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Verification of Passive Power-Assist Device Using Humanoid Robot: Effect on Bending and Twisting Motion

Yumeko Imamura[1], Takayuki Tanaka[2], Ko Ayusawa[1] and Eiichi Yoshida[1]

***Abstract*— A passive power-assist supporter, called *Smart Suit Lite*, aims at reducing the lumbar load utilizing the tension of elastic belts. Its design method is based on a digital human model and motion measurements. This paper presents basic experiments using humanoid robot HRP-4 for verifying the design model of the suit. In the experiment, the joint torques of the robot and the elastic force of Smart Suit Lite were measured. We found that the decrease of the chest pitch torque during slow forward bending motion on the sagittal plane was consistent with simulation results. In addition, the effects for three-dimensional motion including chest pitching and yawing also indicated a similar tendency to the simulation. Because we performed quantitative evaluation of the effects by each part of the suit, these results are considered to provide useful information to the optimization of Smart Suit Lite.**

I. INTRODUCTION

A power assistive supporter *Smart Suit Lite*(SSL) have been developed, which utilizes the tension generated by elastic materials as the assistive force [1]. Its concept is different from force enhancement or automation of work, the brace aims dispersion of the physical load from the overloaded site to the other site and reduces workers' fatigue overall. Backaches are common disorder in workers using their physical power routinely, such as care workers, agriculture workers and industrial workers. It is expected that the reduction in back muscle burden leads to the alleviation of fatigue as well as to the prevention of lumbar disorders.

Fig. 1. Passive power-assist device "Smart Suite Lite".

Fig. 2. HRP-4 with a soft body surface.

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For this purpose, SSL consists of clothes and elastic belts on them shown in Fig. 1. The elastic forces generated by this structure help the wearer to return to the upright position and reduce the burden to their back muscles.

In the development of SSL, a design method for the arrangement and the strength of its elastic belts was proposed, which utilizes a digital human model and motion analysis. Optimal placement of the elastic belts is considered to be different by the target movement, because the different path provides the assistive forces of different magnitudes and direction . Therefore, in the proposed method, we decide some target motions and perform motion measurements and optimization of the arrangement of the elastic belts. Then, we set the desired assistive ratio and design the elastic properties based on the result of the inverse dynamics analysis.

The developed SSL have been verified its assistive effect through various ways. It was confirmed by measuring surface EMG that SSL reduces the activities of back muscles by 24% in average during lifting motion [1]. We have also proposed the effect verification using the humanoid robots [2], [3]. There are some problems when we conduct measurement of human subjects. 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. Humanoid robots have advantages that they can reproduce human motions, provide quantitative measures such as applied torque or force from sensors, and repeat the same motions precisely. It is reported that WABIAN-2 performed some walking experiments using walking assist machine [4]. Boston Dynamics developed PETMAN to simulate how a soldier stresses chemical protection clothing under realistic conditions [5]. We perform verification and validation of the assistive suit which affect the wearer mechanically by using humanoid robot.

In the previous paper [2], we confirmed that the forces of the elastic belts increases the assistive torque applied to the chest joint of the hunamoid robot in the bending motion on the sagittal plane. On the other hand, we cited the following points as the future tasks. One is more detailed modeling of components other than the back elastic belts, which have a supportive effect for the chest torque. The other is targeting more complex motions like sideways object displacement. In this paper, we increased the measurement points of the tension of the elastic belts, and compared with the simulation model. We also added a new motion to be evaluated, which includes the twisting of the body.

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II. Humanoid Robot as Device Evaluator

There are some problems in human subject experiments. There are individual differences on the physique and movement. In addition, even same person, it is difficult to reproducing the same motion. To address those problems, we employ humanoid robot instead of human subjects to evaluate assistive devices. The advantages of using humanoid robot can be considered as follows [3]:

- 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.

In this paper, we use the humanoid robot HRP-4 [6] wearing a soft suit instead of hard plastic cover in order to realize soft surface like a human (Fig. 2). HRP-4 is 1.51 m in height and 39 kg in weight, featuring its body size close to young japanese women. Since its body structure and dimension are is close to human, the robot can wear clothes produced for human. The robot can also obtain the assistive effect, since its weight is light like human. There are many kinds of data, of course, which can be provided only by human subjects. However, there are data such as joints torques, which can be measured only by the humanoid robot. The humanoid robots have a strong advantage in being capable of getting directly these data.

