.

Being on a wheelchair, patients are constrained in the sitting posture, which causes them inconvenience in social life because almost all social environments are designed for able-bodied persons who can stand. Furthermore, the sitting posture makes it difficult for patients to communicate using gestures as they are walking with others because of the difference in viewpoints and upper body heights [6]. In addition, wheelchair users cannot use their hands while they are moving because a wheelchair requires at least one hand for operation. On the other hand, the standing posture has medical benefits on bone metabolism and the circulatory system, as well as mental benefits such as improvement of independence [7]. From this viewpoint, some upright wheelchairs have been developed such as LEVO (LEVO AG) [8] and Superior (Superior Sweden AB) [9].

Personal mobility vehicle (PMV), which is a newly emerging transportation system for individuals, affords mobility functions that can be placed between those of walking and existing vehicles such as automobiles, motorbikes, and bicycles [10], for example, Segway PT (Segway, Inc.) [11] and Winglet (Toyota Motor Corp.) [12]. These PMVs have high controllability and mobility so that users can move in the upright posture. However, they are designed for able-bodied persons who can stand without assistance.

In this paper, we propose a high-mobility PMV with upright posture for assisting persons with disabled lower limbs. We consider people who have healthy upper bodies as the main target of this study because their social independence is expected to be greatly improved owing to the assistance from the lower limbs. Figure 1 shows the developmental target of this research. The PMV has a wearable and passive exoskeleton with locomotive function afforded by electrically driven wheels, and it assists voluntary postural changes such as sitting, standing, and moving in the upright posture through hands-free operation.

II. APPROACH

A schematic diagram of the developed PMV is shown in Fig. 2. It consists of a passive exoskeleton and wheels driven by electric motors. The exoskeleton assists the user with sitting, standing, or maintaining either of the aforementioned postures. In addition, it also works as an interface that infers the user's locomotion intention based on the trunk's joint angle. The user is able to execute upright locomotion by the combination of these devices, and it allows for diverse social activities such as using a vending machine, passing through, opening and closing a door, and using a shelf

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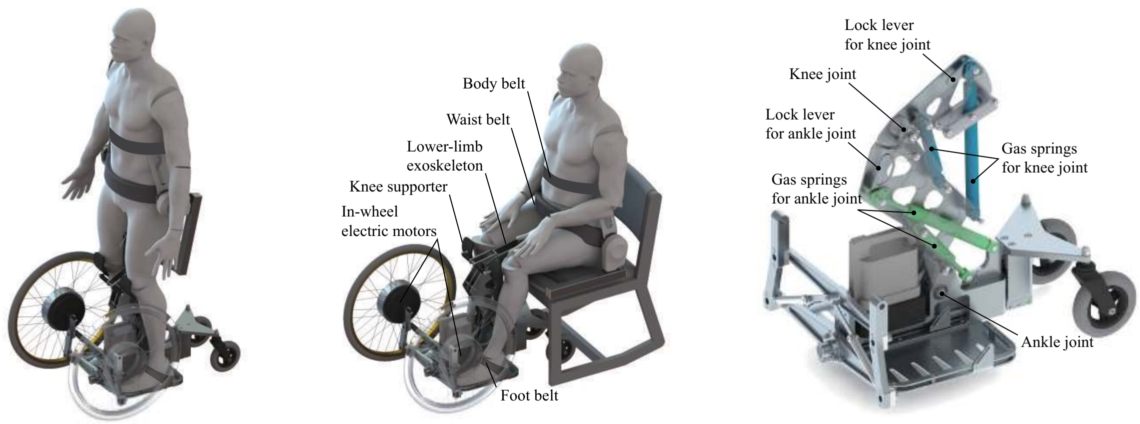

Fig. 2. Outline drawing and internal structure of PMV

designed for use in standing posture. In addition, the PMV facilitates communication with other people using gestures during locomotion, providing an even viewpoint at an equal height.

A. Postural Assistance

People with disabled lower limbs need assistance with inter-postural transitions and posture maintenance. This research aims to assist natural inter-postural transitions using a small, lightweight, and easy-to-wear exoskeleton system. This system affords controllable inter-postural transitions according to weight shifting of the upper body.

In an analysis of the standing motion of a subject (age 23, 180 cm) using a motion capture system (Motion Analysis Co. Ltd., MAC3D), it was observed that the ankle, knee, and hip joints are moved in coordination for maintaining balance in the sagittal plane. Given that the natural transitional motion can be represented by the motion of the three joints, we consider designing the exoskeleton to have three joints corresponding to the above three joints in the human body. To avoid large acceleration or velocity, which may lead to falling, a passive actuation system that stays close to static equilibrium all through the postural transition is adopted.

