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Humanoid Robot as an Evaluator of Assistive Devices

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Abstract— **This paper presents a basic study on feasibility of usage of humanoid robots as an evaluator of assistive devices, by taking advantage of its anthropomorphic shape. In this new application humanoid are expected to help evaluation through quantitative measures, which is difficult with human subjects, and also to reduce the burden coming from ethical concerns with costly tests by human subjects. Taking a passive supportive wear "Smart Suit Lite" designed to relieve the load at lower back as an example, we have conducted pilot experiments by using the humanoid robot HRP-4C. The motion to be performed by the humanoid is obtained through retargeting technique from measured human lifting motion. The supportive effect is first estimated by simulation taking into account the mechanism of the supportive device. The experimentation of humanoid hardware brought us encouraging results on the basic feasibility of this application, as we observed a clear decrease of the torque for lifting when wearing the device as expected by the simulation.**

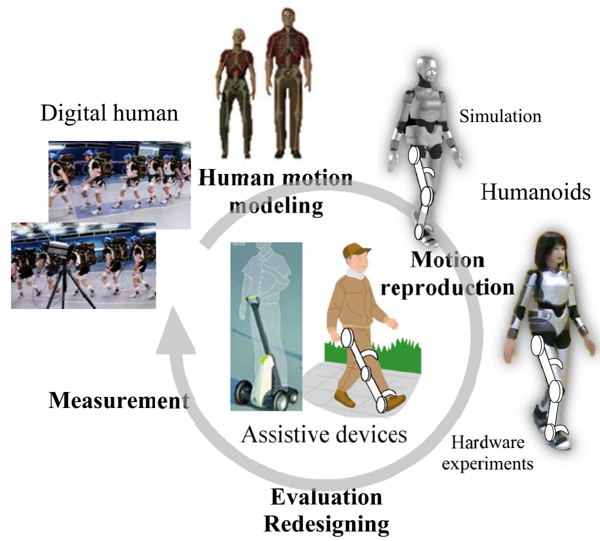

Fig. 1. Evaluation of assistive devices using humanoid

I. INTRODUCTION

In super-aged societies like in Japan, assistive devices are attracting more and more attentions not only just to support difficult motions, but also make them more active by making daily-life motions easier. Indeed, many private companies released prototypes to support walking [1], [2], heavy work [3] or transfer [1], [4].

There are several steps to go through for those devices to be widely spread in the society: among them, safety and usability evaluation are important issues. The former is being addressed in NEDO National Project for Practical Application of Service Robots at Robot Safety Center equipped with facilities for safety testing such as collision-safety or durability. The latter issue, usability evaluation, needs more experiments with subjects. However, this can become a bottleneck due to difficulty in gathering appropriate subjects and reproducing same specific motions. The ethical procedures become more and more rigorous recently, which makes the subject evaluation even more time-consuming.

In this research we study load-lifting as a motion to be supported by assistive devices. Lower back pain is one of the most serious problems for people working in various occupations [5], [6]: especially transportation, agriculture and caregiving. Recently lightweight assistive devices have been developed that help humans to lift heavy loads or maintain difficult bending postures [2], [3], [7]. The main role for those devices is to reduce the load mainly applied to lower back. So far the supportive effects have been validated by human subjects using qualitative methods such as questionnaires, sometimes combined with indirect measurement like motion capturing or EMG. Besides the above-mentioned ethical issues, quantitative evaluation in terms of load reduction has always been difficult due to noise and complex dynamics of human. For example, although we can estimate joint torques by processing data from a motion capture system and force plates, with those external measuring methods it is intrinsically hard to derive the difference between generated torques with and without an assistive device.

For those reasons, we employ a human-size humanoid robot an evaluator of assistive devices. Humanoid robots have advantages that they can reproduce human motions using the devices, provide quantitative measures such as applied torque or force from sensors, and repeat the same motions precisely. This idea has initially been proposed by Takanishi et al., [8], [9], who used their humanoid robot Wabian-2R to evaluate walk-assist machine that the human user grips the handle to support their body with their arms. In this research, we focus on evaluation of wearing-type assistive devices that are closely attached to the human body, by generating humanoid motions that reproduce those of human as faithfully as possible.