III. Power-Assist Device *Smart Suit Lite*

This section describes power assist principle of SSL. Fig. 1 shows a prototype of SSL. Fig. 3 illustrates assist mechanism of elastic materials on one side in schematic diagram. 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. Δl_{AC} denotes the change in length between A and C when the wearer changes postures, and Δl_{AB}, Δl_{BC} denotes the change in length between A and B, B and C respectively.

The elongation of the elastic material $\mathbf{R}_1$ equals $2\Delta l_{AB}$ because $\mathbf{R}_1$ turns up at point B. 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, elastomeric forces are described as follows:

$$F_1 = \frac{2k_1k_2}{k_2 + 4k_1}\Delta l_{AC} \tag{1}$$

$$F_2 = \frac{4k_1k_2}{k_2 + 4k_1}\Delta l_{AC} \tag{2}$$

Then, assistive torque $\tau_{s1} = r_sF_1$ and $\tau_{s2} = r_sF_2$ extend the lumbar joints and hip joints respectively, where r_s denotes moment arms of the elastic material for lumbar and hip joint. Moreover, other elastomeric force F_1 strains the waist belt to tighten the torso at point D, just as a corset does.

It is known that lumbar loads become greater as the waist is bent deeper [7]. 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. The measured values of the elastic properties of SSL used in this paper are $k_1 = 232$[N/m] and $k_2 = 547$[N/m]. The property of the elastic belts at the flanks are 429 N/m.

IV. Experiments

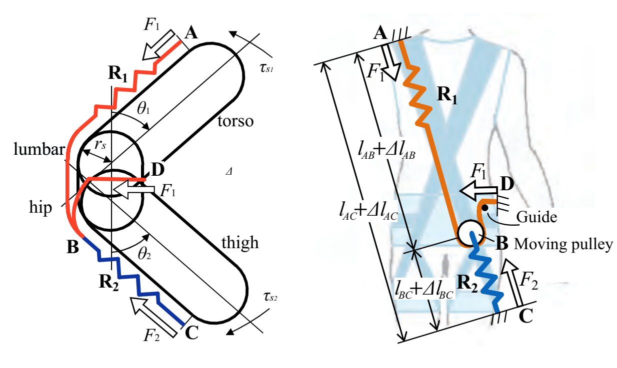
A. Improvements from previous experiments

In the previous experiment [2], we confirmed that the tension of elastic belts at wearer's back increases the assistive torque applied to the chest joint. That result supports the correctness of the assist mechanism of SSL. On the other hand, we cited the following points as the next step.

1) More detailed modeling of clothes is required, because there are components other than the back elastic belts have a supportive effect.
2) Evaluation of assistive effects for more complex motions like sideways object displacement.

For the first point, we improved from two aspects.

One is the modification of a part of the suit. In the structure of SSL, elastic cloths are used at the flank from the waist to the rib cage bottom. It was originally not in the design, and has been added in order to suppress the slippage of the clothes. For this experiment, we modified SSL to be able to adjust the length. We also measured the tension of these elastic cloths by using tension sensors described in section IV-C. The other improvement is about simulation model. Digital human model was originally used as the simulation model of the assistive force. Now, we estimate the tension using a 3D model of HRP-4 shown in Fig. 4. We set four wires on the robot to estimate the elongation of the elastic belts. Two wires cross at the back and the other two wires are placed on the flank. The via-points are placed to across the joints which cause the elongation of elastic belts, and each via-point is fixed on the corresponding link. We can



(a) Lateral view (b) Back view

Fig. 3. Assist mechanism of Smart Suit Lite [1]

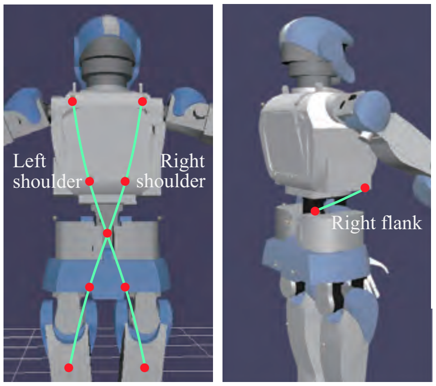


Fig. 4. Model of shapes of HRP-4 and elastic belts of SSL (Green lines). Two wires cross at the back and the other two wires are placed on the both flank. These wires are attached on the robot by via-points (Red dots).

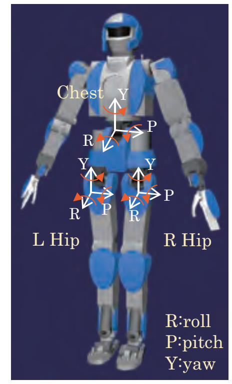


Fig. 5. Definition of a rotation axis of each joint.

compute its position and the change in length of the path by the forward kinematics.

