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Verification of Assistive Effect Generated by Passive Power-Assist Device Using Humanoid Robot

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Abstract— **We are developing a passive power assist supporter called *Smart Suit Lite*. Smart Suit Lite is a compact and lightweight power assist device that utilizes the elastic force of elastic belts, and its purpose is reduction of lumbar load. We have proposed the design method of Smart Suit Lite based on a digital human model and motion measurements. This paper presents the basic experiment using humanoid robot HRP-4C for verifying the design model of the elastic force and its assistive effect. In the experiment, the joint torques of the robot and the elastic force of Smart Suit Lite were measured. We observed the decrease of the chest torque by the assistive force during forward bending motion. Furthermore, the comparison between the simulation results and the experimental result is described.**

I. Introduction

With today's fewer children and rapidly aging society, the demand for fatigue reduction during works is rapidly increasing. One of the most serious problem is low back pain. For example, it is reported that half of all caregivers suffer from backaches in Japan [1]. Hard works such as transportation, agriculture and caregiving involve such movements as deeper forward-bending than in normal daily life activities or the lifting of things while in a twisted posture; these impose undoubtedly heavy burdens on the lower back. It is reasonably expected, therefore, that the reduction of physical burden will lead to the alleviation of fatigue as well as to the prevention of lumbar disorders.

At present, there are a large number of researches for power assist devices to assist muscle forces or to support movement. Wearable power assist devices are attracting a particularly great amount of attention in the today's society. Sankai et al. developed HAL, an exoskeletal robott suit to extend and amplify human physical functions[2]. The effect of HAL in reducing the level of muscle activity has been verified. Kazarooni et al. developed the the Berkeley Lower Extremity Exoskeleton (BLEEX) [3]. BLEEK has been demonstrated to support up to 70kg, walk at speeds up to 1.3m/s.

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In order to prevent lumbar disorders in a more positive way, we are developing a passive power assist supporter called "Smart Suit Lite (SSL)" [4] shown in Fig. 1. It is based on the concept referred to as "KEIROKA" aimed at removing the load and fatigue on the body rather than a force-multiplication. Smart Suit Lite is a compact and lightweight device made of elastic materials (rubber belts) as an assistive power source, and has high safety. A part of the elastomeric forces are utilized as muscle-supporting forces, and remaining force works as pelvic tightening forces like a corset. In previous studies, we proposed the design method for Smart Suit Lite based on the simulation with musculoskeletal dynamics model, and performed the verification experiment of the effect of reducing the muscle activation. It was confirmed that the muscle activities of the back muscles during lifting motion were reduced 24% in average by wearing Smart Suit Lite.

However, there are some problems of validation experiments on human. For example, the estimations have been done under some assumptions about mechanics and physiology, there is a possibility that the motion itself is changed by the assistive devices, and the noise and individual differences are included. In the other hand, the effect verification method using the humanoid robot has been proposed. Humanoid robots have advantages that they can reproduce human motions, use the devices such as Smart Suit Lite, provide quantitative measures such as applied torque or force from sensors, and repeat the same motions precisely. In addition, since humanoid robot HRP-4C(Fig. 2) has a shape of the average Japanese females, it is suitable for verification of such wearable devices. Miura et al. compared the torque of HRP-4C in the lifting motion with and without Smart Suit Lite, and observed a clear decrease of the torque by wearing Smart Suit Lite[5].

In this paper, in addition to the torque measurement of HRP-4C, we newly measured assistive forces generated by Smart Suit Lite, and report the comparison between that experimental results and the simulation results, and discuss the validity of the simulation model for the design of the assistive force or the structure.

