2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Development of Pneumatic Lower Limb Power Assist Wear driven with Wearable Air Supply System

Daisuke Sasaki, *Member*, *IEEE*, Toshiro Noritsugu and Masahiro Takaiwa

Abstract— **Many kinds of power assist device have been developed, and are driven with various actuators such as an electric motor, a hydraulic cylinder and so on. By using the exoskeleton, a high generated torque actuator can be introduced. An assist performance of these devices becomes high. On the other hand, a realization of exoskeleton which has the same D.O.F of a human is not easy from considerations about a size and strength of device. In this study, the power assist wear for lower limb is developed. The developed wear is like trousers. A human can be assisted by just wearing trousers on which the pneumatic soft actuators are put. The pneumatic soft actuator has a high power weight ratio, and has a light weight. These features contribute to realize the simple structure which is like clothes. In this paper, the structure of power assist wear is discussed, and the application of power assist wear to assist going up and down stairs are described.**

I. Introduction

Many kinds of wearable power assist device have been developed [1-5]. These are constructed with an exoskeleton, which is driven with actuator such as an electric motor, a hydraulic cylinder and so on. By using the exoskeleton, a high generated torque actuator can be introduced. Thus, an assist performance of these devices becomes high. It is expected that these devices are introduced in many fields, such as welfare, factory and so on. On the other hand, a realization of exoskeleton, which has same D.O.F of human, is not easy from considerations about a size and strength of device. Therefore, a human movement is restricted by an exoskeleton of which D.O.F is less than a human joint.

In order to decrease a restriction, a simple structure which is like clothes is an ideal. Accordingly, the power assist device of which the structure is like trousers is developed in this study. This device, hereinafter the power assist wear, can assist a human without an exoskeleton. In addition, a human can be assisted by just wearing trousers on which the pneumatic soft actuators are put. In the developed wear, expansion force of pneumatic actuator, which has a high power-weight ratio, is applied to a human body through the inextensible cloth. Smart Suit Lite[6], which can reduce a burden at a trunk, is one of the assist device which is constructed with flexible materials and has simple structure. The developed device, which supports posture of lower limb for a healthy person, is also constructed with flexible materials. In addition, this device can regulate tension of flexible material by increasing / decreasing pressure of pneumatic soft actuators. In addition, compressed air to drive this wear is generated from wearable air supply system. This air supply system is designed based on air power[7] and pneumatic energy[8]. Therefore, this wear can be driven without an external air compressor. In this paper, the structure of power assist wear is discussed, and then actuator and air supply system are evaluated based on pneumatic energy. Finally, the applications of power assist wear to assist going up and down stairs are described.

D.Sasaki, T.Noritsugu and M.Takaiwa are with Graduate school of natural science and technology, Okayama University, 3-1-1 Tsushimanaka, Kita-ku, Okayama, 700-8530, Japan (corresponding author to provide phone: +81-86-252-1111 ext.8063; fax: +81-86-251-8062; e-mail: daisuke@ sys.okayama-u.ac.jp).

II. Structure of Power Assist Wear

Overview of developed power assist wear is shown in Fig. 1. This wear consists of the actuator and air supply system in backpack as shown in Fig. 2. The actuator shown in Fig.3 is attached by a hook-and-loop fastener between the outer and inner wears. The expansion force from actuator is applied to a lower limb through the inextensible cloth attached on the outer wear. Lower end of inextensible cloth is attached at a heel in order to prevent moving the bottom of wear upward. Upper end of cloth is attached at a waist. The jacket is fixed at a waist by hook-and-loop fasteners. This jacket not only attaches the air supply system on a human body, but prevents moving the wear downward. The main components are described in the following:

A. Pneumatic actuator

Pneumatic actuator attached on this wear is composed of the balloon and circular actuators as shown in Fig.3. The balloon actuator is arranged to generate the assist force for this wear. The circular actuator is used to attach stably the balloon

Fig. 1 Overview of lower limb power assist wear

actuator onto a human body since the balloon actuator and a human body have curved surfaces.

The balloon actuator is composed of a rubber balloon and circular cloths as shown in Fig.4. The initial diameter of rubber balloon without pressurizing is 140[mm]. The circular cloths are seamed each other so that the diameter becomes 140[mm]. The rubber balloon put into circular cloths can expand to only height direction because cloths restrain expansion to circumferential direction. The weight of this actuator is 20[g].

