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Dynamic Assistance for Human Balancing with Inertia of a Wearable Robotic Appendage

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***Abstract*— A reduced balance ability can lead to falls and critical injuries. To prevent falls, humans use reaction forces and torques generated by swinging their arms. In animals, we can find that a similar strategy is taken using tails. Inspired by these strategies, we propose an approach that utilizes a robotic appendage as a human balance supporter without assistance from environmental contact. As a proof of concept, we developed a wearable robotic appendage that has one actuated degree of freedom and rotates around the sagittal axis of the wearer. To validate the feasibility of our proposed approach, we conducted an evaluation experiment with human subjects. Controlling the robotic appendage we developed improved the subjects' balance ability and enabled the subject to withstand up to 22.8 % larger impulse disturbances on average than in the fixed appendage condition.**

I. INTRODUCTION

Humans have an ability to dynamically maintain balance during standing and locomotion. This ability helps us to perform tasks in our daily lives and prevents us from falling over due to unexpected errors or external disturbances. As our ability to maintain balance is reduced due to aging or disability, we are more at risk of falling. Balancing ability can also be reduced if we are concentrating on other tasks. For example, when carrying something, we cannot fully exploit the upper body for balancing.

To stabilize body attitude, humans use various strategies such as foot placement adjustment and upper body motion. The arms also play a role in stabilizing the body attitude. For example, we use the inertia of our swinging arms to recover after tripping. Previous studies showed that the arms contributed to control the whole body attitude by generating reaction forces and torques [1][2]. In animals, we can observe a similar strategy of using the inertia of their tail. Researchers have revealed that a tail of cat contributes to its stability[3].

Inspired by these strategies, we propose an approach that utilizes the inertia of wearable robotic appendages to augment the wearer's balance ability without the appendages contacting with the environment. As a proof of concept, we developed a backpack-type wearable robotic appendage to assist the wearer in maintaining lateral balance with its reaction force and torque. We designed the hardware and developed the physical prototype which has one actuated degree of freedom (DoF) based on a reduced order model (Figure 1. To validate the feasibility of our proposed approach, we conducted an experiment with human subjects.

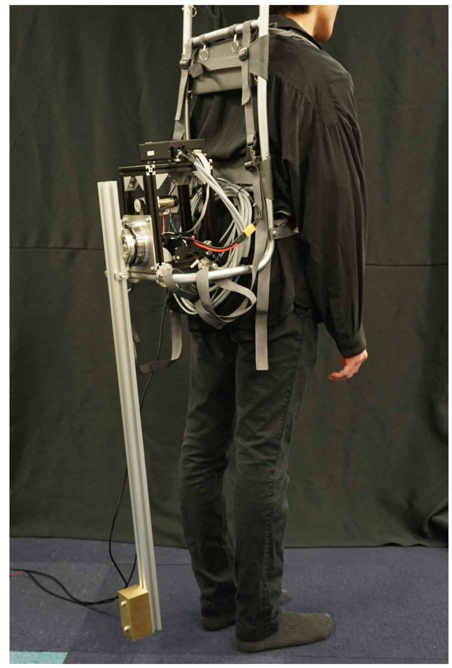

Fig. 1. Appearance of the developed wearable robotic appendage. It has one actuated DoF which rotates around the sagittal axis.

Our proposed approach also contributes to establishing a method for adding another function to supernumerary robotic limbs (SuperLimbs). SuperLimbs is a recently proposed approach to human augmentation that utilizes wearable robotic arms to support the wearers in performing tasks and enhancing their ability [4]. Our approach can be implemented in SuperLimbs to prevent falls in an emergency while assisting the the wearer in performing a task. We believe that our approach has a potential to complement research on SuperLimbs because it is independent of the end effector's shape.

This paper is organized as follows: 1) we propose a new approach that utilizes wearable robotic appendages as a balance supporter without it contacting with the environment, 2) we present the development of a backpack-type physical prototype that has one actuated DoF, 3) we describe an experiment with human subjects which was conducted to demonstrate that our approach contributes to augmenting their balance ability. To the best of our knowledge, this is the

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first approach to make use of a robotic tail for human balance and evaluate its effect with a human subject experiment.

II. RELATED WORK

Our work builds on methods using artificial tails in robotics, researches on SuperLimbs, and wearable devices for supporting wearer's balance ability.