II. Power-Assist Device and Simulation Model

A. Smart Suit Lite

This section describes the construction and power assist principle of Smart Suit Lite. Fig. 1 shows a prototype of Smart Suit Lite. Fig. 3 illustrates assist mechanism in schematic diagram. It shows a modeled elastic material on one side, though Smart Suit Lite has two sets of elastic materials. Elastic material $\mathbf{R}_1$ on the torso with generated elastomeric force F_1 is linked by a moving pulley to elastic material $\mathbf{R}_2$ on the thigh with generated elastomeric force F_2, and they are arranged to connect the shoulders and legs on the back. Each elastic modulus is k_1 and k_2. Elastic material $\mathbf{R}_1$ is turned up at point B and connected to the waist belt at point D. With Δl_{AC} denoting the change in length between A and C when the wearer changes postures, Δl_{AB} denoting the change in length between A and B, and Δl_{BC} denoting the change in length between B and C.

The elongation of the elastic material $\mathbf{R}_1$ equals $2\Delta l_{AB}$ because $\mathbf{R}_1$ turns up at point B. Elastic materials generate the following elastomeric forces:

$$F_1 = 2k_1 \Delta l_{AB} \tag{1}$$

$$F_2 = k_2 \Delta l_{BC} \tag{2}$$

With $2F_1 = F_2$, $\Delta l_{AC} = \Delta l_{AB} + \Delta l_{BC}$, the ratio of elongations of the elastic material between the torso and the thigh is expressed by a relational expression $\Delta l_{AB} : \Delta l_{BC} = k_2 : 4k_1$. From these equations, assistive torque τ_{s1} and τ_{s2} which extend the lumbar joints and hip joints respectively is expressed as follows:

$$\tau_{s1} = r_s F_1 = \frac{2k_1 k_2 r_s}{k_2 + 4k_1} \Delta l_{AC} \tag{3}$$

$$\tau_{s2} = r_s F_2 = \frac{4k_1 k_2 r_s}{k_2 + 4k_1} \Delta l_{AC} \tag{4}$$

where r_s denotes moment arms of the elastic material for lumbar joint. Moreover, other elastomeric force F_1 strains the waist belt to tighten the torso, just as a corset does.

$$F_1 = \frac{2k_1 k_2}{k_2 + 4k_1} \Delta l_{AC} \tag{5}$$

Fig. 1. Passive Power-Assist Device "Smart Suite Lite"

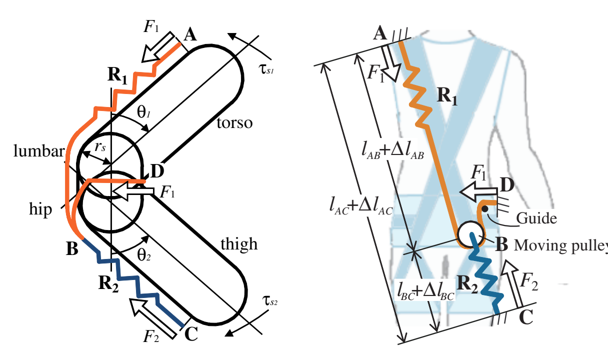
Fig. 2. Humanoid HRP-4C[7]

It is known that lumbar loads become greater as the waist is bent deeper [6]. Since elongations Δl_{AC} of the elastic material increase as the wearer bends the waist deeper, any postures imposing heavier burdens generate greater assistive forces.

B. Simulation Model

We have proposed the design method of the elastic material properties and arrangements in consideration of the muscle assistive effect [4]. In the proposed method, target assist ratio is defined as the rate of reduction in the muscle activation, the elastic properties has optimized to minimize the difference between the target assist ratio and the estimated assist ratio during target motions. For analysis of the assistive force, the musculoskeletal simulator SIMM (Software for Interactive Musculoskeletal Modeling; MusculoGraphics) and "skin segment model" have been used.