The circular actuator is composed of the rubber balloon stick, which is 32[mm] in initial width, and circular cloths as shown in Fig.5. The circular cloths are seamed each other so that the outer and inner diameters become 140, 60[mm]. By putting the rubber balloon stick into the circumference of this cloth, the circumference of cloth can expand to height direction. On the other hand, the center of cloth does not expand. The balloon actuator can be attached stably onto a human body through connecting at the center of circular actuator. The weight of this actuator is 20[g]. Pressure range in which a subject does not feel pain even when the actuator is pressurized is determined as driving pressure range.

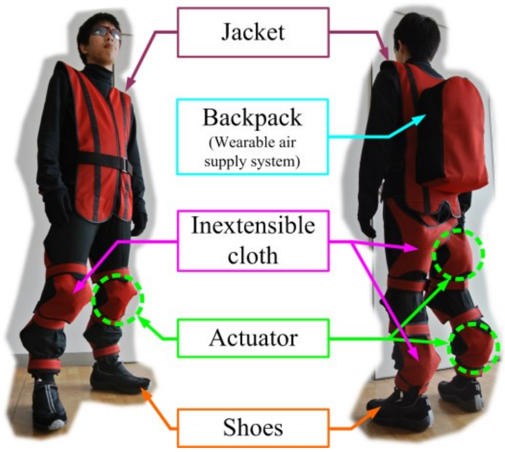


Fig. 2 Structure of power assist wear


(a) Initial state

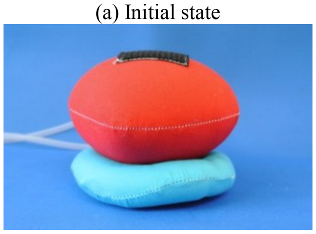
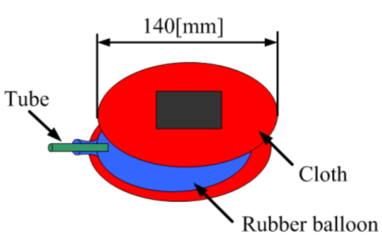

(b) Pressurized state

Fig. 3 Overview of pneumatic actuator



(a) Structure

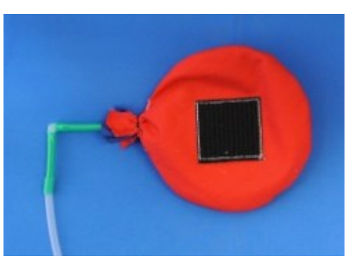

(b) Over view

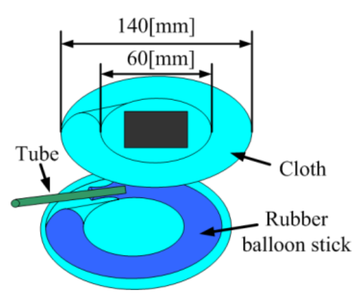
Fig. 4 Balloon actuator

B. Wearable air supply system

The air supply system is composed of variable volume tank, air pump, pressure-switch, controller and battery, on-off valve. The backpack houses these components as shown in Fig.6. One variable volume tank, four air pumps and one pressure-switch are used per one lower limb. The numbers of tank and pump are determined based on energy consumption of actuator as described in section III. The pressure-switch turns off the pump when the inner pressure of tank is higher than 35[kPa]. Conversely, the switch turns on the pump when the inner pressure is lower than 30[kPa]. Compressed air stored in tank is supplied to the actuator through on-off valve. The whole weight of this system is 3.7[kg]. The weights of battery and pumps are 1.5, 0.7[kg], respectively. This system can be driven for almost 1 hour by driving air pumps intermittently.

C. Variable volume tank

The inner pressure of an air tank is decreased when supplying compressed air from an air tank to an actuator. In a previous air tank which has a constant volume, this pressure drop becomes larger according as a tank becomes smaller. Thus, charged pressure in tank must be high if downsizing a



(a) Structure

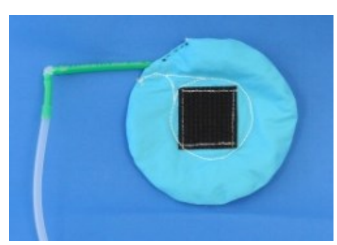

(b) Overview

Fig. 5 Circular actuator

tank volume. Conversely, tank volume must be large in order to decrease charged pressure.