A. Tails in robotics

We can observe that animals use their tail for stabilizing their body [3][5]. In the field of bio-inspired robotics, the effectiveness of using actuated robotic tails to enhance the stability of mobile robots has been demonstrated. Chang-Siu et al. presented a lizard inspired approach to reorient a mobile robot's body in the air [6]. In addition to this work, the benefits of having a tail for various tasks have been demonstrated such as hopping of one-legged robot [7], locomotion of bipedal robot [8], high-speed turning [9], acceleration and braking [10] in a wheeled robot, and recovering from a disturbance in a quadruped robot [11]. Our basic idea is to apply these methods to the human body as one function of a wearable robotic appendage. We can utilize benefits and findings of these methods. However, the problem is more challenging in our case due to the softness of the human body.

B. SuperLimbs

Thanks to the advancement of robotic technologies, wearable robots have been used to augment our ability beyond physical constraints. SperLimbs is an approach that uses wearable robotic arms that can move without restricting the wearer's movement while supporting wearer's task [4][12]. Parietti et al. proposed a method for stabilizing the wearer's body during an aircraft assembly task [13] by contacting with the environment via SuperLimbs. In addition to the wearable extra arms approach, Gonzalez et al. proposed wearable robotic legs and a control method to support the wearer's task [14]. We investigate an approach to stabilize wearer's body attitude without contact with the environment. Artificial tails for human have been proposed in previous studies [15][16]. However, such research has not evaluated their benefit for human balance assistance.

C. Balance support with wearable device

To augment human balance ability, several methods using wearable mechanical devices have been investigated. Wojtara et al. proposed a method to support human balance with a wearable reaction wheel [17]. Similarly, as an approach to using momentum exchange for human balance, the use of control moment gyroscopes has also been investigated [18][19][20]. While these methods utilize flywheels for human balance augmentation, we focus on an approach using a wearable robotic arm like a robotic tail. Although our proposed method's workspace can be limited unlike the methods using flywheels, we can take advantage of the tail-like approaches, which can provide greater torque in a shorter time [11]. Additionally, our approach allows the wearable arms to be used as manipulators when there is no need to support wearer's balance.

III. HARDWARE DESIGN

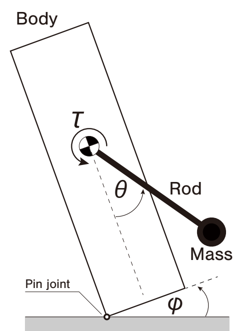

Fig. 2. Reduced order model in coronal plane. It consists of the human body modeled as rigid body and mass-less rod attached a point mass.

Accurately modeling the physical interaction between a human body, which is soft and has high DoFs, and a rigid wearable appendage is much more challenging than modeling the dynamics of robots that consist of only rigid parts. As a proof of concept, we designed the robotic appendage's hardware based on a reduced order model depicted in Figure 2. This model has a nonlinear dynamics described in Eq.1.

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} \tag{1}$$

Where,

$$\boldsymbol{q} = [\phi, \theta]^T \tag{2}$$

In this paper, we focus on movement in the coronal plane. We assumed that the robotic appendage consists of a mass-less rod attaching a point mass to the the wearer's center of mass (CoM). The appendage was assumed to have one actuated DoF. According to previous research in robotic tails [21][11], we can obtain a larger reaction force and torque by increasing the moment of inertia (MoI) of the robotic appendage. MoI is quadratically dependent on length while only linearly dependent on mass. By increasing the length of the rod, a relatively large MoI can be obtained while suppressing the static load on the wearer. On the other hand, there is a trade-off that increasing the length of the rod limits its workspace. The rod length was determined to be $0.9\,\mathrm{m}$ to enable the robotic appendage to obtain a large MoI while avoiding contact with the ground during its movement. The mass attached to the rod was selected to be $2.0\,\mathrm{kg}$ based on the fact that a $10\,\mathrm{kg}$ load added to the pelvis is known to have a significant effect on the wearer's movement [22]. The actual total weight of the hardware was about $9\,\mathrm{kg}$ without cables and a battery. We selected an aluminum extrusion for the rod because of its light weight and rigidity. For the mass's material, we selected brass because of its high density.

We used a brushless DC motor for the actuator. The MAXON EC-4pole (200W) was selected for its high power density. Then, a numerical simulation was performed to determine the optimal gear ratio as described in [9][11].