The skin segments model body surface shapes, as shown in Fig. 4. Smart Suit Lite has a mechanism by which elastic materials are elongated according to changes in body surface length, and then generate assistive power. Therefore, the assistive power generated in movements can be obtained by modeling the relationship between human postures and body surface shapes. We first prepare a three-dimensional skin segment representing the shape of a body surface and add it to the model in SIMM. The skin segment is divided into many segments to represent changes in body surface length by gaps created between the segments. Specifically, to represent elongations of the skin over the lumbar joints, the lumbar segment is divided according to the lumbar spine. Each segment moves in conjunction with lumbar joint angles against the pelvic coordinate system. Assuming that changes in the length between segments in a certain route on the body surface are given by $\Delta l_{(i-1)i}$, total elongation Δl on the torso is expressed by the total sum of such changes in



(a) Lateral view (b) Back view

Fig. 3. Assist mechanism of Smart Suit Lite[4]

length between segments.

$$\Delta l = \sum_{i=1}^{5} \Delta l_{(i-1)i} \qquad (6)$$

Skin segments around the hip joints are divided in a similar way. The skin segment is adjustable in terms of its sizes and transformation matrixes. Therofore it enables us to prepare a model that suits an experimental subject. A model that is resized for HRP-4C is shown in Fig. 5.

We have designed the arrangement and elastic properties of the elastic belts for Smart Suit Lite which targets 25% reduction in activities of back muscles in typical nursing care motions. Designed Smart Suit Lite is shown in Fig. 6(a). It has confirmed that the activities of the erector spinae is reduced 24% on average by wearing the Smart Suit Lite. The measured values of the elastic properties of the Smart Suit Lite used in this research is shown in Fig. 6(b),(c). In this paper, this Smart Suit Lite is used in verification experiment.

III. Humanoid Robot as Device Evaluator and Target Motion

As mentioned in the introduction, there are some problems that make subject experiments difficult. Especially individual differences is large, and it is difficult to reproduce the same motions even by same person. To address those problems, we adopt the experiments using a humanoid robot instead of human subjects. The expected advantages this replacement are the following[5]:

- As humanoid robots have the same morphology as humans, they can physically simulate usage of the device in real life in a similar manner to humans.
- Humanoid robots can repeat exactly the same motions and provide quantitative measures such as joint trajectories, torques or applied forces.
- Ethical problems can be cleared for experiments with risks of injury.

Since joint torque is difficult to be measured from human motions, the humanoid robots have a strong advantage in being capable of getting directly these data. Humanoid robot used in this experiment is HRP-4C shown in Fig. 2. HRP-4C is 1.58 m in height and 43 kg in weight, featuring its body parameters like link length and size close to the measured average of women of 19-29 years old in Japan [7]. Therefore, it is considered that HRP-4C is appropriate as a subject of assistance by Smart Suit Lite.

For evaluating assistive devices, robots have to perform motions like human. In this paper we use a motion created using retargeting technique, which is adapted to reproduction of whole-body motion. The retargeting technique generates a motion pattern which satisfies both dynamic consistency of the robot and preservation of the original human motion[8].

By its structure, Smart Suit Lite supports the muscles of lower back during lumbar extension and maintaining forward-bending position or kneeling position. Therefore we choose bending motion from the waist as a motion for evaluating Smart Suit Lite. The snapshots of the generated