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In this paper we investigate the feasibility of this new application of humanoid robot as an evaluator through fundamental experiments of human motion reproduction. As an example of assistive device to evaluate, we adopt a passive assistive wear "Smart Suit Lite" that supports the load at the lower back with elastic bands [3]. After describing this application in Section II, human motion measurement and retargeting to the humanoid platform HRP-4C [10] are presented in Section III. Simulation results and experimental results on the supportive torque are provided in Sections IV and V before concluding the paper.

II. Humanoid Robot as Device Evaluator

The problems that make subject experiments difficult are the following:

- Recruiting a sufficient number of subjects in specified range of gender, age, degree of disability.
- Reproducing the same motions for specific evaluation
- Going through rigorous ethical procedures

To address those problems, we aim at developing a methodology of using a humanoid robot instead of human subjects to evaluate assistive devices. The expected advantages this replacement are the following:

- 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.

Figure 1 shows how the humanoid robot can be integrated in the loop of product design and development of assistive devices. Even though the final evaluation is made by humanoid robot, it is important to collect some sample human motion data at the beginning phase of the development. We then apply suitable modeling methods to the measured motions to express them with appropriate parameters according to the performance indicator to be evaluated. Representative joint trajectories during lifting motions are extracted in our case of supportive device. In another case of assisting periodic motions like walking, statistical analysis such as principal component analysis may be useful to characterize the motions with a few parameters.

Finally the parameterized motions are converted so that they can be reproduced by the humanoid robot. The physical motion execution makes it possible to test the assistive device from various aspects by assessing various quantitative measures. Since joint torque is always difficult to be measured or computed from captured human motions, we have a strong advantage in being capable of getting these data directly from the robot in real life.

Of course we can also make use of simulations to test different parameters settings and product configurations. Experiments are however extremely important to validate those simulations reflects the real interactions between the device and human/humanoid.

III. Human Motion Measurement and Retargeting

In this section, conditions on human motion capturing and motion generation retargeting the captured data are described.

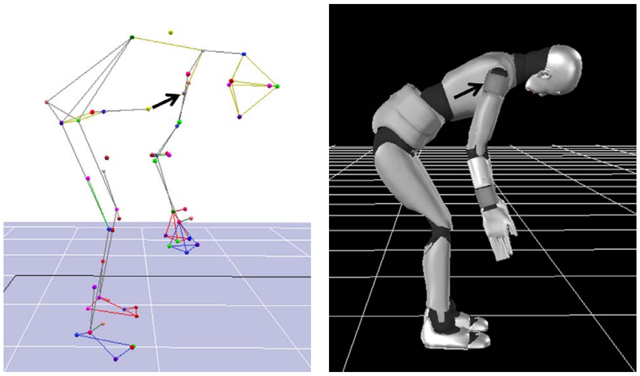
To evaluate an assistive device for humans, robots have to perform same motion as humans do, which meets objectives of the evaluation. An assistive wear "Smart Suit Lite" [3] is adopted for a case study in this paper. The device supports stretching the muscles of the lower back as shown in Fig. 2, so that wearer can avoid back pain while bending down for a long time or repeatedly, for instance in agricultural tasks or transportation service. We thus choose a motion of bending forward from the waist holding a dumbbell in the both hands. The motion data is acquired by a motion capture system, and duplicate motion pattern for humanoid robot is generated.

Motion capture data is widely used for creating the motion of human-like characters in the field of computer graphics [11]. In the field of robotics, some studies demonstrated their created motion on a real human-like and human-sized robot. Japanese traditional dancing has been realized on humanoid HRP-2, based on the motion capture data of a professional dancer [12] [13], and Chinese Kungfu has been also realized on BHR-01, based on the motion capture data of "Taiji" [14]. In this paper we use an efficient retargeting technique adhering fundamentally to these studies [15], which is adapted to reproduction of whole-body motion preserving many kinematic and dynamic constraints for the humanoid.

