AN ASSISTIVE SUIT WITH INTENTION DETECTION USING PNEUMATIC ARTIFICIAL MUSCLES

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ABSTRACT Various powered exoskeletons have largely been developed using inflexible exoskeletons consisting of rigid linkage elements and electric, pneumatic, and hydraulic actuators. In this paper, a wearable assistive suit that uses pneumatic artificial rubber muscles (PARMs) for actuators and consists of soft materials is developed. The advantages of PARMs such as light-weight, high power-weight ratio and direct drive are suitable for the suit.

The assistive suit consists of PARMs, waist supporters, knee supporters, and shoes. A wearer equips the supporters and puts on the shoes with nylon belts. PARMs are located anterior surface of thigh and facies posterior cruris. These PARMs assist the gait by supporting performing of bi-articular muscles. PARMs located anterior surface of thigh provide torques for flexion of hip joints and extension of knee joints. PARMs located facies posterior cruris provide torques for plantar flexion of ankles and flexion of knee joints.

Most of existing power assistive systems detect the walking intention of the user by bioelectrical sensors, motion sensors, speed sensors, or angle sensors. The proposed assistive suit utilizes the back-drivability of PARMs and assists the gait with intention detection from the difference of internal pressure. PARMs located facies posterior cruris are also used as the sensors of intention detection. When the wearer starts walking, the extension forces are transmitted to them and that increases their internal pressure. After that, the pressure is decreased as extension forces disappears, just before the swing phase. The assistive suit detects the walking intention by monitoring the pressure derivative falling a pre-defined threshold.

We conducted experiments with the proposed assistive suit on a treadmill. Experimental results by electromyogram (EMG) show the effectiveness of the assistive suit and the intention detection method.

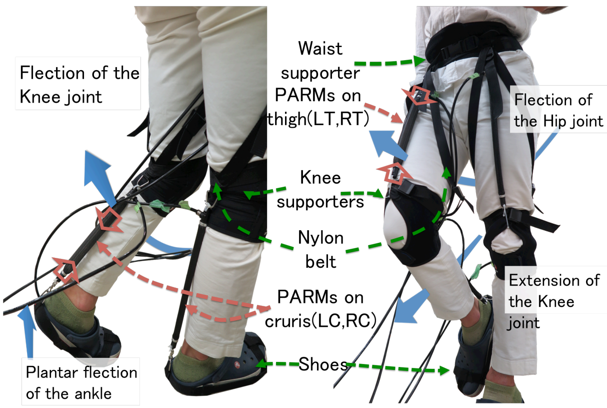

Fig. 1 The schematic of the assistive suit

1. INTRODUCTION

In recent years, various power assistive devices have been developed. They are electrically, pneumatically, or hydraulically-driven devices. Pneumatically-driven systems are light-weight and have high power-weight ratio, realizing powerful direct-drive assist devices. A lightweight soft assistive suit using pneumatic artificial rubber muscles (PARMs) for gait assistance has been developed by Michael Wehner[1].

These assistive devices mostly wear sensors, bioelectrical sensors, speed sensors, or angle sensors to detect the walking intention of wearer. However installing many sensors increases the cost of sensors themselves and making them tolerant of outdoor environment. Therefore it is important for the assistive devices to reduce or omit sensors.

2. LIGHT-WEIGHT SOFT ASSISTIVE SUIT

2.1 Bi-articular muscles

Muscles that cross two joints rather than just one are called “bi-articular muscles”, such as the hamstrings which cross both the hip and the knee.