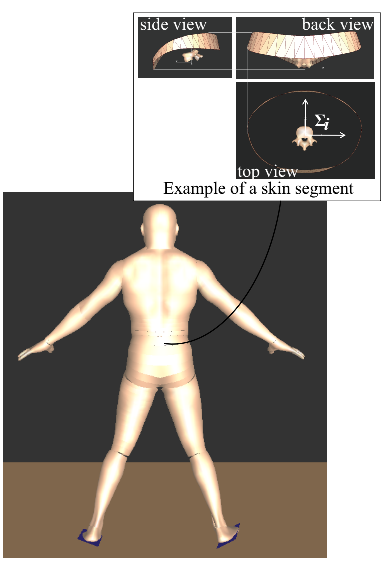


Fig. 4. Skin segment model

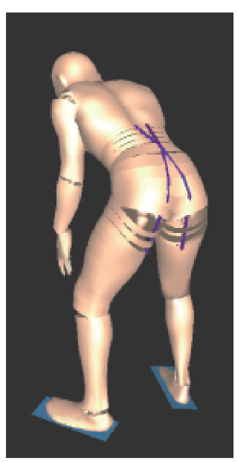
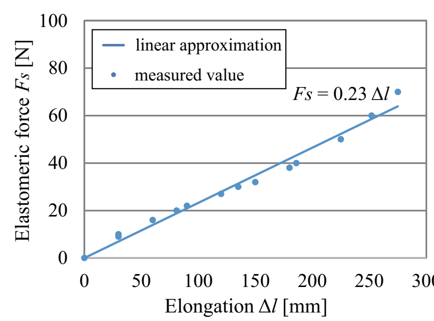
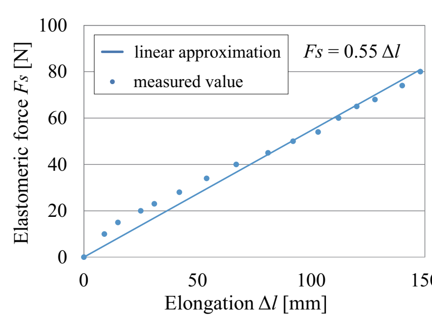


Fig. 5. Skin segment model of female with standard proportions

(a) Placement of elastic belts



(b) Elastic property of elastic belts of the back



(c) Elastic property of elastic belts of the legs

Fig. 6. Smart Suit Lite for Caregiving Movements

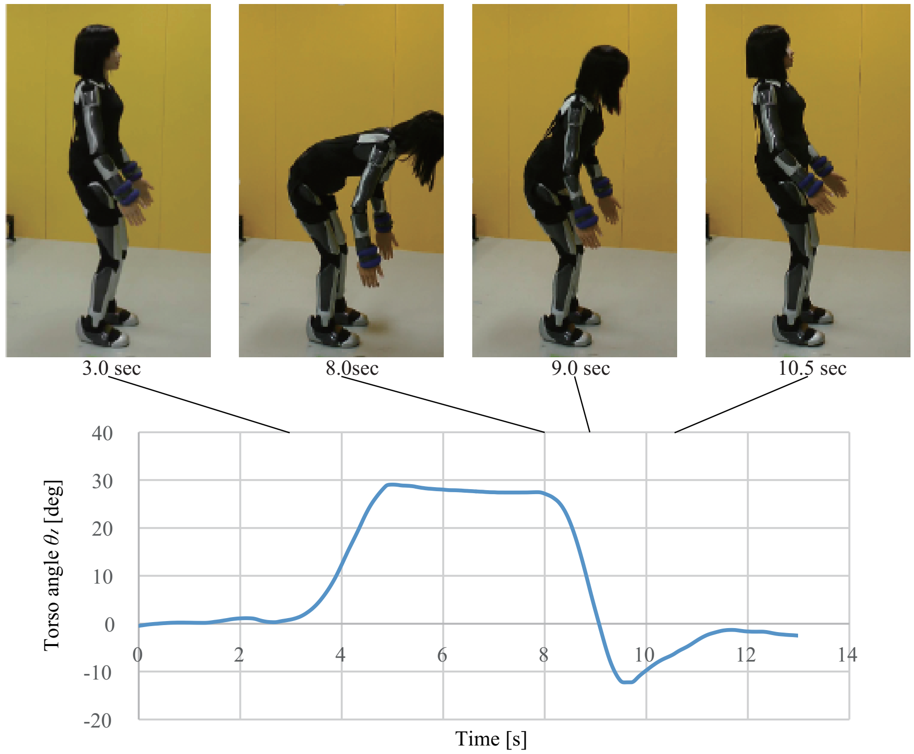


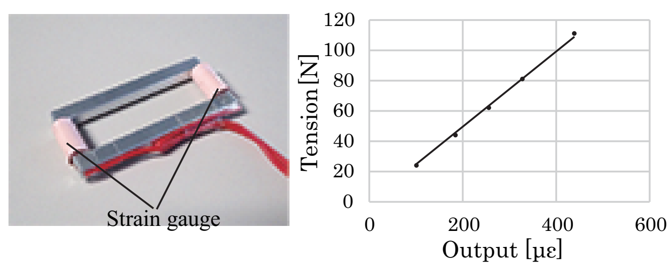
Fig. 7. Experiments of lifting motion by HRP-4C

motion and torso pitch angle are shown in Fig. 7. HRP-4C started bending from about 4 seconds after the start of motion, tilting the the upper body near horizontal after 8 seconds. Then, it got up and return to the upright position in about two seconds.