To realize assisted postural transition, which is similar to normal motion while keeping it close to equilibrium, we first model inter-postural motion, as shown in Fig. 3, based on the above analysis. We then calculate joint moment to realize that each joint of the exoskeleton is in equilibrium at each instant of time. Finally, the required moment for changing user posture is calculated.

1) Postural Transition Model: The model includes the standing, sitting and intermediate postures.

For ensuring smooth start of postural transition in the standing posture (Fig. 3 (a)), the moment in the knee joint should be loaded in the flexing direction. We determine the standing posture as the thigh inclined 10[deg] backward and the shank inclined 10[deg] forward. In this posture, the center of gravity of the user's body is within the supporting area. For the sitting posture (Fig. 3 (c)), the shank should stay outside of the space below the hip so that the user can sit on

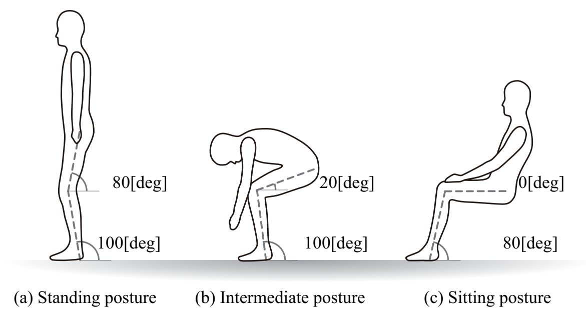

Fig. 3. Attitude of lower limbs at each posture

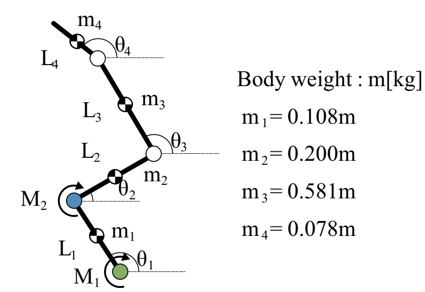

Fig. 4. Calculation model of joint moment

a normal chair. This posture is therefore defined as the shank inclined 10[deg] backward. In addition, an intermediate posture (Fig. 3 (b)) is predetermined for simplifying the motion of the knee and ankle joints. We found that natural postural transition was realized by adopting the posture shown in the figure. The ankle joint stays fixed during the transition between the standing and the intermediate postures ((a) and (b), respectively), and the knee joint stays fixed during the transition between the intermediate and the sitting postures ((b) and (c), respectively). Furthermore, it is considered that the upper body should not be tilted beyond the vertical in the backward direction without supporting material on the back to eliminate any discomfort in the user during postural transition.

2) Calculation of Joint Moment: The mass of each limb is estimated by scaling the ratio of the entire body mass using Matsui's body parts mass index [13]. These estimated values are then used for computing the moment on each

Fig. 5. Overview and usage example

joint according to the model shown in Fig. 4. At this time, the position of the center of gravity of each limb is assumed as located at the lengthwise center.

$$M_1 = \left(\frac{1}{2}m_1 + m_2 + m_3 + m_4\right) gL_1 cos\theta_1 + M_2 \quad \text{(1a)}$$

$$M_2 = \left(\frac{1}{2}m_2 + m_3 + m_4\right) gL_2 cos\theta_2 + \left(\frac{1}{2}m_3 + m_4\right) gL_3 cos\theta_3 + \frac{1}{2}m_4 gL_4 cos\theta_4, \quad \text{(1b)}$$

where m_i denotes the mass of each limb, L_i denotes the length of each limb or body segment, and θ_i denotes the attitude of each limb. Equations (1a) and (1b) give the static moment acting at the ankle and knee joints, respectively, for each posture through the posture transition. The correspondence between these symbols and the model is shown in Fig. 4.

3) Exoskeleton Design: Gas springs are used for generating moment at the joints. These springs are passive devices having strong output with minimal size, thus making the exoskeleton system compact and lightweight.

The exoskeleton is designed for inducing inter-postural transitions as users shift their weight forward or backward by tilting their upper body. The alignment and specifications of the devices are chosen such that they can generate joint moments that are between the maximum and minimum moments. These can be loaded by the user's body when the upper body is vertical and bending forward, respectively. The user can thus control the motion of inter-postural transitions by exceeding or trailing behind the moment equilibrium between the moment generated by the devices and that loaded by the attitude of the user's upper body. Details of the specifications are described in section III-A.