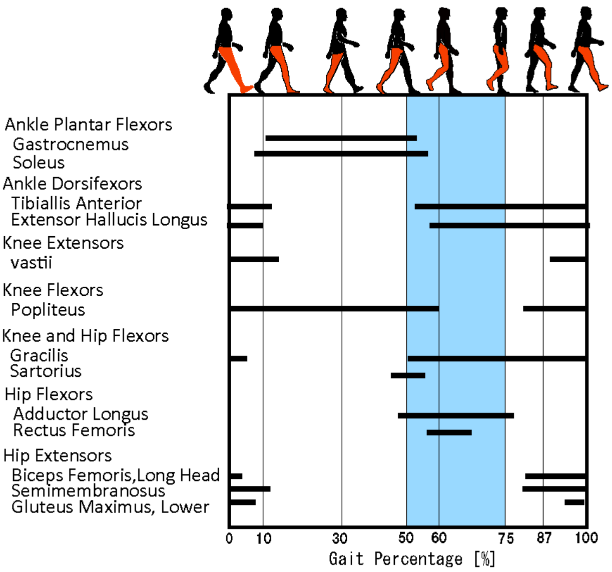

Fig. 2 Diagram of when the muscles in the leg are active

The contraction of the bi-articular muscles acts on two joints. Therefore the action is affected by the angle of the joints and how to locomote the joints. The rectus femoris muscles are placed on the middle of the front of the thigh. They help the flexion of the hip joint and the extension of the knee joint. The gastrocnemius muscles are placed on the back part of the cruris. They help the flexion of the knee joint and the plantar flexion of the ankle joint. In the proposed assistive suit, PARMs are used to assist the bi-articular muscles of the wearer.

2.2 Gait phase

In order to assist the wearer's walking effectively, PARMs have to work when the moments act on the joints of the wearer. Therefore we have to detect the current gait phase of the wearer. Human being walking is roughly divided into two phases: stance phase and swing phase. The stance phase is the gait phase that lasts from the heel strike to toe off, which accounts for 60% of one gait cycle. The swing phase is the gait phase when the foot swing forward, which account for 40% of one gait cycle. For the detailed classification of the gait phase, the gait phase based on the RLANRC method are applied. Our suit is active for the duration specified by the shaded region(see Fig.2), to assist ankle plantar flexion, knee flexion, and hip flexion. The gait percentages correspond to the following periods of the gait: 0-10%: Loading Response; 10-30%: Mid-stance; 30-50%: Terminal stance; 50-60%: Pre-swing; 60-75%: Initial swing; 75-87%: Mid-swing; 87-100%: Terminal swing.

2.3 Assistive suit specification

A wearable assistive suit which uses PARMs for actuators and harnesses of soft materials is developed.

Fig. 1 shows the schematic of the assistive suit. The assistive suit consists of PARMs, a waist supporter, knee supporters, and shoes. A wearer equips the supporters and put on the shoes with nylon belts. The PARMs are located on the anterior surface of thigh and the facies posterior cruris. These PARMs assist the wearer's

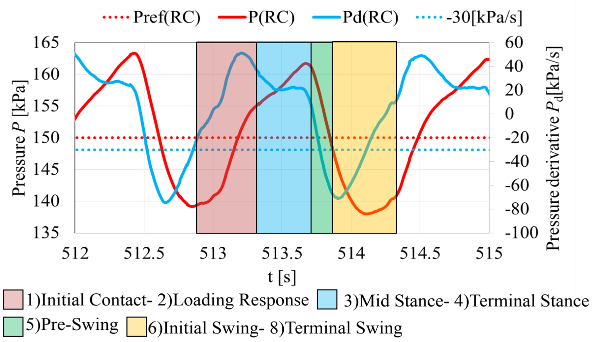

Fig. 3 The change of the internal pressure and its derivative (the PARM on cruris)

bi-articular muscles.

Each PARM is represented as **LT**, **LC**, **RT**, and **RC**, respectively. The prefix **L** and **R** are represented as the left leg and the right leg respectively. **T** and **C** are represented as the thigh and the cruris respectively. PARMs on **LT** and **RT** provide torques for hip flexor and knee extensor. PARMs on **LC** and **RC** provide torques for ankle plantar flexor and knee flexor. The assistive suit utilizes the back-drivability of the PARMs to detect the walking intention of the wearer without additional sensors using the derivative of internal pressure[2], i.e., the PARMs on **LC** and **RC** are used even as the sensors for the walking intention detection.

3. GAIT ASSISTIVE CONTROL

3.1 Preliminary experiment for walking intention detection

The PARMs on **LC** and **RC** are used even as the sensors of the walking intention detection. The wearer starts walking with pre-pressurizing the PARMs at the predefined initial pressure, then the extension forces are transmitted to the PARMs and the pressures increase. In this experiments, we determine the condition of the walking intention detection of the wearer by monitoring the pressure and its derivative of the PARMs.

We recorded the internal pressure and its derivative of the PARMs on the cruris for 10[s] while the wearer walks at 2.0[km/h] on a treadmill. The PARMs are applied the initial pressure 150[kPa].