For the second point, we employed new motions described in the next section.

B. Target motions

We use the following two motions[8] in the experiment. Fig. 5 shows the definition of a rotation axis of each joint.

1) bending forward from the waist shown in Fig. 6 (named as "bending motion").
   HRP-4 starts bending from about 4 seconds after the start of motion, tilting the the upper body near horizontal after 6 seconds. Then, it gets up and returns to the upright position in about two seconds.
2) Twisting motion to lift up object at the side shown in Fig. 7 (named as "twisting motion").
   HRP-4 lifts up the imaginary object that is placed at the left lower position and puts it on the right higher position by twisting the waist after 13 seconds, and then puts it back to the original position after 27 seconds.

As can be seen from figures, the bending motion is the motion on the sagittal plane, and the twisting motion is complex motion of chest yaw and pitch. These motions are created based on measured human motions with the motion retargeting method. The retargeting technique is used to reproduction of whole-body motion of human for the robot with a different structure from human. This technique generates a motion pattern which satisfies both dynamic consistency of the robot and preservation of the original human motion [8].

C. Method

We have conducted validation experiments with HRP-4 wearing SSL and making motions shown in the previous section. In order to evaluate the effect of SSL, we measured the joint torques. Each joint torques were calculated using input signals of electric motors with identification techniques [9] of robot's mechanical properties. The joint torques were measured with sampling rates at 200 frames per second. The tensions of each elastic belt of SSL were also measured by the tension sensor. The sensor is composed of strain gauges and an aluminum frame, and records the strain of the frame at sampling frequency of 1kHz. The details of the sensor were described in [2]. SSL was adjusted before each trial by checking the value of the tension sensors in order not to generate tensions and not to loosen in the upright posture.

D. Results

1) Tension of elastic belts: Examples of the tension measured in the bending motion are shown in Fig. 8. The gray lines show measured tension, and the red dashed line is tension simulated by using the model shown in Fig. 4. Since the tension of left and right elastic belts will be the same ideally against motion on the sagittal plane, they are plotted in the same graph. The measurement was performed three times. From the figure, we can see that the obtained tensions are generally close to the expected value, although there are variations depending on the state of initial wearing.

Next, an example of the measured tension and estimated tension in the twisting motion are shown in Fig. 9. The tension by the elastic belt on the right shoulder showed a similar tendency to the simulation. On the other hand, the tension on the left shoulder showed a different tendency from the simulation. The measured tension by the belt on the left shoulder produced a jagged waveform pattern. It could not be reproduced in the simulation. We consider that this jagged waveform pattern was caused by rolling of right hip joint (shown in Fig. 7), because the belt on the left shoulder is attached to right thigh.
In addition, the tensions of the belts on the flank in the twisting motion are also shown in Fig. 10. The shape of the waveform is similar to the simulation results, but the measured value of the left elastic belt was approximately half of the simulated value. These problems did not occur when the target motion was on the sagittal plane. In this respect, improvements in the simulation model will be necessary.

2) Assistive torque in the bending motion: Then, the assistive torque generated by SSL in the bending motion is described. Since the assistance by SSL targets the lumbar, we focus on the chest joint torques that corresponds to the lumbar of human. An example of the measured chest pitch

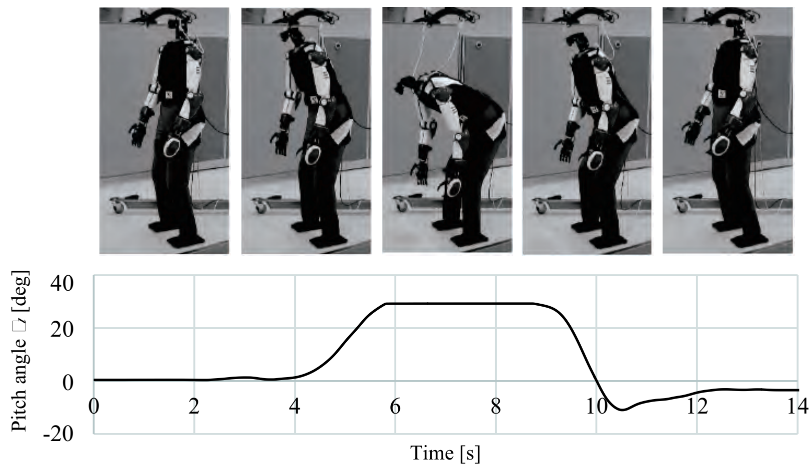


Fig. 6. Bending motion of HRP-4.