B. Locomotion Assistance

Upper limbs have significant roles such as handling objects and posing gestures for communicating with others even while locomotion. However, most powered wheelchairs are joystick-controlled. In this regard, we propose a control interface that is embedded in the exoskeleton so that the upper limbs of the user are unoccupied. In addition, we implement a method for preventing falling.

1) Wheel Control by Hands-free Interface: First, the attitude of the user's trunk is inferred according to the joint angle of the exoskeleton segments.

$$\theta_B = \gamma\left(\frac{\theta_R + \theta_L}{2} - \theta_\gamma\right) \quad (2)$$

$$\theta_T = \delta \tan^{-1}\left(\frac{L_A(\cos\theta_L - \cos\theta_R)}{W_B}\right), \quad (3)$$

where θ_B and θ_T are the tilting and torsion angles of the trunk, respectively (Forward tilting and counterclockwise torsion are defined as positive). θ_R and θ_L are the orientation angles of the exoskeleton segments attached to the right and left sides, respectively, of the user's trunk. These are measured against the horizontal plane. L_A denotes the length of the exoskeleton segment from the fixing point on the user's trunk to the rotation center. W_B denotes the width of the user's trunk. γ and δ are the coefficients for adjustment. θ_γ is offset.

Then, the control values of the velocity υ and angular velocity ω of the PMV are calculated in proportion to the inferred trunk attitude, respectively.

$$\upsilon = \alpha\theta_B \quad (4)$$

$$\omega = \beta\theta_T \quad (5)$$

These values are restricted to the [-100,100] range by thresholding. Offset and coefficient parameters α, β, γ, θ_γ and δ are determined experimentally.

2) Falling Prevention: Powered wheelchairs that can carry the user in the standing posture are already available in the market. However, these wheelchairs need a large-sized mechanism for preventing falling, thus making the device difficult for the user to use indoors, especially at home. On the other hand, with the use of a small mechanism, wheelchair stability deteriorates because the position of the center of gravity rises. Furthermore, it is necessary to consider the inertial force, slope, and gap on the road.

In this study, the PMV is controlled with low acceleration for avoiding instability in the forward and backward directions, and it is equipped with a leaning mechanism for securing lateral stability. After carrying out investigations in outdoor environments such as pedestrian roads, and inclines, we design the lean mechanism such that it could be tilted by a maximum of 11[deg] from the vertical axis. In addition, the PMV is designed to avoid falling down a slope or gap.

On the other hand, large upper body motion may disturb PMV stability. To reduce danger of falling, we install electromagnetic brakes in the hip joints of the exoskeleton. User motion is constrained if any irregular motion is detected in the sensor data of each joint angle.

III. SYSTEM CONFIGURATION

An overview of the developed PMV is shown in Fig. 5. Locomotion in the upright posture and voluntary postural changes between the standing and the sitting postures are realized by the combination of the passive exoskeleton system and the electrically driven wheels. For example, the

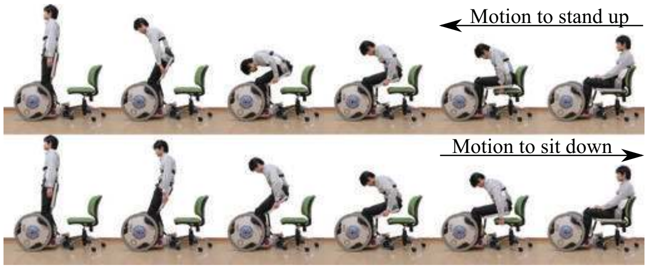

Fig. 6. Motion of inter-postural transition using exoskeleton assistance system

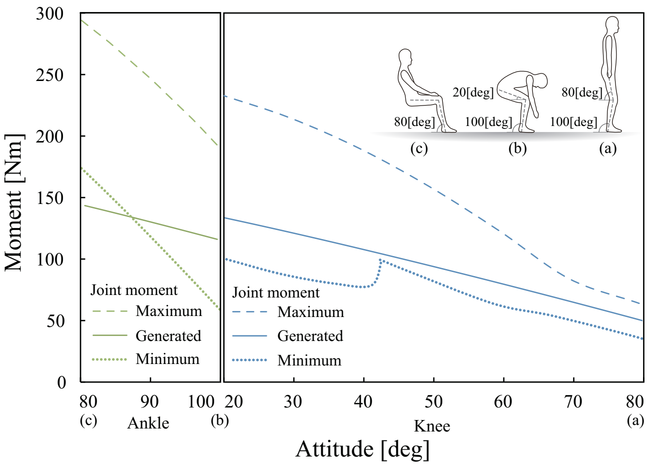

Fig. 7. Relationship between loaded and generated moment on joints

user can approach a shelf and easily handle an object owing to the compact design of the PMV. Figure 6 shows an image sequence of the motion involved in inter-postural transitions using the exoskeleton system.