All motions used in this study were captured by Vicon Motion Systems, a 3D optical motion capture system with 10 cameras. Sampling rate was 200 frames per second. The subject was a male adult. He wore 55 optical markers as appropriate on his body, as shown in the Fig. 3a. He held a 3kg dumbbell in his both hands, stood with his feet shoulder-width apart, and bent down. Three trials were performed.

The output of the motion capture system consists of trajectories taken by markers placed on the performer's body. A pair of markers forms a vector, as shown in Fig. 3a,

Fig. 2. Assistive wear "Smart Suite Lite"



(a) (b)

Fig. 3. A snapshot of captured motion: (a) View of captured markers. (b) Generated pattern of HRP-4C.

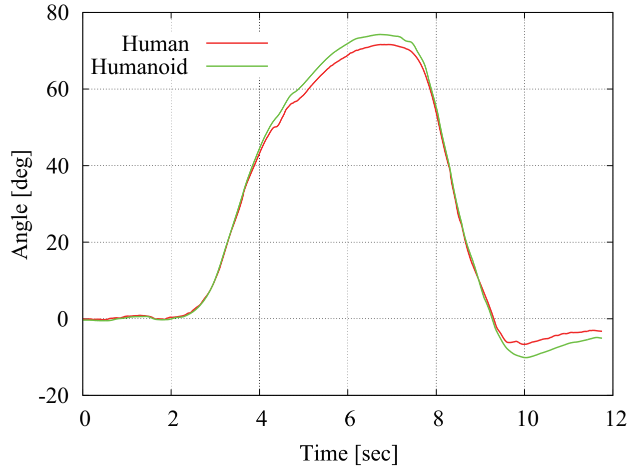


Fig. 4. Comparison of upper body inclination angle.

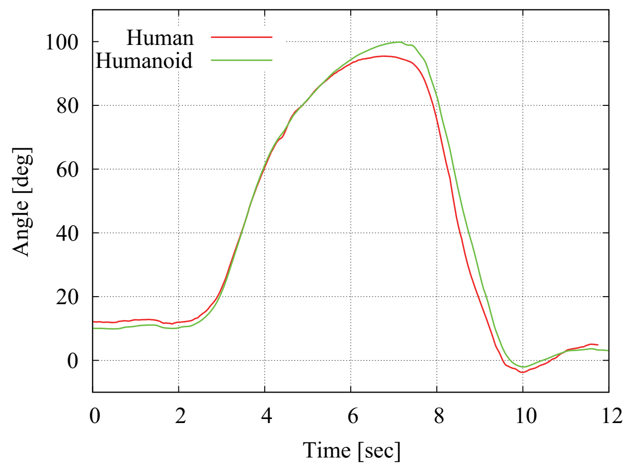


Fig. 5. Comparison of relative angle between upper body and thigh.

which was matched with each of the link vectors of the robot illustrated in Fig. 3b. Offsets are added to the reference vectors, assuming the human upper body and waist to be perpendicular to the floor at the beginning of the performance. Joint angles of both the arms and the chest of the robot were determined iteratively so that the square sum of direction error between the vector of the pair of markers and the link vector of the robot is converged.

The angles of the leg joints and torso joints of the robot were also obtained by iterative computation for solving inverse kinematics between the foot positions at the extracted supporting phase and the position of the robot's trunk. The vertical displacement of the trunk, the joint angles obtained from the motion capture data, joint limits, and joint velocities were considered in null-space. Since subject's and robot's figure are different, feasible motion cannot be generated just by kinematic imitation.

The trunk position was modified by using the dynamics filter with preview control of ZMP [16]. The floor reaction force of the performer was not measured, and target ZMP position of the robot was fixed at the mid-point of 5cm front of the ankle joints on the floor all through the motion. This approach imposes a constant height of the hip, so we regard the movement of the hip's height as an error within the allowable limits. However it may cause a problem with inverse kinematics when the knee joints are almost straight, and this still warrants further investigation. Finally the generated pattern satisfying both dynamic consistency and preservation of the original human motion was obtained.