The variable volume tank can store pneumatic energy, which is calculated from a pressure and flow rate, by converting it to elastic energy in a rubber material. In addition, compressed air can be discharged from tank by elastic force of rubber material. By decreasing tank volume, the charged pressure before supplying a compressed air can ideally become low since this tank can decrease the pressure drop when discharging compressed air. Then, this tank has a small volume initially, and the tank volume grows larger as compressed air is charged in the tank.

In order to realize this feature, the variable volume tank as shown in Fig.6 is introduced in this wear. This variable volume tank is composed of the rubber balloon, which has 50[mm] in the initial diameter, and the circular cloth, which has 140[mm] in the initial diameter, as shown in Fig.7(a). The diameter of this circular cloth is the same as the circular cloth for balloon actuator. It is the difference between this tank and the balloon actuator that the inner rubber balloon for this tank is smaller than the rubber balloon for actuator. Thus, the inner rubber balloon can expand when charging compressed air. This cloth limits the expansion of inner balloon to prevent excessive expansion. Seven balloons, which are stacked as one layer balloon, are used in this tank. The inner rubber balloon expands as shown in Fig.7(b) when charging compressed air. The weight of this tank is 20[g].

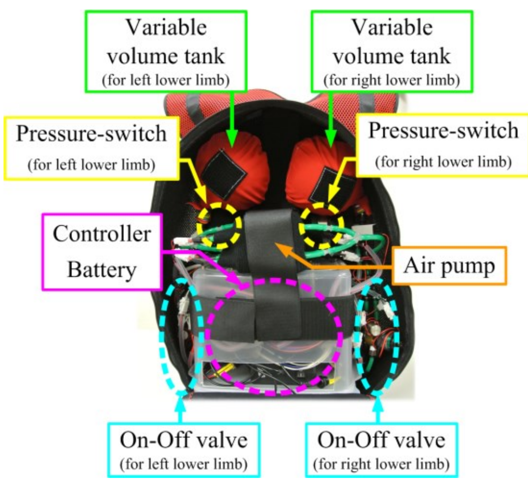
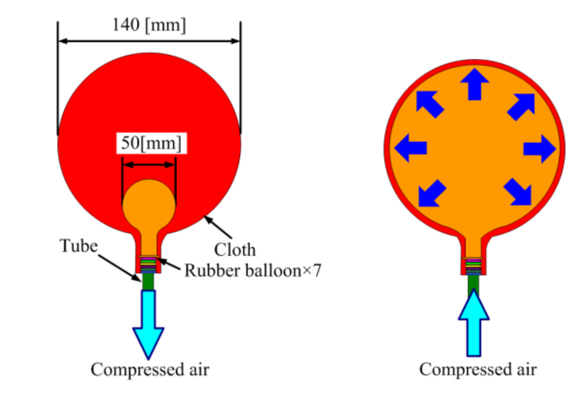


Fig.6 Structure of wearable air supply system



(a) Initial state (Discharged state) (b) Charged state

Fig.7 Principle of variable volume tank

III. Energy Characteristics of Each Component

A. Pneumatic energy

Movement of compressed air from a pump to an actuator via tank is considered in this study as a viewpoint of movement of energy. Each component is evaluated in this section by air power and pneumatic energy.

A pneumatic actuator requires supplying air power to drive itself. This air power is calculated from pressure and flow rate as follows:

$$W_{ap} = P_a Q_a \ln \frac{P}{P_a} \quad (1)$$

W_{ap} [W], P_a, P [kPa] and Q_a [m^3/s] represent air power, atmospheric pressure, absolute pressure and flow rate under atmospheric state, respectively. Pneumatic energy is defined as a time integration of air power. In this study, this energy is calculated by PC as follows:

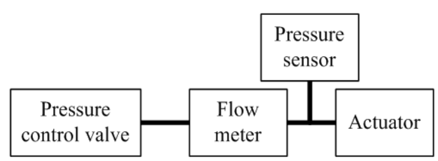
$$E_{air}[k] = t_s \sum_{i=1}^{k} W_{ap}[i] \quad (2)$$

E_{air}, t_s (= 1[ms]) are pneumatic energy, sampling time of PC. k shows sampling number. k is defined as 1 when starting to supply compressed air. W_{ap} shows the above air power calculated at each sampling number.