A. Hardware

The developed PMV consists of the passive exoskeleton system called passively assistive limb, which assists the user in changing and maintaining posture; lean mechanism, which improves lateral stability; and the electrically driven wheels, which carry the above-mentioned structures. The specifications of the PMV are listed in Table I, and the internal structure of the exoskeleton is shown in Fig. 2 (right).

According to the postural transition model described in section II-A.1, the necessary joint moments that are statically equivalent to the moment loaded by the user's body are calculated. The loaded moment varies depending on the tilting of the upper body. When the upper body is bent to the forward limit, the moment applied is the minimum. When the upper body is aligned with the vertical, the maximum moment is applied in each lower limb posture. Figure 10 shows the temporal profile of each joint angle when a subject (age 23, 180 cm) made a postural transition from standing to sitting. In this task, the subject was asked to bend his trunk and head forward as much as possible while maintaining natural movement. This profile is used for calculating the minimum loaded moment.

Figure 7 (left) shows the typical (i.e., minimum, as dotted

Fig. 8. Link mechanism for leaning

TABLE I
SPECIFICATION OF PMV

dimension [cm]	Width 66 Length (Standing) 85 (Sitting) 114 Height (Standing) 133 (Sitting) 91 Wheel base (Max.) 58 (Min.) 49 Tread (F) 56 (R) 25
Mass	36.8[kg]

line) and maximum (as broken line) moments on the ankle joint for each posture during transition between the sitting and the intermediate postures, whereas Fig. 7 (right) shows the same values for the knee joint during transition between the intermediate and standing postures. According to the design policy described in the section II-A.3, the exoskeleton mechanism is designed such that the moment generated by the spring system lies between the typical and the maximum moments calculated above.

In the initial phase of the transition from sitting to standing, a certain domain exists where the loaded moment is greater than the generated moment. Regardless of the upper body posture, in this domain, the exoskeleton remains with the lower limit and the sitting posture is maintained. For starting the transition, the user should push up their own body with their hands. In this manner, the postural transition is induced based to the user's definitive intention of standing up.

The length fixable gas springs are used for driving the exoskeleton system. The attitude of the exoskeleton can be fixed and the exoskeleton is designed to be compact because the spring has strong output with compact size. The ankle and knee joints of the exoskeleton are driven by a pair of gas springs, and the length of one spring in each pair can be fixed.

The PMV is equipped with a lean mechanism, shown in Fig. 8, for ensuring stability during turning or moving on a slope. This mechanism has a pair of springs that keeps the PMV in vertical plane. The PMV starts to lean when the user tilts their upper body to more than 3[deg], and the mechanism allows the PMV to tilt up to 11[deg] from the vertical plane. In addition, foot belts, knee supporters, a waist belt, and a body belt are equipped for fixing the exoskeleton on the user, as shown in Fig. 2.

B. Control System

Figure 9 shows the control system configuration. The angles of the sideling tilt, as well as those of the ankle, knee, and hip joints are observed using potentiometers, and the control values are computed by equations (2-5). The