IV. Experiments

A. Experimental Conditions

We have conducted basic experiments with HRP-4C wearing Smart Suit Lite that makes the bending motion shown in the previous chapter. In order to evaluate the load reduction effect, we measured the joint torques for the motion with and without Smart Suit Lite. Measurements with Smart Suit Lite were performed five times. The joint torque of HRP-4C is measured and estimated from the current of the motor at a sampling frequency of 200Hz. Assistive force of the elastic belts of Smart Suit Lite were also measured by the tension sensor shown in Fig. 8(a). The sensor is composed of two strain gauges (KFG-5-120-C1-23L3M2R, KYOWA ELECTRONIC INSTRUMENTS CO., LTD.) and an aluminum frame, and records the strain of the frame at sampling frequency of 1kHz through a sensor interface (PCD-300B, KYOWA ELECTRONIC INSTRUMENTS CO., LTD.). By arranging in series with the elastic material as shown in Fig. 9, the sensor is able to measures the elastic force during motions. The relationship between the output of the sensor and the tension is shown in Fig. 8(b).



(a) Tension sensor (b) Property of sensor

Fig. 8. Structure and property of tension sensor

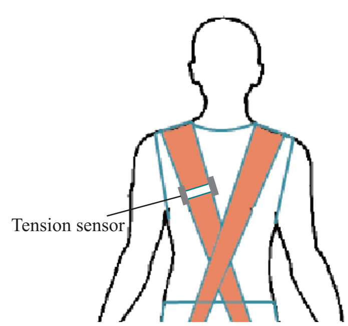


Fig. 9. Mounting position of tension sensors

B. Results and Consideration

Since Smart Suit Lite aims to reduce the torque at the lower back, we focus on the chest pitch angle and torque

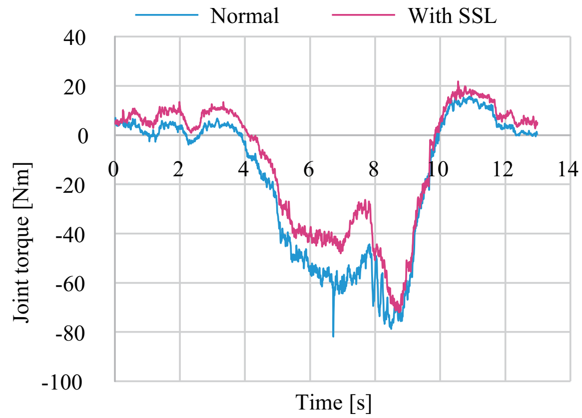


Fig. 10. Changes in chest torque by assistance of Smart Suit Lite

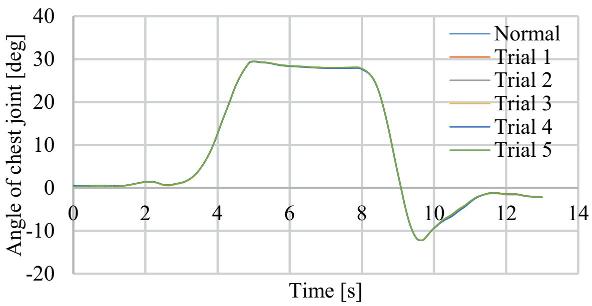


Fig. 11. Angle of chest joint in all trials

that corresponds to the lumbar of human. Fig. 10 shows an example of the measured torque at the chest pitch joints with and without Smart Suit Lite. It was confirmed that the average of the absolute value of the joint torque decreased when wearing Smart Suit Lite at all trials. The average of the reduction ratio of chest pitch torque during 3-10 seconds is $23.4 \pm 2.5\%$.

We also verified that wearing Smart Suit Lite does not change the resultant joint trajectory of the robot as shown in Fig. 11. The mean square error of the angle of the chest joint compared with non-assistance condition was 0.3 deg or less at maximum. This is an error of about 0.7% for the range of joint angle (-12.2 - 29.5 deg).