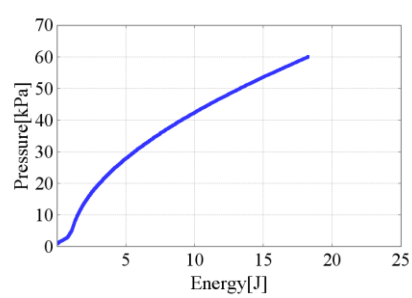
B. Characteristic of balloon actuator

Fig.8(a) shows the experimental setup for measuring energy consumption of pneumatic actuator. The balloon actuator is pressurized linearly from 0[kPa] until 60[kPa] in 180[s] by the pressure control valve. Air power and pneumatic energy are calculated from flow rate and pressure, which are detected by the flow meter and pressure sensor shown in this figure.

Fig.9 shows the extension torque characteristic of this wear. In this experiment, the mannequin, which wears this device, is flexed by force sensor. Each actuator is kept same constant pressure. The extension torque is calculated from



(a)Experimental setup



(b) Relation between pneumatic energy and pressure

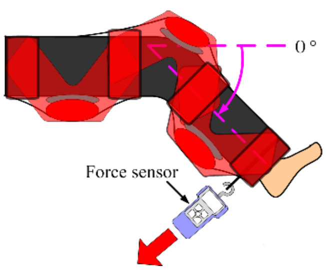
Fig.8 Energy characteristic of balloon actuator force measured by force sensor. The difference of generated torque at 20[kPa] and 30[kPa] is small as shown in the result. Thus, it is expected that the assist performance is kept even if pressure fluctuates between 20[kPa] and 30[kPa]. Pneumatic energy to drive the balloon actuator is 3-6[J] as shown in Fig.8(b).

C. Variable volume tank

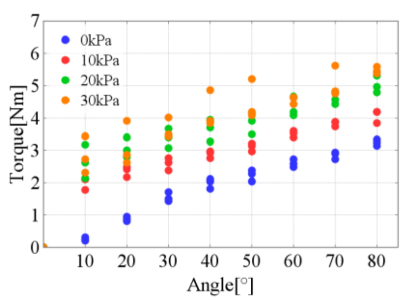
Fig.10(a) shows the experimental setup to measure energy characteristic stored in variable volume tank. This setup is the same one which measures balloon actuator. The variable volume tank is pressurized linearly from 0[kPa] until 60[kPa] in 180[s] by the pressure control valve.

This tank does not expand in pneumatic energy range less than almost 3[J]. This tank stores pneumatic energy by increasing tank pressure in this energy range. Thus, tank pressure is increased rapidly as shown in Fig.10(b) when compressed air flows into tank. This tank expands when pneumatic energy is increased more than 3[J]. Expansion of tank is restrained by circular cloth when pneumatic energy is almost 15[J]. This tank can store pneumatic energy by increasing tank volume between 3[J] and 15[J]. Then, increase in tank pressure is small when compressed air flows into tank. Tank pressure over 15[J] is also increased rapidly when compressed air flows into tank. Pneumatic energy must be stored by increasing tank pressure since tank volume is restrained.

From this result, by using this tank in energy range between 3[J] and 15[J], pressure drop can be decreased even when pneumatic energy is discharged to actuator from tank.