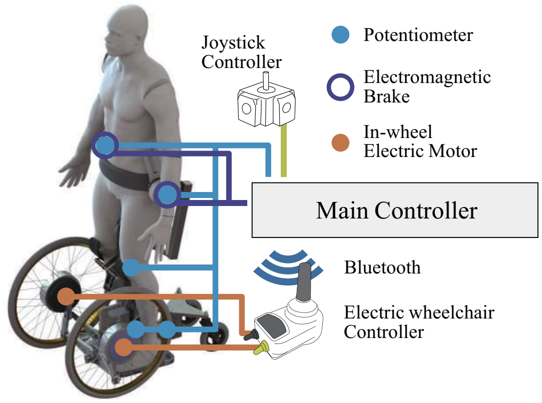

Fig. 9. Control system configuration

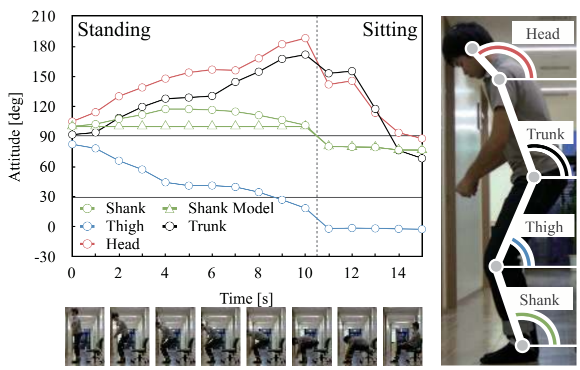

Fig. 10. Result of experiment on postural transition measurement

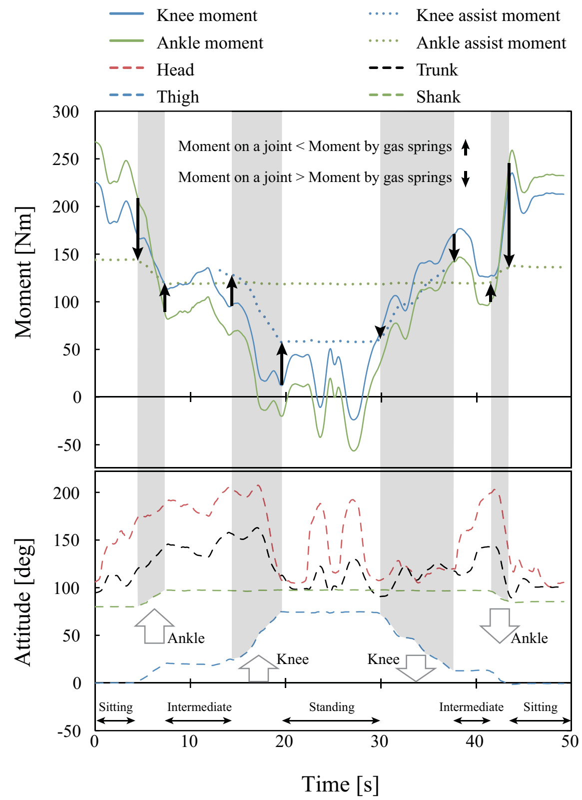

Fig. 11. Attitude of body segments and joint moment in inter-postural transition

main controller operates the electrically powered wheelchair unit by sending control values. In addition, it controls the electromagnetic brakes installed in the hip joint of the exoskeleton for avoiding falling by constraining the user's trunk motion.

The PMV has a small-sized joystick, and the user can choose to operate the PMV using the joystick or in the hands-free mode. Modified electrically driven wheels (JWX-1, Yamaha Motor Co., Ltd.) are used in this system. The PMV can move forward, backward, as well as turn using a pair of in-wheel electric motors.

The control circuit was modified for accommodating control commands not only from the joystick but also from other sources for controlling the velocity and angular velocity, which come from equations (4) and (5), respectively, in this case. The user can control the PMV well enough using the interfaces, because they can perform path planning and replanning continuously during locomotion, just as is possible with the joystick. The parameters in equations (2-5) are determined through the following preliminary experiment; $\alpha = \beta = 571$, $\gamma = \delta = 1$, and $\theta_\gamma = 1.57$ are used.

IV. EXPERIMENTS

A. Natural Postural Transition

An experiment is conducted for investigating the inter-postural transition model described in section II-A.1, and acquiring data on ankle and knee motions.

The angles between the horizon and the shank, thigh, trunk, and head-neck are measured with reference to the marker position. The attitude transition of each limb is shown in Fig. 10. In the figure, the postures at time 0[s], 10[s] and 15[s] correspond to panels (a), (b), and (c), respectively, of Fig. 3. A difference of up to 20[deg] is observed between the ideal and real transitions. This difference is attributed to the motion or maintaining balance during posture change. The ideal transition is shown as the "Shank Model" in the figure.

B. Postural Assistance by PMV

Postural assistance in standing up and sitting down was investigated.

The postural transition is assisted as desired, and a healthy subject (age 23, 180 cm, 72 kg) can change posture based on the attitude of the upper body after a few trials.

The user can stand without exerting force on the muscles of their lower limbs owing to the supporters at the knee and the waist. Moreover, a smooth sitting-down motion is realized by tilting the trunk backward.