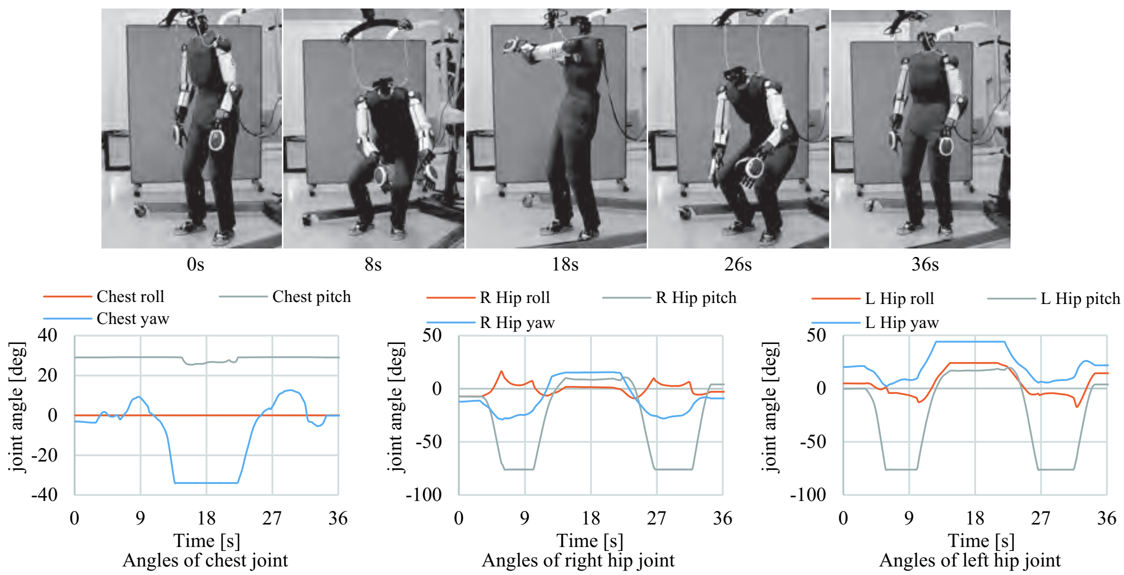


Fig. 7. Twisting motion of HRP-4.

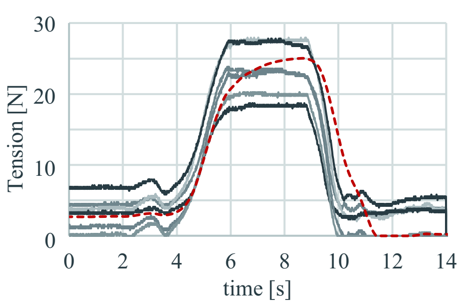


Fig. 8. Tensions generated by the elastic belts on the shoulder at the bending motion. Gray lines are measured tension, and red dashed line is simulated tension.

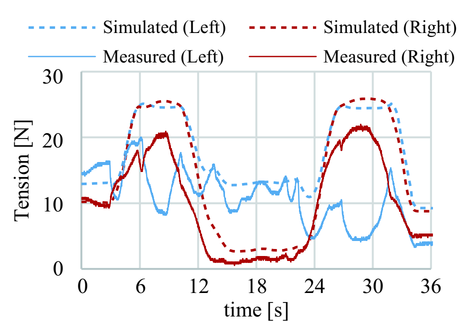


Fig. 9. Tensions generated by the elastic belts on the shoulder at the twisting motion.

torque is shown in Fig. 11. Here, the difference between torque τ_c when wearing SSL and torque τ_{c0} when non-wearing SSL is defined as the assistive torque $\hat{\tau}_{s1}$ applied to the chest pitch.

$$\hat{\tau}_{s1} = \tau_c - \tau_{c0} \tag{3}$$

The results are shown in Fig. 12. Fig. 13 shows the assist torque $\hat{\tau}_{s1}$ against the tension of the elastic belts, which is plotted for each sampling period. Here, since the variation is small especially in the forward bending phase which is moving at a slow pace, the results during forward bending

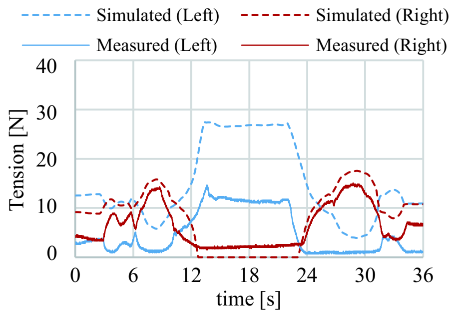


Fig. 10. Tensions generated by the elastic belts on the flank at the twisting motion.