In contrast, the measured tension of the elastic belts have a variation per each trial as shown in Fig. 12. The average value and the standard deviation of the maximum of tensions is 20.3 ± 1.7N. This variation is considered to be caused by the initial conditions of wearing and the slip of the suit during motions. Moreover it is considered that this variation also affected the variations in the ratio of decrease in the joint torque. Therefore it is necessary to improve the standardization method of the condition of wearing and the technique preventing the slip of the suit as a future work.

Then, the assistive torque generated by Smart Suit Lite is described. Here, the difference between torque τ_c when wearing Smart Suit Lite and torque τ_{c0} when non-wearing

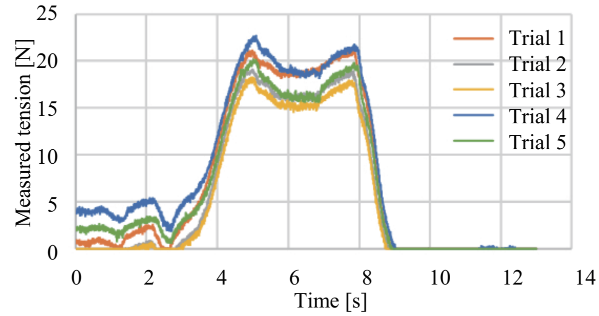


Fig. 12. Measured tension of elastic belts in all trials

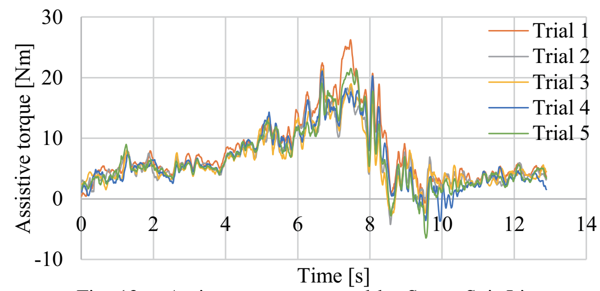


Fig. 13. Assist torque generated by Smart Suit Lite

Smart Suit Lite is defined as the assistive torque $\hat{\tau}_{s1}$ applied to the chest joint. The value of the torques were smoothed by the moving average of 0.1 seconds. The results are shown in Fig. 13.

$$\hat{\tau}_{s1} = \tau_c - \tau_{c0} \tag{7}$$

Fig 14 shows results plotted the assistive torque $\hat{\tau}_{s1}$ against assistive force (tension of the elastic belts) for each sampling period. It is considered that the assistive torques is proportional to the assist force as shown in (3). The correlation coefficients ware larger than 0.8 at all trials, thus it is found that there is a strong positive correlation between the assistive torques and the tension of the elastic belts. In addition, the variation is small especially in the forward bending phase which is moving at a slow pace as shown in Fig. 15. It is considered that because dynamic effect and the displacement of the suit are small in the phase. Equation between the assistive torques $\hat{\tau}_{s1}$ and the tension F_1 is obtained by following linear approximation.

$$\hat{\tau}_{s1} = r_s F_1 + \tau_{s10} \tag{8}$$

where r_s means moment arm of the assistive force for the chest joint, and τ_{s10} means the initial assistive torque generated in the upright position. We have obtained $r_s = 0.22$, $\tau_{s10} = 4.54$. From this reslut, it is found that the joint torque is decreased 4.54Nm even in a state which the tension is not working. It can be considered that components of Smart Suit Lite other than the back elastic belts have a supportive effect for the chest torque. Therefore more detailed modeling of clothes is required.