Generated humanoid motion is compared with the captured human motion data to validate the accuracy of reproduction. While it is not possible to make robot's motion perfectly coincide with the human's, we however believe that the following criteria are important to assess the capacity of motion reproduction for the evaluation of the assistive device: the inclination angle of the upper body concerns the load by gravity, and the relative angle between upper body and thigh affects the extension of the elastic bands.

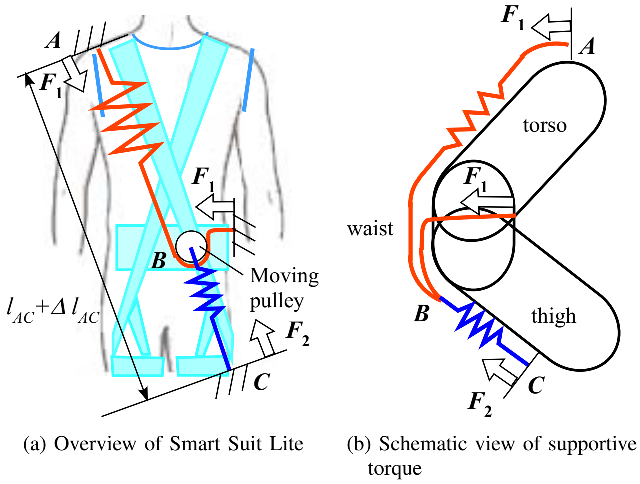
A comparison of inclination angle of the upper body between the performer and the robot is shown in Fig. 4, and relative angle (set to zero when the figure is completely upright) between the upper body and the thigh is also shown in Fig. 5. The average error during the motion was 1.62° and 2.86° respectively in Figs. 4 and 5. Those results show that the human and robot motions agree well with respect to above two criteria.

IV. Simulating supportive torque with Humanoid

Simulations and experiments can be exploited in a complementary manner for device evaluation. Simulation is useful to estimate the expected supportive effect by modeling the interaction between the assistive device and robot. We can also check the function of the device by changing physical parameters or design configurations of both the device and the robot. Hardware experiments validate the physical correctness of the estimated supportive effects based on various quantitative indicators. This physically-grounded experimental data provides strong support to parameterized simulation results.

A. Modeling Supporting Mechanism

The basic function of "Smart Suit Lite" in Fig. 2 is to reduce the torque at the lower back by stretched elastic bands fixed at the shoulders (A) and thighs (C) as shown in Fig. 6a.



(a) Overview of Smart Suit Lite (b) Schematic view of supportive torque

Fig. 6. Mechanism of "Smart Suit Lite" [3]

The quantitative measures to be evaluated depend on the evaluated device. Since one of the most important supportive effects is reduction of the torque applied to the lower back, we here estimate the generated torque by the elastic bands by simulations. Imamura et al. [3] modeled the device mechanism based on a pulley-like support fixation at B and the two-joint human model at the waist and the hip in Fig. 6b. To summarize briefly, by denoting the force generated by the total extension of the elastic bands between A and C by $f(\Delta l_{AC})$, the pulley-like mechanism results in the forces F_1 and F_2 applied to the shoulder and thigh fixing points as follows:

$$F_1 = \frac{2}{5} f(\Delta l_{AC}), \quad (1)$$

$$F_2 = \frac{4}{5} f(\Delta l_{AC}). \quad (2)$$

It has been shown that the elastic band has a nonlinear relationship to the extended length due to the specially knitted material:

$$f(\Delta l_{AC}) = k\sqrt{\Delta l_{AC}}. \quad (3)$$

Therefore in the simulation, we will estimate the torques applied to the pitch axis joints (around y axis in Fig. 7b) at the torso and the hip, which are most significant during the lifting motion, using HRP-4C [10] as the humanoid platform. HRP-4C has been designed for entertainment as a principal application, such as master of ceremonies at an event, or as a model at a fashion show. It measures 1.58m and weights 43kg, featuring its body parameters like link length and size close to the measured average of women of 19-29 years old in Japan.

B. Estimating Supportive Torque

In the following, we describe how to compute the length of the extended elastic band during the converted humanoid motion. The method is presented for humanoid geometry but it can be applied more precise geometry of a digital human model.