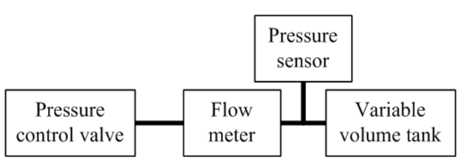


(a)Experimental setup

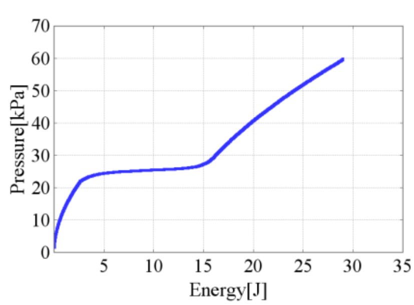


(b) Relation between angle and extension torque

Fig.9 Extension torque characteristic of this wear



(a)Experimental setup



(b) Relation between pneumatic energy and pressure

Fig.10 Energy characteristic of variable volume tank

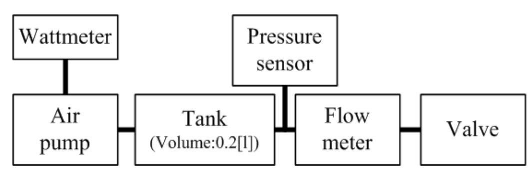
D. Air pump

Fig.11(a) shows the experimental setup to measure output air power from air pump. In this system, rolling air pump (OKENSEIKO Co.Ltd. RFP32B03R) is used. The Constant volume tank, which has 0.2[l] in volume, is connected with output port of air pump to reduce pressure fluctuation. In order to measure air power at each back pressure, pressure in constant volume tank is controlled by regulating discharged air to atmosphere. The valve is connected with output of tank to regulate discharged air. The flow meter detects the flow rate of discharged air to atmosphere, and the pressure sensor measures the back pressure.

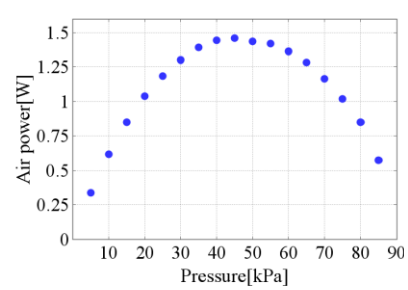
Fig.11(b) shows air power at each back pressure. It is assumed in this wear that the actuator is pressurized in 1[s]. In addition, only balloon actuator put on knee joint is pressurized in order to save pneumatic energy. Pneumatic energy to drive the balloon actuator is 3-6[J] from the above. Air pump must output 3-6[W] so that pump can supply compressed air in 1[s]. Thus, four pumps are introduced in this air system since the outputs at 20, 30[kPa] are about 1.1, 1.3[W] as shown in Fig.11(b).

IV. EXPERIMENT TO VERIFY ASSIST EFFECT

In this section, this device is applied to assist going up and



(a)Experimental setup



(b) Relation between pressure and air power

Fig.11 Air power of pump

down stairs. It is expected that the load applied to the supporting leg can be reduced.

Inner pressure of actuator for supporting leg must be increased or be kept high. Conversely, compressed air in actuator for other leg must be decreased to avoid influence of movement. ON-OFF valves are used to increase or decrease inner pressure. These valves are switched based on contact sensors. Contact sensors detect contact states between heel/hallux and floor, and are put on insole as shown in Fig. 12. The controller switches valves to exhaust air in balloon actuator at knee as follows:

Exhaust: The inner pressure of actuator of leading leg is decreased when raising a foot of leading leg from floor.

Supply: The inner pressure of actuator of leading leg is increased when a foot of leading leg contacts a floor and a heel of supporting leg is raised from a floor.

The stair has 75[cm] in width, 30[cm] in depth and 18[cm] in height. Subject is male, who is 22 years and has 168[cm] in height, 55[kg] in weight. Subject moves as follows and shown in Fig.13, 14:

Going up/down stair

0 - 3s: Subject stands straight.(Fig.13,14 (a))

3 - 4s: Subject lifts and moves the right foot to upper/lower stair. (Fig.13,14 (b),(c))

4 - 5s: Subject lifts and moves the left foot. (Fig.13,14 (c),(d))

5 - 6s: Subject stands straight.(Fig.13,14 (e))

6 - 7s: Subject lifts and moves the left foot to upper/lower stair. (Fig.13,14 (f),(g))

7 - 8s: Subject lifts and moves the right foot. (Fig.13,14 (g),(h))

8 - 9s: Subject stands straight.(Fig.13,14 (i))

9 - 14s: Subject repeats the same movements as ones from 3s until 8s.

14-17s: Subject stands straight.(Fig.13,14 (j))

The above experiments are performed in either case with and without the wear. EMG is measured at the vastus lateralis muscle and gastrocnemius muscle, which are shown in Fig.15, in the left leg. In addition, the knee and ankle angles of both legs are measured. Knee and ankle angles are defined as Fig.16. In the experiment about using the wear, compressed air is supplied from wearable air supply system.