On the other hand, the estimeted moment arm is 0.22m. Since

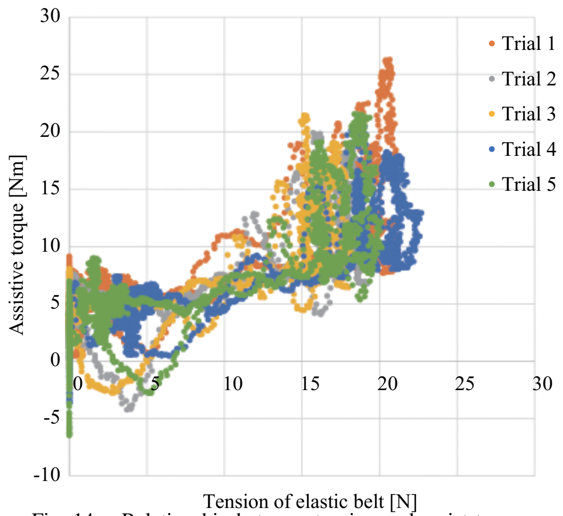


Fig. 14. Relationship between tension and assist torque

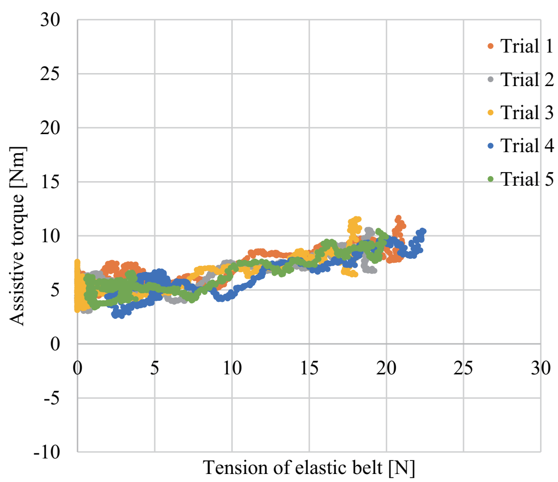


Fig. 15. Relationship between tension and assist torque during forward bending motion (2-5 sec)

there are two elastic materials on the back symmetrically in fact, twice the force is applied to the chest joint. Therefore actual moment arm will be half, and be calculated to be 0.11m. It is a reasonable value considering the body shape of HRP-4C. From these results, it is verified that the tension of the elastic material at wearer's back increases the assistive torque applied to the chest joint. Finally, comparison of the measured value with the estimated value of the assistive force will be described. The estimated value is obtained by using the skin segment model and the elastic properties described in section II-B. The results are shown in Fig. 16. The correlation coefficient is 0.81, and the maximum value was almost the same. However, there is a period that there is no tension in spite of high tension in the estimate value (9-10sec). It is considered because the elongation due to the bending of the hip joint is not transmitted to the elastic belts because of the friction or the slip of the suit. Therefore there is a need for modeling in consideration of the friction in each

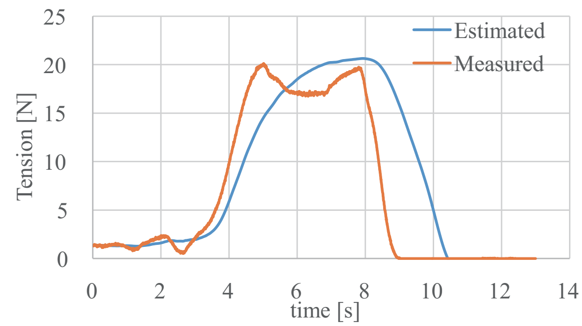


Fig. 16. Comparison between measured tension (average of 5 trials) and estimated tension

part.

V. Conclusions

In this paper, the results of evaluation of Smart Suit Lite by humanoid robots were described. We confirmed that the tension of the elastic belts at wearer's back increases the assistive torque applied to the chest joint. This result supports the correctness of the assist mechanism of Smart Suit Lite.

The points that must be improved in the simulation model also became clear by the experiment . It is found that there is components of Smart Suit Lite other than the back elastic belts have a supportive effect for the chest torque. Therefore more detailed modeling of clothes is required. Furthermore, there is a need for modeling in consideration of the friction and the slip in each part for more accurate estimation of the transmission of forces. In future work, It is possible to improve the simulation model by feeding back the results and estimate the assist effect more accurately. In addition, the future direction includes evaluation of assistive effects for more complex motions like sideways object displacement.

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