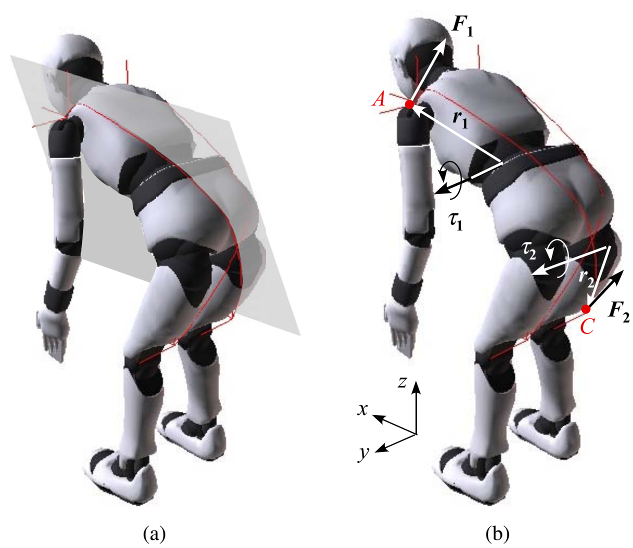
The elastic band is here modeled as a string stretched around the body that passes over concave geometry. As this string is always convex, it can be derived as the intersection between a plane including the two fixed points of the elastic band and the 3D convex hull wrapping the involved body parts at each robot configuration as illustrated in Fig. 7a. The plane including the string in Fig. 7a is chosen to be vertical to the frontal plane.

We can obtain the extension Δl_{AC} from the calculated length AC to derive F_1 and F_2 in Eqs. (1) and (2). Assuming that those forces are applied at the fixed points A, C in the tangent direction on the body, the force vectors $\boldsymbol{F_1}$ and $\boldsymbol{F_2}$ are computed. The most important joint torque values to evaluate the supportive effect for lifting motions are $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$ in Fig. 7b around pitch axes at the torso and the hip respectively. This is computed as $\boldsymbol{\tau}_i = \boldsymbol{r}_i \times \boldsymbol{F}_i$ $(i = 1, 2)$ around the joint axis generated with the moment arm $\boldsymbol{r}_i$ at each fixed point (Fig. 7b).

Figure 8 depicts the length of the two elastic bands over time, distinguished by connection to right and left hip joints. As can be seen, the band is extended approximately 15 cm during the bending motion. The difference of length comes from the fact that the humanoid motion converted from human measurement is not completely symmetric.

Figure 9 show the absolute value of expected torque around the pitch joints at the torso and the hip (the direction of generated torque is opposite). For this computation, the experimentally measured value of the coefficient k=69.7 is used in Eq. (3). The torque is computed by taking into account the extension already applied at the starting standing configuration, which is 0.1 m. The torque at the torso pitch joint is the sum of torques from two bands whereas the hip joint torque comes from each band. This is static torque applied throughout the motion that compensates the torque caused by gravity of the upper body.

We can observe that the estimated supportive torque at the torso pitch joints around is more significant than the hip



(a) (b)

Fig. 7. Computing length of elastic bands. (a) The elastic band computed as the intersection between the convex hull and the plane (b) computation of toque at torso and hip pitch joints

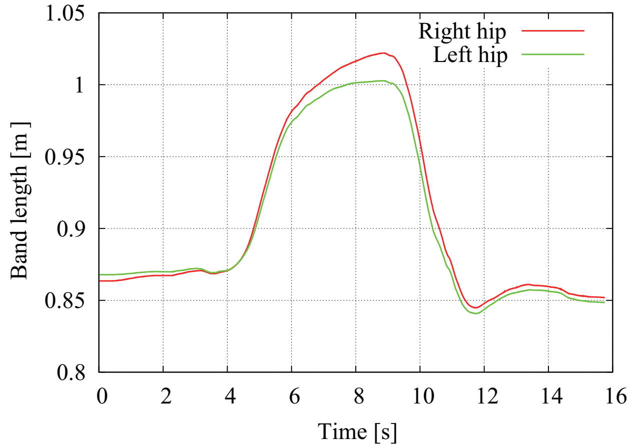


Fig. 8. Simulated length of elastic bands.