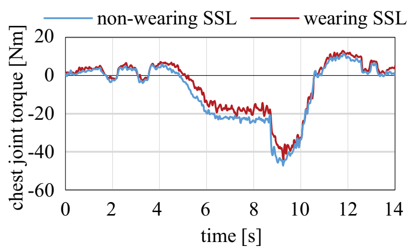


Fig. 11. An example of measured joint torques of chest pitch during the bending motion.

(3–6 sec) are shown in the figure. The assistive torques are considered to be proportional to the assist force as shown in (1). The correlation coefficients were larger than 0.8 at all trials, thus there is a strong positive correlation between the assistive torques and the tension. The same tendencies were seen during whole motion period, although there are more variations. Equation between the assistive torques $\hat{\tau}_{s1}$ and the tension F_1 is obtained by following linear approximation.

$$\hat{\tau}_{s1} = r_s F_1 + \tau_{s10} \tag{4}$$

where r_s means moment arm of the assistive force for the chest pitch joint, and τ_{s10} means the initial assistive torque generated in the upright position. We have obtained $r_s = 0.23$[m], $\tau_{s10} = 0.34$[N·m]. In the previous report [2], the joint torque is decreased even in a state which the tension is not working. It was considered that some components of SSL other than the back elastic belts have a supportive effect for the chest torque. This time, the decrease in joint torque in the upright posture τ_{s10} was little. We adjusted the elongation of the elastic belts before each trial by checking the output

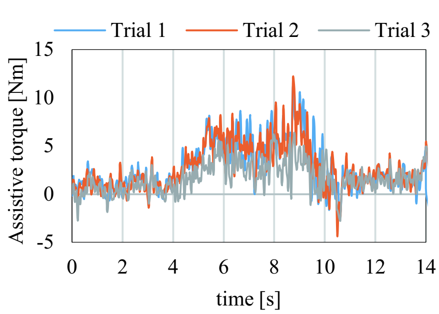


Fig. 12. Computed assistive torque applied to the chest pitch joint.

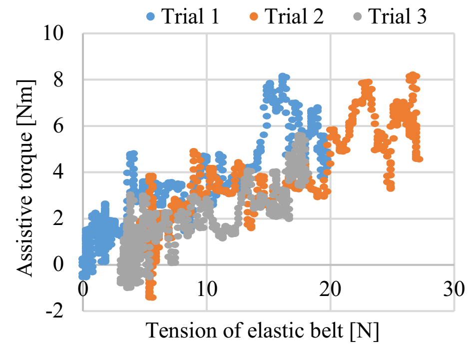


Fig. 13. Relationship between the tension (Fig.8) and the assist torque (Fig.12) during forward bending (3–6 sec) in the bending motion.

of the tension sensor in order not to work in the upright posture, especially by the elastic belts at the flank. Therefore, the assistive torque in the upright position, which was not in the design, is considered to be minimized.

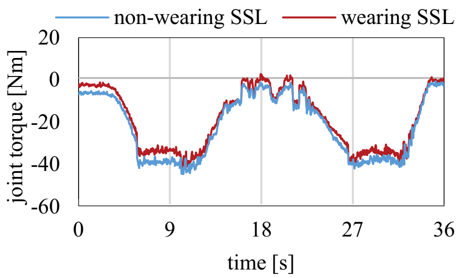
The estimeted moment arm r_s is 0.23m. Since there are two elastic materials on the back symmetrically and the bending motion is movement on the sagittal plane, twice the force is applied to the chest joint. Therefore actual moment arm will be half, and be approximately 0.12m. Now, we estimate the moment arm of the elastic belts between shoulder and waist acting on the chest pitch joint by using simulation model shown in Fig. 4. As a result, the moment arm is 0.118m at upright position, and 0.125m at maximum flexion. Thus we conclude that simulation and actual suit have a good agreement in the two-dimensional and slow bending motion.