Fig. 3 shows the internal pressure and its derivative of the PARMs. We found the cyclic change of the internal pressure. We considered that the current gait phase can be determined from the cyclic changes. The color areas in Fig. 3 represent one gait cycle. The gait phases starts from the Initial Contact. The extension force is transmitted to the PARM on the cruris and the internal pressure increase between the Mid Stance and the Terminal Stance (see blue area). The heel off from the ground in the Pre-Swing (see green area), then the extension force disappears and the internal pressure decreases.

We assist the wearer between the Pre-swing and the Initial Swing. Therefore the timing which starts the assist should be determined by the detection of the Pre-Swing.

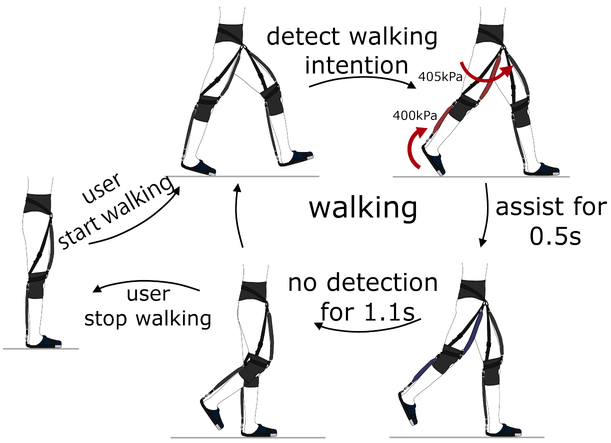

Fig. 4 The state diagram of the gait assistive control

As shown in Fig. 3, the pressure derivative falls and gets negative between the Terminal Stance and the Pre-swing, in this timing, it is required for the PARMs to be actuated. Therefore, we can detect the timing by the predefined threshold of the internal pressure derivative.

3.2 Gait assistive control method

We set the predefined thresholds of the pressure derivative as -30[kPa/s]. When the pressure derivative of either leg PARM becomes less than the threshold, the step inputs are applied to PARMs for 0.5[s]. If the threshold is higher than the -30[kPa/s], just little movements cause incorrect intention detection of the walking, and if the threshold is less than -30[kPa/s], a large or quick motion is required to detect the walking intention.

We set the non-detection time in order not to detect the walking intention wrongly. Once the pressure exceeds the threshold, the walking intention detection is not performed for predefined time 1.1[s]. If the non-detection time is shorter than the predefined, the PARMs are unintentionally driven by the false walking intention detection. Fig. 4 shows the state diagram of the gait assistive control method. The gait assistive control is consisting of the following phases:

0) Resting (initial pressure: **LC**, **RC**: 150[kPa], **LT**,**RT**:0[kPa])
1) Start walking
2) Intention detection (by monitoring the pressure derivative **LC** or **RC** falls less than the threshold -30[kPa/s])
3) Assist walking (applying the step input to **LT**, **RT**: 405[kPa], **LC**, **RC**: 400[kPa])
4) Non detection(for 1.1[s] to prevent the failure)

While the wearer keeps walking, the assistive suit continuously detects the walking intention (go to the phase 1). When the wearer stop to walk, the phase shift to the phase 0 and stop assisting. The assist control method is applied to each leg separately.

Using the above-mentioned assistive control method, we verify whether the proposed assistive suit is possible to assist the gait.

Fig. 5 The experimental conditio

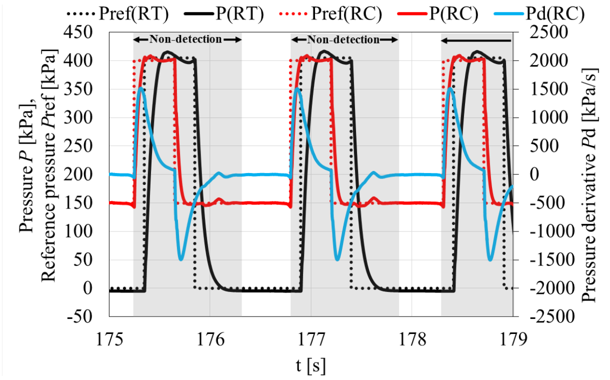

Fig. 6 The change of internal pressures and its derivative of the PARMs during walking (left leg)

4. EXPERIMENT

In this section, we perform some experiments and verify the effectiveness of the proposed system.