(a)Overview of shoes

(b) Overview of insole

Fig.12 Shoes in which contact sensors are attached

Fig.17, 18 show iEMG and each joint angle when going up and down stairs. iEMG, which is one of an index of a muscle activity, is calculated from a moving average of an absolute value of EMG. iEMG is increased when a measured muscle generates the contraction force. In this experiment, iEMG is the moving average from 0.1[s] before.

iEMG of vastus lateralis decreases at 7-8, 13-14[s] when Fig.17(b) is compared with (a). The vastus lateralis must generate large muscular force at 7-8, 13-14[s] to lift body. Similarly, Gastrocnemius must generate the plantar flexion torque at 4, 10[s] to support body since body weight torque is applied to ankle in dorsal flexion direction. iEMG of gastrocnemius decreases at 4, 10[s] as shown in figures. It is confirmed from these results that the muscular load can be decreased by using the wear when going up stairs.

iEMG of vastus lateralis decreases at 3-4, 9-10[s] when Fig.18(b) is compared with (a). The vastus lateralis must generate large muscular force at 3-4, 9-10[s] to support body. It is also confirmed that the muscular load can be decreased by using the wear when going down stairs.

This device, which generates extension torque, becomes resistance of knee flexion by delay of pressure response in actuator when subject moves lower limb ahead such as 4-5[s] in Fig.17(b), Fig.18(b) even though extension torque is decreased by exhausting compressed air in the actuator. This

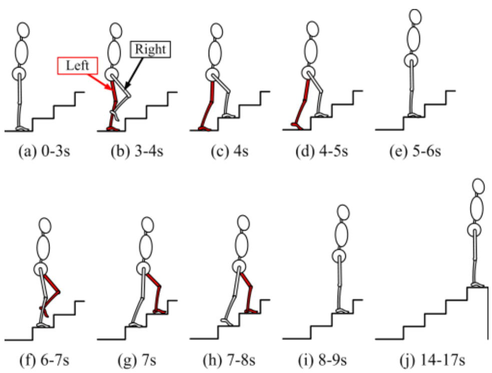


Fig.13 Outline of going up stairs

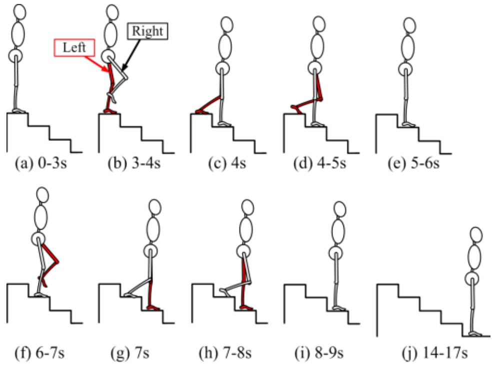


Fig.14 Outline of going down stairs

matter occurs in exchange for decrease in driving pressure of actuator. The decrease in resistance of knee flexion without increasing driving pressure is future work in this study.

V. Conclusion

In this study, the power assist wear for lower limb has been developed to realize a simple structure which is like clothes. Body load can be reduced although compressed air is generated from wearable air supply system. From the results, it is expected that this wear is applied by a stand-alone. The down-sizing and weight reduction of whole system are future works of this study.

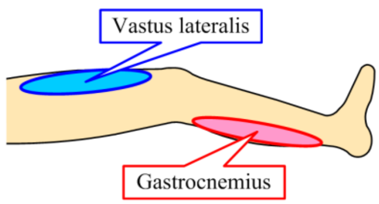


Fig.15 Measured points of EMG

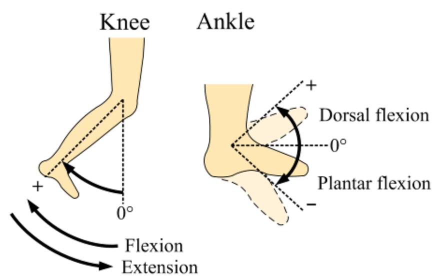
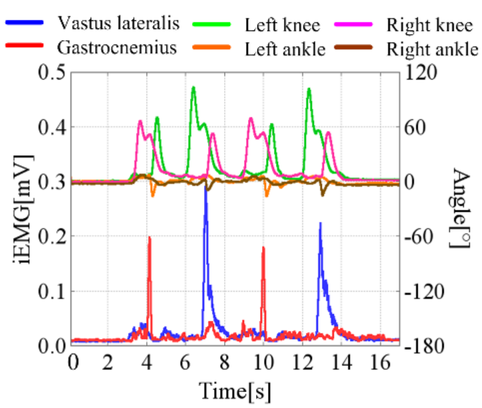
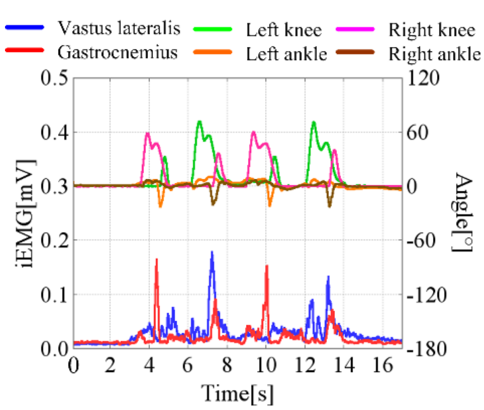


