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Stationary Torque Replacement for Evaluation of Active Assistive Devices using Humanoid

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***Abstract*— This paper presents a method called "stationary torque replacement" for evaluating the supportive effect of active wearable assistive devices that are designed to help humans move with actuators, by using a humanoid robot. The proposed method allows the humanoid to estimate torque equivalent to the output supportive torque of the assistive device in static postures retargeted from measured human motions. The scheme is characterized by quantitative evaluation under situations close to actual human usage with a humanoid that reproduces human motions by maintaining its balance the wearable devices. In order to validate the proposed method, we have evaluated an active wearable device "Muscle Suit" powered by pneumatic actuators by using the full- size humanoid platform HRP-4.**

I. INTRODUCTION

In super-aged societies like Japan, wearable assistive devices are expected not only to support the elderly but also to reduce the heavy load of caregivers in various situations. Many types of assistive devices have been developed and even commercialized, for example to increase mobility, health monitoring and workload reduction. In this work, we focus on wearable devices that support human motions at the lower limb passively [1] and actively with actuators [2], [3], [4], [5], [6], [7], which is one of the promising devices attracting more and more attention in the field of constructions, caregiving, and logistics where heavy-load work is required. Those devices are generally lightweight and designed for the users to wear easily and to reduce especially the load applied to lower back.

For those devices to be recognized and diffused in the society, their evaluation is an important issue. Most evaluation still relies on experiments with human subjects. The usual process is to ask them to test those devices and to answer questionnaires. However, it is difficult to quantitative evaluation because of subjective nature of questionnaires. As an alternative, we can measure motions of a human wearing the assistive device with a motion capture system and apply dynamic analysis to estimate joint torques to evaluate supportive effects. Though, the disadvantages is that we can only estimate the joint torques indirectly, thus the analysis is prone to be largely influenced by errors. Moreover, those human experiments suffer from several problems such as risk of injury, lack of repeatability and heavy ethical procedure. To solve those issues, there are studies of evaluating the devices with using humanoid in place of human subjects. Nelson et al. developed the humanoid "PETMAN" [8] for testing protective clothing. Miura et al. proposed an evaluation method using a humanoid [9] for a passive wearable assistive device called "Smart Suit Lite" [1] that supports the lower back with elastic bands. In this work, the humanoid executes a lifting motion converted from a measured human motion by using a technique called retargeting [10]. The study compared the torso joint torque with and without the suit and showed that the torque was effectively reduced when wearing it. In this work, as the supportive torque by the passive suit was relatively small, the humanoid just repeated the same trajectory retargeted from a human motion for comparison. In the case of *active* devices that are more powerful, however, this scheme cannot be applied due to the conflict of torques from the device and the robot.

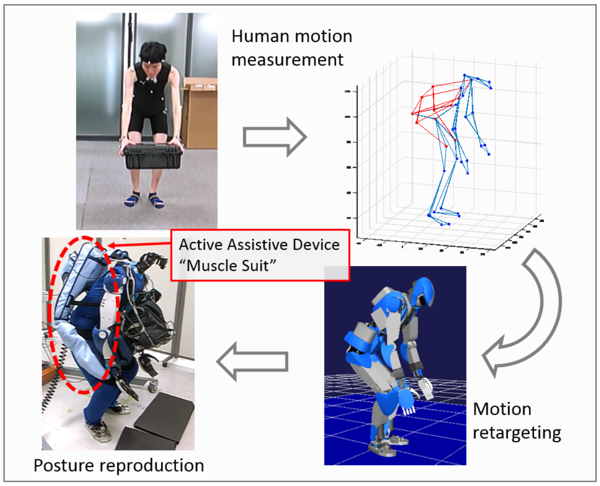

Fig. 1. Procedure of Human Motion Reproduction

In this paper, we introduce a new evaluation method called "stationary torque replacement" for active wearable devices like "Muscle Suit" by using a humanoid robot as shown in Fig. 1. Since there have been no studies for such active devices to the best of our knowledge, we focus on the quantitative evaluation of static supportive torque. The contribution of the paper is to address the major difficulties in the control of the humanoid with such powerful devices and the reproduction of human posture wearing the device while maintaining the balance. For the first issue, we introduce the stationary torque replacement estimating static torque by activating the device and the robot actuators in turn. Concerning the second point, the stable posture is generated from measured human motion wearing the device by applying a

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retargeting method proposed in [11].

An alternative evaluation method is to measure the supportive torque by using a simple planar link mechanism emulating the hip and torso joints fixed on the ground. While that is effective as quantitative evaluation, the fixed feet may not allow reproducing the human posture balancing on the ground. Our proposed method is advantageous in the sense that the humanoid robot can better reproduce the situation where human users utilize the device.