4.1 Walking experiment with assistive suit

First, we performed the walking experiment on the treadmill using the proposed assistive suit and the assistive control method. We confirmed that the wearer with the assist can walk at the speed of 1.0~4.5[km/h] and the assistive suit can detect the walking intention continuously. We verified by the sensory evaluation that PARMs on each legs work as expected.

After the gait phase shifts to the Mid Stance in each legs, the extension force are transmitted to the PARM on the cruris. When the gait phase shifts to the Pre-Swing phase, the extension force are not transmitted them and the internal pressure of the PARM starts to decrease, then the assistive suit detects the intention using the threshold of the pressure derivative and assists the wearer's gait. When the wearer stops walking, the pressure derivative does not fall less than the threshold and hence the assistive suit does not detect the walking intention, i.e., it does not assist the wearer's gait.

For verifying that the proposed assist control performs as expected, we recorded the internal pressure and its derivative of the PARMs while the wearer walks on the treadmill at the speed of 2.0[km/h] with the assist. Fig. 6 shows the change of the internal pressure and its derivative of the PARMs during walking. We verified that the assist control performs as expected.

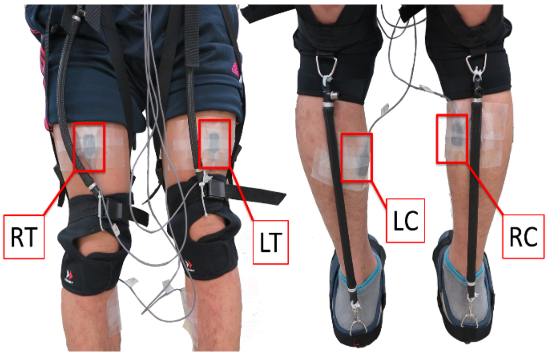

Fig. 7 The position of the electrodes

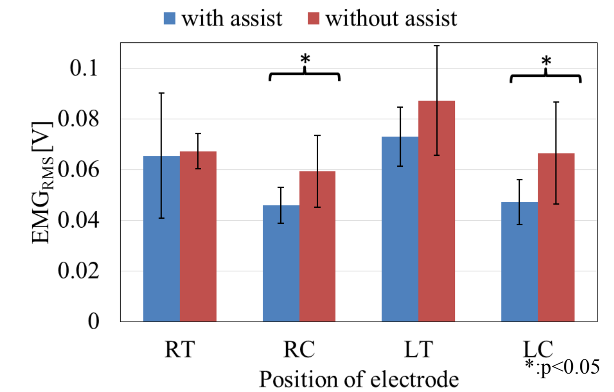

Fig. 8 The evaluation result

4.2 Evaluation experiment using electromyogram

We perform an evaluation experiment for verifying the effectiveness of the walking assistive control. The evaluation experiment is performed under the following experimental conditions.

- The wearer walks on the treadmill at the walking speed of 2.0[km/h]
- Electromyogram(EMG) signals are recorded during walking. The sampling time is 1[ms].
- The position of the electrodes is shown in Fig. 7.
- The trial is performed 7 times.
- A healthy male aged in his 20's

We recorded EMG signals and calculate the RMS values. The RMS values are used just for a evaluation of the effectiveness of the assistive control. The RMS value is defined as follows:

$$\mathrm{EMG_{RMS}} = \sqrt{\frac{1}{N}\sum_{i=0}^{N-1}\mathrm{EMG}_i^2} \quad (1)$$

Fig. 8 shows the evaluation result. The average $\mathrm{EMG_{RMS}}$ values can be a one of the index for the evaluation how strong the wearer uses their muscles. The value with the assist are less than the values without the assist. The results show that the wearer with the assistive suit can walk more comfortably.

CONCLUSION

We developed a wearable, lightweight, soft assistive suit which can detect the wearer's walking intention without wearing sensors. The condition of the walking intention detection of the wearer is determined by the preliminary experiment and we found that the assistive suit can detect the intention using the threshold of the pressure derivative of the PARM. We performed walking experiment and recorded the internal pressure of the PARMs and its derivative for verifying that the assistive suit perform as expect. We recorded the EMG signals during walking with the assist. Using the RMS values of EMG, we verified the effectiveness of the assistive control.

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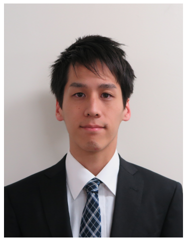

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