TABLE I

PARAMETER VALUES FOR A NUMERICAL SIMULATION

Parameter	Value
Body Mass	60 kg
Body Moment of Inertia	$12\,\mathrm{kgm}^2$
Tip Mass	2.0 kg
Rod Length	0.9 m
Height of Center of Mass	1 m
Gear Efficiency	0.5

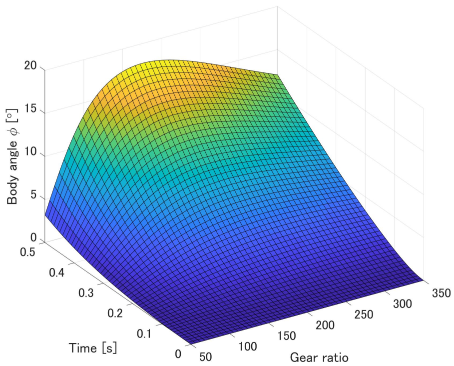

Fig. 3. The relationship among gear ratio, the time of interest, and body angle ϕ.

Table I shows physical properties used for the numerical simulation. The human body's MoI was determined based on [23], and was set to be $12\,\mathrm{kg\,m^2}$. We performed the numerical simulation using Simulink based on the dynamics equation 1 with the initial conditions, $\phi = 0$, $\theta = 0$. We assumed that the the nominal voltage was applied to the motor during the performance. We also assumed that the motor has a linear torque-speed curve $T = \mu N T_0(1 - \frac{\omega}{\omega_0})$, where, T is the motor's torque, μ is the gear efficiency, N is the gear ratio, T_0 is the stall torque, ω is the speed after the gear transmission, and ω_0 is the no load speed. We determined the gear ratio based on the change of the body angle ϕ according to applied torque in a time of interest. Figure 3 shows the result of the numerical simulation. The optimal value of the gear ratio changes according to the operation time. For example, the optimal value of the gear ratio is about 230 when the time is $0.25\,\mathrm{s}$, and it is about 170 when the time is $0.5\,\mathrm{s}$. Recovering from the falling requires a quicker response. Therefore, we determined the reduction ratio to be about 230. We used a timing belt and a pulley mechanism with a strain wave gear for its light weight and high load capacity. Considering commercially available options and the gear property, we selected the gear combination with an actual ratio of 230.4. The motor was controlled by a Windows 10 PC with an Intel Core i9-8950HK 2.90G Hz CPU through the motor driver, EPOS4 70/15, from MAXON. Figure 4 shows an overview of the hardware implementation. We used 6 cells LiPo battery as the power supply for the motor in the following experiment.

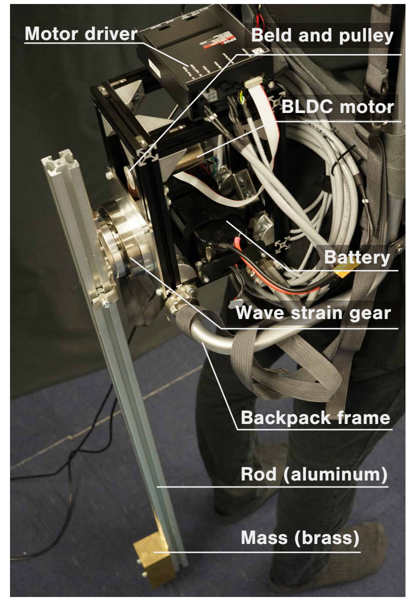

Fig. 4. The implementation of the robotic appendage prototype.

IV. EXPERIMENT

To validate the feasibility of our proposed approach, we designed an experiment with human subjects. We aimed to evaluate the balance support capacity of the developed appendage in respose to impulse disturbances in the lateral direction. All experiments were carried out with the permission from the Local Ethics Research Committee at the University of Tokyo, Japan.

A. Setup

Figure 5 (a) shows the experimental setup. We developed an apparatus for disturbance generation. The apparatus consists of a brushless DC motor, MAXON EC 90 flat (260W), and a belt-pulleys mechanism. Its reduction ratio is 2.8. This apparatus can generate disturbances with its actuator by pulling a rope attached to the subject. The magnitude of the disturbance was calibrated by linear regression based on samples pre-measured with a force sensor. As a result of the regression, we were able to predict the output magnitude of the disturbance with the coefficient of determination $R^2 = 0.98$ within the torque range used in this study.

We set the apparatus to apply a specified force to the rope for a short period to emulate an impulse disturbance (Figure 5 (c) shows an example of this disturbance). To prevent the rope's slack, we set the apparatus to pull the rope with a constant weak force in the initial state. We fixed the apparatus at $0.88\,\mathrm{m}$ height from the ground. We also developed a foot sensor for the appendage control (Figure 6). The details of how sensor information was used is described in the control law section.