The attitudes of the shank, thigh, trunk, and head-neck are measured using the motion capture system for verifying whether a postural transition can be performed by weight shifting in conjunction with tilting the trunk. We investigated the relationship between the magnitudes of the moment generated by the gas springs and that loaded on joints of the exoskeleton according to posture of the subject. The results of the calculated moment on the ankle and the knee, and the moments generated by the gas springs are shown in Fig. 11. The white upward arrows in the figure indicate joint

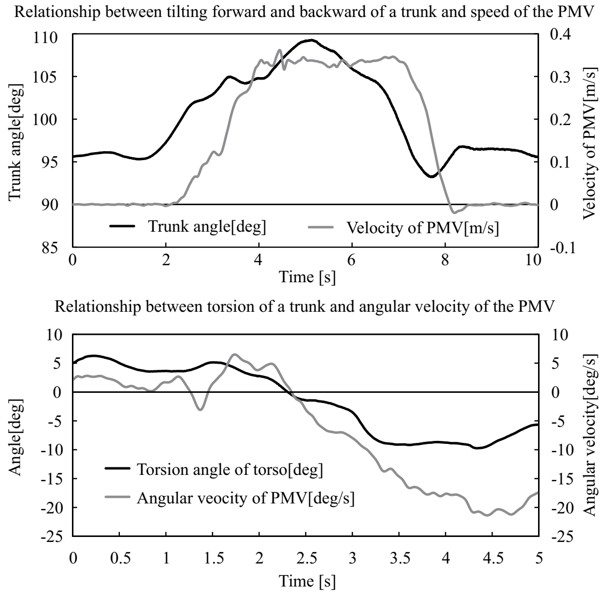

Fig. 12. Experimental result of locomotion assistance

motions that contribute to standing up, and the downward arrows indicate motions that contribute to sitting down.

In the initial phase of standing up, the loaded moment on the ankle is greater than the generated moment. Therefore, the user needs to assist this motion by pushing on the seat surface. Once the ankle angle reaches 100[deg], the loaded moment becomes smaller than the generated moment, and the subject maintains posture without support. The loaded moment is smaller than the generated moment when the upper body is tilted forward. Furthermore, the motion of sitting down commences when the upper body is tilted backward. At around 34[s] in the figure, it is observed that the body motion speed is controlled via moment equilibrium between the loaded moment, based on upper body attitude, and the generated moment.

C. Locomotion Assistance by PMV

Locomotion in the upright posture based on trunk attitude was examined using the developed PMV. For the sake of safety, a walking aid is used in this experiment.

The subject can navigate the vehicle in any direction by tilting his trunk. The speed of the PMV and the attitudes of the trunk and the PMV are measured using a motion capture system. Through the experiment, it has been demonstrated that motion control functions appropriately according to the relative attitude of the PMV and the trunk of the subject. The attitude of the trunk in the front-back direction is calculated from a line segment between the 7th cervical spine and the sacrum. The attitude of the twist direction is calculated from an segment between right-and-left shoulder. The relationship between the forward and backward tilting of the trunk and the PMV speed is shown in the upper part of Fig. 12. It is stationary in the initial phase, accelerated according to the attitude of trunk, and then stopped by the backward tilting of the trunk. Then, the lower part of Fig. 12, clearly shows that it is possible to control the PMV's angular velocity based on the twist angle of the trunk.

V. CONCLUSIONS

This paper proposes a standing mobility vehicle consisting of a passive exoskeleton and electrically driven wheels. The exoskeleton is designed for maintaining the standing and sitting postures of the user, as well as assisting inter-postural transitions and hands-free locomotion control. An assessment of the developed prototype verified advantage of the proposed approach. The developed PMV can maintain the user posture, as well as its motion can be controlled based on the attitude of the user's trunk without the use of their upper limbs.

One of the important situations in day-to-day PMV use is transferring a user from a bed to the PMV. The bed was configured at a height suitable for the PMV. The subject was then asked to perform the motion without using lower limb muscle as much as possible. The whole motion of transferring and wearing the PMV took about 100[s], and it was required for the user to handle their lower limbs using their upper limbs. Through this validation, it was confirmed that users can carry out the entire procedure on their own.

The developed PMV is tailor-made for the subject. A mechanical adjustment system for other users of different sizes and body weights will be developed. Further investigation for ensuring PMV stability will be conducted in the future, as well as application to outdoor environments and other subjects.

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