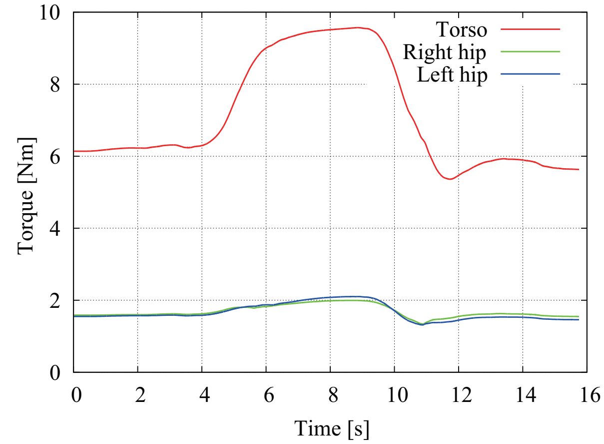


Fig. 9. Estimated supportive torque.

pitch joints from Fig. 9. This property comes from the design of Smart Suit to support the load applied to the lower back. This is also due to the moment arm at the hip joint is smaller than that of torso joint.

V. Experiments

We have conducted basic pilot experiments with HRP-4C wearing Smart Suit Lite that makes the converted lifting motion at Section III. The snapshots of the motion are shown in Figure 10. We attached 1 kg weight at each wrist to simulate the lifting task. The closer view from the backside is shown in the upper row of Fig. 10. Although the black color makes it difficult to see, we can observe how the white elastic bands at the shoulders and thighs are extended when the robot bends down. The whole motion is seen the pictures of side view in the lower row of Fig. 10.

In order to evaluate the load reduction effect, we compared the torque at the pitch joints at the torso and the hips for the motion with and without the wear. The joint torque is estimated from the current at the motor and reduction ratio by