B. Subjects

We recruited six subjects (6 male, age: *mean*=23.5 years old and *SD*=2.2, height: *mean*=$1.72\,\mathrm{m}$ and *SD*=0.03, weight: *mean*=$60.6\,\mathrm{kg}$ and *SD*=6.2).

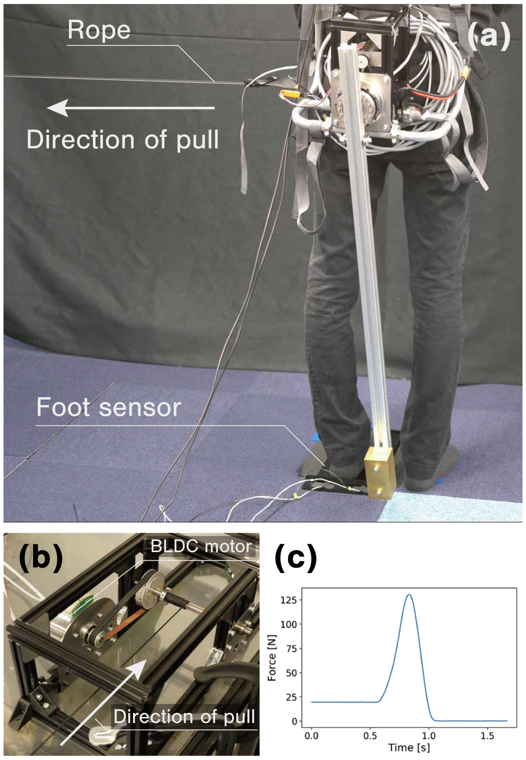

Fig. 5. (a) The experimental setup. This includes a foot sensor and (b) the apparatus which pulls the rope attached to the subject with a brushless DC motor at a defined peak force. (c) An example of a generated disturbance measured by a force sensor.

No participants had any physical disabilities.

C. Procedure

We conducted the experiment with two conditions: 1) the controlled condition and 2) the fixed condition. In the controlled condition, the appendage was controlled according to a control law described in the next section. In the fixed condition, the appendage was fixed to the initial position during experimental trials. The experiment consists of ten sessions with the controlled condition and ten sessions with the fixed condition. Each session was carried out alternatively. In each session, we increased the magnitude of the disturbance by $10\,\mathrm{N}$ per trial and examined whether the subjects' foot left the ground. If the subject's any of the subject's feet did not leave the ground, we increased the disturbance's magnitude. If the subjects' foot left the ground, a disturbance of the same magnitude as in the last trial was provided. If the subjects' foot left consecutively in two trials, the disturbance's magnitude at that time was recorded as a threshold value, and the session was terminated. To alleviate fatigue, the subjects were allowed to take a break between each session.

We instructed the subjects wearing the appendage to stand upright and fixed it to the subject with fastening belts attached to the backpack frame. We asked the subjects to place the left foot on the foot sensor with the feet aligned. We attached the rope to the subjects' hip with one loop. To ignore the effect of swinging subjects' arms, we instructed the subjects to cross their arms in all trials. We also instructed the subjects to maintain the center of pressure (CoP) of the feet as centered as possible and to withstand the disturbance without moving their feet. Before the start of each trial, a calibration step was performed to calculate x_{init}. Before starting the experiment, we performed several trials under the appendage controlled condition to familiarize the subjects with the behavior of the system.

D. Control law

We designed a feedback control law for the robotic appendage according to the position of the subject's CoP. Assuming that the motor torque is proportional to the current, we controlled the torque τ as follows:

$$\tau = \begin{cases} k_T k(x - x_{init}) & (x - x_{init} > \epsilon) \\ 0 & (\text{otherwise}) \end{cases} \tag{3}$$

The robotic appendage was controlled proportionally according to the position of subject's CoP x estimated by pressure sensors installed under the subject's left foot (Figure 6). We used FSR-408 force sensing resistors as pressure sensors. We developed the control system according to equation 3 with this sensing setup. At the beginning of each trial, the position of the CoP in the steady state was measured, and we defined it as x_{init}. k_T is the torque constant of the motor. This parameter is obtained from the motor's data sheet, and it is $13.7\,\mathrm{mNm/A}$. The proportional gain k was determined empirically in a preliminary experiment. We defined ϵ to prevent unnecessary movement of the robotic appendage caused by the body sway in a stable state. k and ϵ were $2700\,\mathrm{A/mm}$ and $1.2\,\mathrm{mm}$ respectively. The appendage position θ was set to the initial position ($\theta = 0$, in Figure 2) in each trial. We also defined the limited range of the rotation, and we set it to $0 < \theta < \frac{5}{6}\pi$. In this experiment, we ignored the case where the subject's CoP moved to the right side from the initial position, in other words, when $x - x_{init} < 0$.