Fig.16 Angle definitions

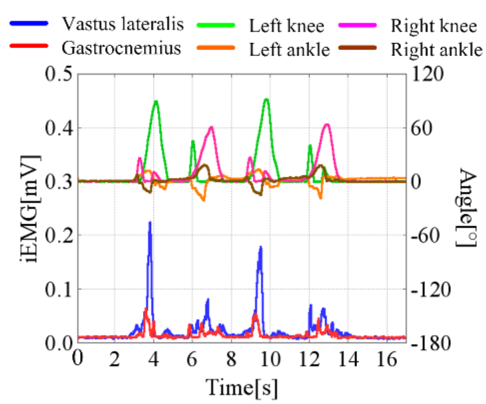


(a) Without wear

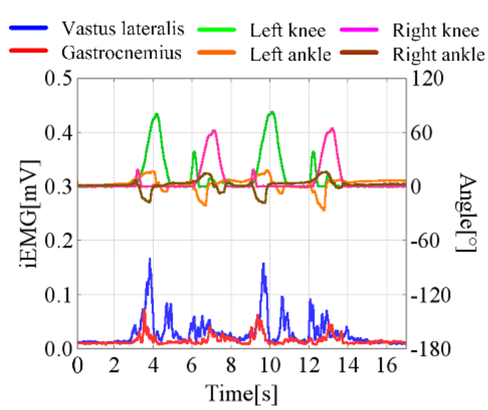


(b) With wear

Fig.17 iEMG and joint angles about going up stairs



(a) Without wear



(b) With wear

Fig.18 iEMG and joint angles about going down stairs

References

[1] T.Kawabata, H.Satoh, Y.Sankai, “Working Posture Control of Robot Suit HAL for Reducing Structural Stress,” Proc. of the 2009 IEEE Int. Conf. on Robotics and Biomimetics, pp. 2013-2018, 2009.

[2] J. C. Perry, J. Rosen, S. Burns, “Upper-Limb Powered Exoskeleton Design,” IEEE/ASME Trans. on Mechatronics, Vol.12, No.4, pp.408-417, 2007.

[3] T. G. Sugar et al., “Design and Control of RUPERT: A Device for Robotic Upper Extremity Repetitive Therapy,” IEEE Trans. on Neural Systems and Rehabilitation Engineering, Vol.15, No.3, pp.336-346, 2007.

[4] Y. Muramatsu et al., “Quantitative Performance Analysis of Exoskeleton Augmenting Devices –Muscle Suit– for Manual Worker,” Int. J. of Automation Technology, Vol.5, No.4, pp.559-567, 2011.

[5] G. S. Sawicki, K. E. Gordon, D. P. Ferris, “Powered Lower Limb Orthoses: Applications in Motor Adaptation and Rehabilitation,” Proc. of the 2005 IEEE 9th Int. Conf. on Rehabilitation Robotics, pp.206-211, 2005.

[6] Y.Imamura, T.Tanaka, Y.Suzuki, K.Takizawa, M.Yamanaka, “Motion-Based-Design of Elastic Material for Passive Assistive Device Using Musculoskeletal Model,” J. of Robotics and Mechatronics, Vol.23 No.6, pp.978-990, 2011.

[7] T.KAGAWA, “Energy Comparison of Electric and Pneumatic Actuators,” Proc. of the 5th JFPS Int. Symp. on Fluid Power , pp.345-351, 2002

[8] T.Iwawaki, D. Sasaki, T. Noritsugu, M. Takaiwa, “Development of Portable Energy-Saving Type Air Supply System – 1st Report: Effect of Variable Volume Tank –,” J. of Robotics and Mechatronics, Vol.24 No.3, pp.464-471, 2012.