3) Change in torque in the twisting motion: Next, we will describe the change in torque for the twisting motion. Fig. 14 shows the joint torques of the chest pitch, roll and yaw respectively. Although SSL reduced the torque of pitch and roll, the yaw torque was increased. SSL generates the forces which make a wearer return to the upright position, that is, it interferes with the postural change. This force works as a assistive force when the wearer maintains the inclined posture under gravity or attempts to back to the upright position. However, it became the load for the yawing which is hardly affected by the gravity. Therefore, we define the effect of SSL $\hat{\tau}_e$ as following expression, which evaluates the amount of reduction in joint torque in absolute value.

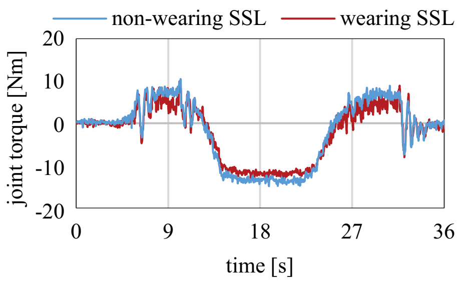
$$\hat{\tau}_e = |\tau_{c0}| - |\tau_c| \tag{5}$$

where τ_c is the torque when wearing SSL and τ_{c0} is that when non-wearing SSL as previously mentioned. If this evaluation value is positive, SSL exerts assisting effects to the joint. Conversely, if the evaluation value is negative, SSL exerts resisting effects that prevents wearer's motion. Fig. 15 shows the results of $\hat{\tau}_e$ smoothed by the moving average of 0.1 seconds.

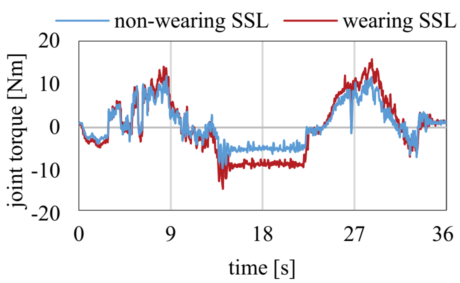
Finally, we measured isolated effects of respective elastic belts by removing the other three elastic belts. The average values of the SSL's effect $\hat{\tau}_e$ on each chest joint over the whole motion are shown in Fig. 16. From the figure, we found that all elastic belts has the assistive effect for pitch and



(a) chest pitch



(b) chest roll



(c) chest yaw

Fig. 14. An example of measured joint torques during the twisting motion.

roll. Although the belts on the back shoulder have the greater effect for the pitch, four belts show equivalent efficacy for the roll. In addition, all elastic belts have the resisting effect for the yaw, and the belt on the left flank has the greatest effect. Thus, since the influence on the joint torque of each elastic belts are different, it is meaningful that we redesign SSL when the target motion of the assistance is changed. The designer should consider what the target motion is or which joint has priority on assistance to design the arrangement and strength of the elastic materials.

V. CONCLUSIONS

We conducted basic experiments using humanoid robot HRP-4 for verifying SSL. In the experiment, the joint torques of the robot and the elastic force of SSL were measured. As a result, we found that simulation and actual suit have a good agreement in the two-dimensional and slow bending motion. We also measured isolated effects of respective elastic belts

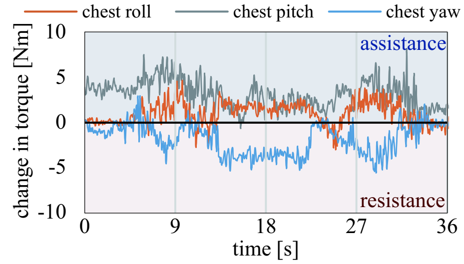


Fig. 15. Change in absolute values of chest joint torques during twisting motion.

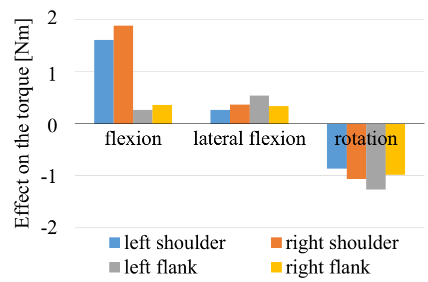


Fig. 16. Effect on the torque by each elastic belts of SSL (average during twisting motion).

by releasing the other elastic belts. The differences in the influence on the joint torque of each elastic belts were quantitatively observed. Therefore, it is meaningful that we design the elastic belts by considering physical load dispersion in accordance with the target motion.

However, there were differences in the tensions of the elastic belts between the measured value and the simulated value in the twisting motion. The cause is considered that path of the elastic belt was changed significantly by roll of hip joint. Improvement of the simulation model considering this point is future work.

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