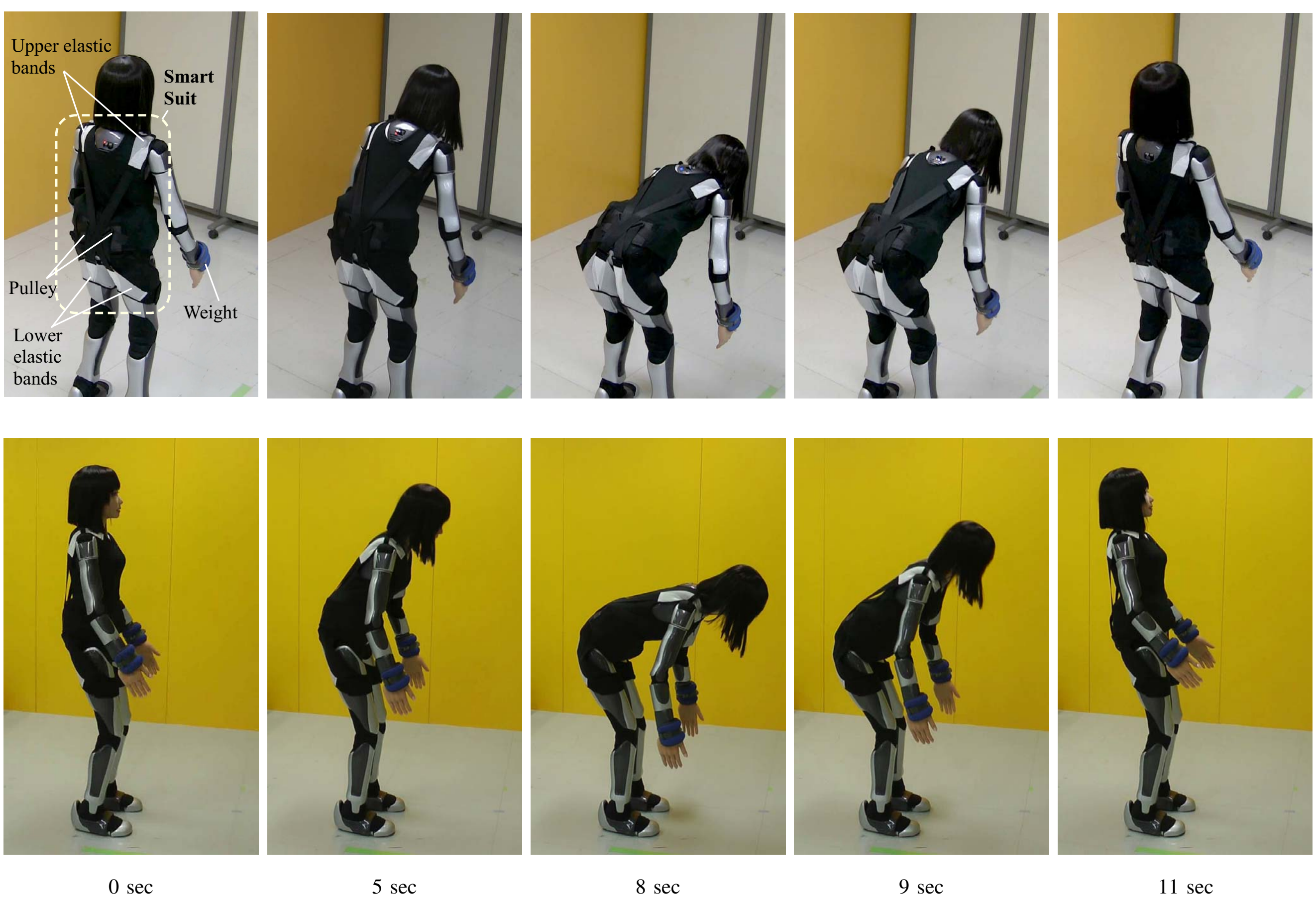


Fig. 10. Experiments of lifting motion by HRP-4C

removing high-frequency noise. Five trials were conducted for each condition.

Figures 11 and 12 show the measured torque at the pitch joints at the torso and the hip from typical trials of trials with and without Smart Suite. The averaged maximum torque among five trials on each condition is listed in Table I. As expected by the simulation results in Section IV, we can recognize a significant supportive effect at the torso pitch joint during the bending motion. The consistency of the assistive effect can be confirmed from Table I as there is high repeatability observed over all the trials. We also verified from the data log that wearing Smart Suit does not change the resultant joint trajectory of the robot, which means the effort itself for lifting the upper body is reduced. On the other hand, the difference of hip pitch joints between the results with and without Smart Suit is not clear compared to the torso, as observed in Fig. 12.

Figure 13 shows the effective supportive torque computed from Figs. 11 and 12 taking its directions into account. The general tendency in time variation in this figure agrees with Fig. 9: the torso joint torque is supported more intensively than the pitch joints. It is also noticed that the torso supportive torque starts increasing at around 4 sec and keeps the high value until 9 sec when a sudden drop occurs due to the steep decrease of the length of elastic bands (Fig. 8). The experimental results exhibit the difference of the magnitude between the simulated and measured torque: the supportive torque is more than expected in the simulation. We will need further investigation to address this mismatch. We currently suppose that it comes from the incorrectness in modeling the property of elastic bands in Eq. (3) and also from the assumption that the generated force is applied to one point in Fig. 7b while it is rather applied on a surface.

In spite of those modeling issues, we could show the feasibility of using a humanoid robot as an evaluator of assistive devices. It is especially important that the supportive effect has been validated in a quantitative manner with joint torque, which is still difficult even with sophisticated human measuring systems.