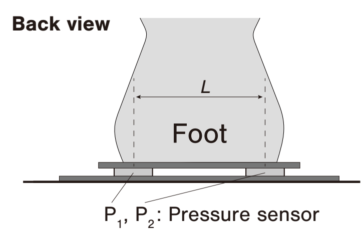

Fig. 6. Diagram of the foot sensor for measuring the CoP. We estimated the CoP as $x = \frac{p_1}{(p_1+p_2)}L$. p_1 and p_2 are values of P_1 and P_2 respectively. L is the distance between two sensors and it was $85\,\mathrm{mm}$.

V. RESULTS

We collected the threshold values in 20 sessions per subject and compared the controlled condition with the fixed condition. Figure 8 depicts the collected results for each subject. The statistical significance (α) was determined at a one-sided p-value of $\leq$ 0.05. The threshold values were significantly different according to the conditions within all

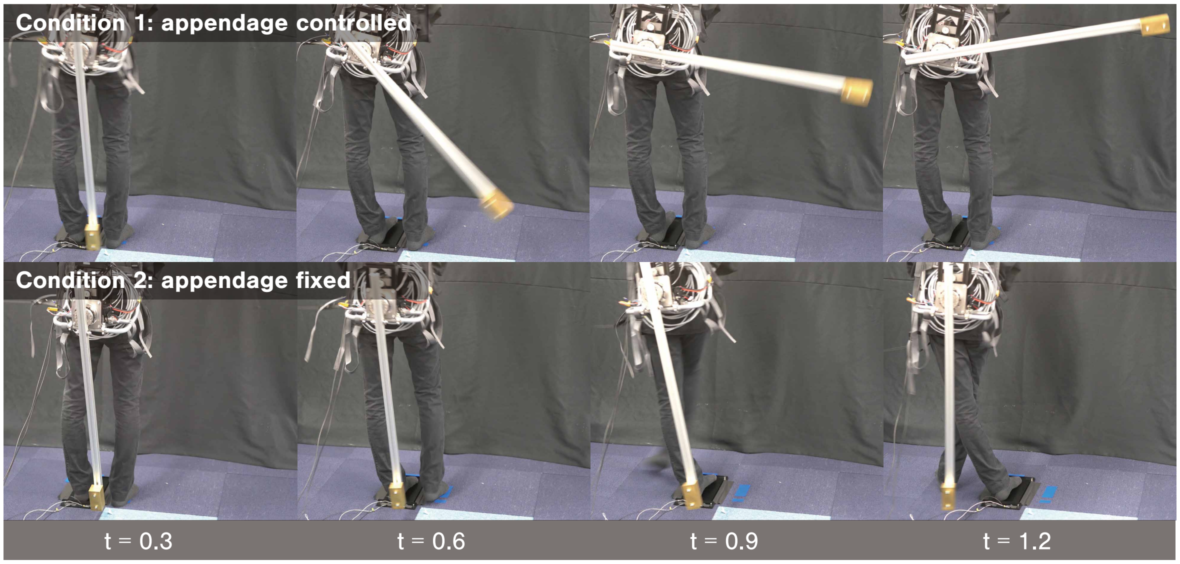

Fig. 7. Snapshots taken by a standard camera at 30 fps (The time at which the rope started to move was set to t = 0). In condition 1, the appendage was controlled with a feedback loop according to the foot sensor value. In condition 2, the appendage was fixed to the initial position.