TABLE I

MAXIMUM ABSOLUTE TORQUES DURING MOTION

		torso pitch	hip pitch right	hip pitch left
With Smart Suite	Mean	68.9	60.3	64.8
	Std. dev.	1.0	1.6	1.7
Free Motion	Mean	92.2	65.5	69.4
	Std. dev.	4.4	1.3	1.9

Unit: [Nm]

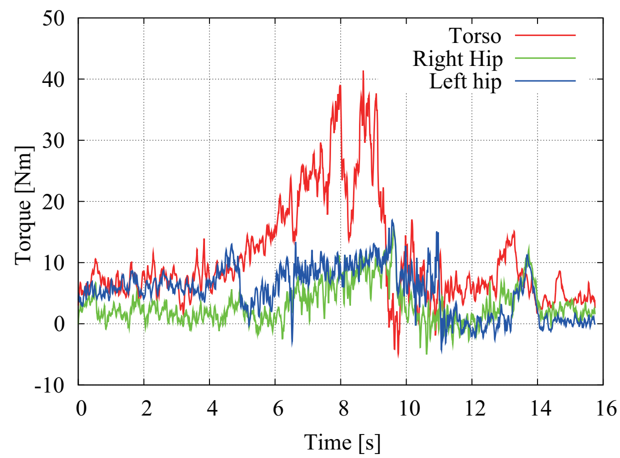


Fig. 13. Experimental result of supportive torque.

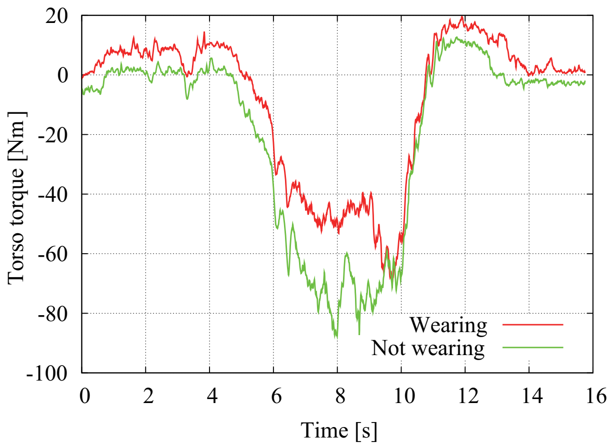


Fig. 11. Measured torso torque with and without Smart Suit.

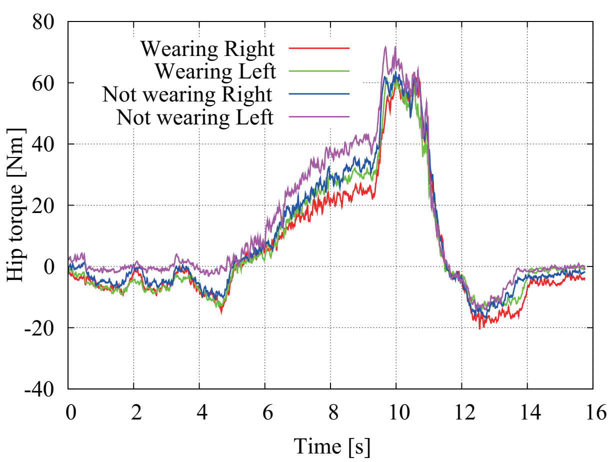


Fig. 12. Measured hip torque with and without Smart Suit.

VI. CONCLUSIONS

We presented a new application of humanoid robots as an evaluator of assistive devices. Taking a supportive wear Smart Suit Lite as an example, we have shown feasibility of this humanoid application through the experiments with the humanoid robot HRP-4C. In order to verify the supportive effect during lifting, measured human motion is converted to a trajectory feasible to humanoid by motion retargeting method. The comparison showed that the reproduced humanoid motion has good correspondence to the human's in order to evaluate the assistive effects. The supportive device "Smart Suit Lite" is introduced as an example and its supportive torque is first estimated through simulations based on its mechanical model that allows computing the length and the generated force of the elastic components. We finally confirmed that the supportive torque is effectively generated by conducting hardware experiments. It was found that the load reduction effect mainly appears at the torso joint that supports the upper body, which corresponds to the original motivation of the device development to relieve the lower back pain.

The fundamental results encourage us to keep pushing forward the challenge towards a general humanoid-assisted design method of those devices. This future direction includes evaluation of assistive effects for more complex motions like sideways object displacement and also possible suggestions for the design improvement. Although only a specific supportive device is dealt with in this paper, we believe the basic approach can be applied to other types of devices designed to assist walking or human transfer.

VII. ACKNOWLEDGMENT

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