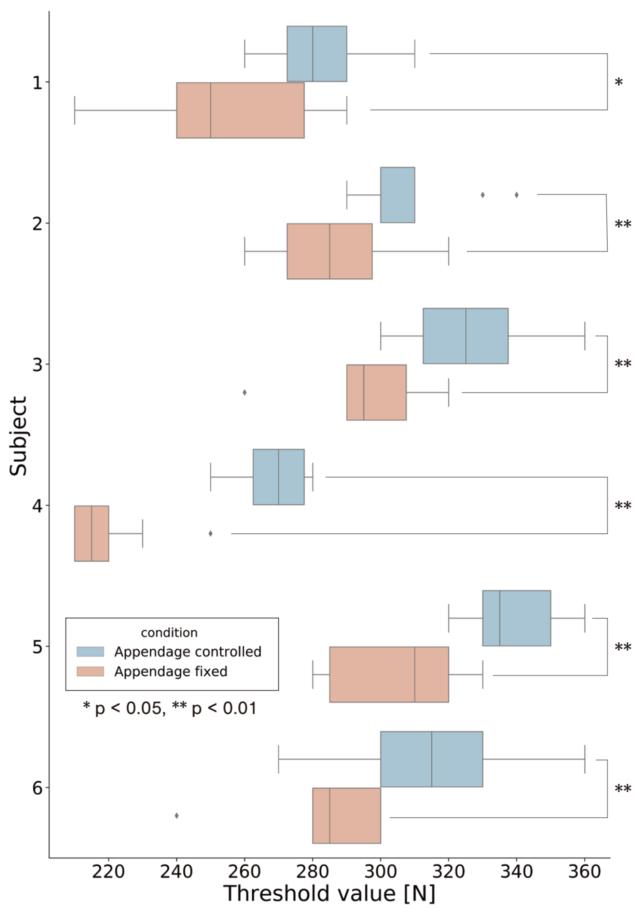

Fig. 8. Comparison of the threshold value in each subject with and without control of the appendage.

subjects (Wilcoxon rank sum test). On average, the appendage control increased the threshold value of the subjects by 11.9 % compared to the case where it was fixed. In the subject with the largest increase in the threshold value, the increase rate of the mean was 22.8 %. Converted to the peak value of the disturbance magnitude, this increase was by $50\,\mathrm{N}$ (from $219\,\mathrm{N}$ to $269\,\mathrm{N}$). On the other hand, the lowest increase rate was 8.0 % (from $286\,\mathrm{N}$ to $309\,\mathrm{N}$).

Figure 7 shows snapshots of the experiment in each condition. We found that the appendage could react to the disturbance to stabilize the subject attitude. We concluded that our proposed approach is beneficial for stabilizing the wearer's attitude against a disturbance.

A. Discussion

Although the result shows that our proposed approach enhances the wearer's balance ability, we found several issues where improvements could be made. During the experiment, we observed that the appendage reached the defined limit angle and stopped suddenly several times. We found that the sudden stop caused a negative effect on the subject's balance and could lead to the loss of the balance. We identified that the system would be improved by optimizing its trajectory including acceleration and deceleration.Another issue is how to attach the appendage to the human body. While the current prototype is fixed to the body by tightening the belt, a little play exists between the body and the backpack frame. This problem can be resolved by optimizing the parts to be attached to the human body or using ergonomic shapes. We also found that the appendage started moving a little after the disturbance provided. We concluded that the time it took for a provided disturbance effect to be reflected on the sensor was one cause of this delay. Introducing a sensor fusion approach using another sensor, such as an accelerometer, can suppress this delay.

As a first step, we adopted the linear control law, and did not take into account individual physical properties and strategies. We concluded that our proposed approach could be used more efficiently by applying non-linear controls or adopting machine learning approaches. In addition, our observation suggested that the foot sensor could be used as an communication interface for the wearer. Although we aimed to control the appendage independently of the wearer's will, we found that the wearer could control the appendage at will by changing the pressure distribution of the foot sole. By inferring the wearer's intention from the pressure pattern of the feet sole with a wearable sensor module, the autonomous control and the wearer's control could be switched and used at will.

VI. Conclusions and Future Work

We proposed a novel approach that utilizes a wearable robotic appendage as a balance support device without it contacting with the environment. As a proof of concept, we developed a prototype that has one actuated DoF and rotates around the sagittal axis of the wearer. To validate the feasibility of our proposed approach, we conducted an experiment with human subjects. We designed the control method to respond to the CoP of the subjects' foot sole. We provided impulse disturbances to the subjects and compared the conditions with and without the robotic appendage control. The experimental results demonstrated the effectiveness of our proposed approach. It was shown that, by controlling the appendage, the stability of the subjects' body was improved.

In this research, the developed hardware has only one DoF to simplify the problem and control. Therefore, it can only deal with disturbances in the coronal plane and the effective working range is limited. Additional DoFs will be a promising avenue to improve our proposed approach and enable the appendage to also function as a manipulator, as is proposed in research on SuperLimbs. We would like to investigate advanced control methods for the appendage that has such multiple DoFs. Furthermore, while we focused on balance assistance in the standing situation in this experiment, we would explore the interactions during cyclic motion of the wearer, such as during locomotion. We believe this work can be a baseline for further investigation and inspire other works on wearable robotics.

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