This paper is organized as follows. After detailing the evaluation method in Section II, the experimental results of evaluation of Muscle Suit using the humanoid HRP-4 are presented in Section III. The effectiveness of the proposed method is discussed in Section IV before concluding the paper in Section V.

II. STATIC TORQUE REPLACEMENT FOR ACTIVE ASSISTIVE DEVICES

In this research, we aim at applying the evaluation method using a humanoid that we have been developing for passive wearable assistive devices [9] to active ones. This requires a control scheme that allows the humanoid robot to adaptively follow the external force from such active devices during dynamic motions. As a first step toward this goal, this paper presents a method for evaluating static supportive torque of active devices. The postures for evaluation are extracted from the humanoid trajectory retargeted from human motions [11]. As described later, this evaluation method using a humanoid is effective because the static assistive torque can be determined when the target posture is given. The proposed evaluation method can therefore "replace" the assistive torque by the measured joint torques of a position-controlled humanoid robot like HRP-4 [12], together with torque estimation based identification technique [13].

A. *Human Motion Retargeting to Humanoid*

Our framework requires that a humanoid robot imitate several motions of a human subject. In the framework, we utilize an efficient motion retargeting method [11] that can reproduce the human whole body motion with a humanoid robot. The method solves the simultaneous optimization of the following three problems: geometric identification for body structures morphing between a human and a robot, motion generation of a robot, and motion reproduction with human motion capturing. Thanks to the geometric parameters identification, the method can compensate the difference of the body structure between the two.

Here is the flow of the procedure of human motion reproduction shown in Fig.1:

1) A motion of a human subject with an assistive device is recorded by a motion capture system.
2) The dynamics model of a robot was modified in order to realize the same loaded condition in the first process; we add the simple model of the device on the back and the model of the weight if the human lifts up an object.
3) The motion of the robot is generated according to the simultaneous optimization shown in [11] taking into account the constraints such as joint limits or balance.
4) Several key frames are extracted from the generated motion. Each of them is performed as a static posture by a humanoid robot, where the robot wears the device and has the corresponding weight.

The data obtained from the internal sensors during the static posture is finally utilized to estimate the supportive torques, which is to be mentioned in the next subsection. Due to the difficulty of the evaluation when the robot performs the sequenced motion, our framework utilizes the static postures that are extracted from the retargeted motion. In this paper, therefore, we basically focus on the slow motion of lifting up objects. Since we finally utilize the static postures, the static balance conditions are considered in the third process. In the fourth process, by considering the typical scenario of the device usage, for instance caregiving motions, several representative static postures are extracted from that retargeted motion for supportive torque measurement.

B. *Principle of Stationary Torque Replacement*

The static supportive torque for given posture is estimated by activating actuators of either the device or the humanoid in turn. The equation of static equilibrium in each joint of humanoid with assistive device can be expressed as:

$$\tau_{G,i}(\boldsymbol{\theta}) = \tau_{Joint,i} + \tau_{Assist,i} \tag{1}$$

where

$\tau_{G,i}$ is torque from the gravity and weights
(which is function of general coordinate $\boldsymbol{\theta}$)
$\tau_{Joint.i}$ is the joint torque of robot
$\tau_{Assist,i}$ is the supportive torque from assistive device
(at the joint without support : $\tau_{Assist,i} = 0$)

The right hand side of Eq. (1) means the stationary torque which is actuated by the two system in order to realize the static equilibrium condition. Since the joint torque $\boldsymbol{\tau}_{Joint}$ form Eq. (1) can be observed with the current sensor in

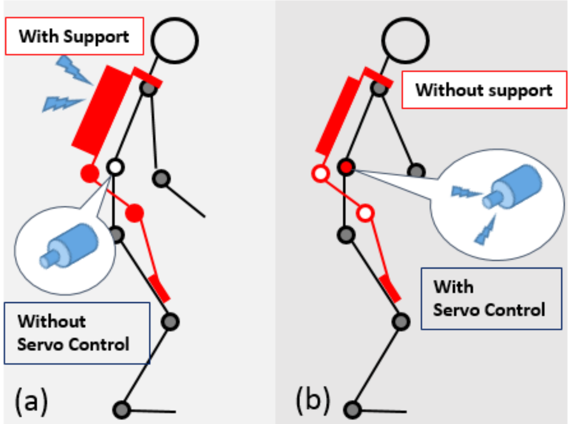

Fig. 2. Measuring Method of Supportive Torque

each joint, we can calculate the supportive torque $\boldsymbol{\tau}_{Assist}$ by following four steps, as shown in Fig. 2.

1) The humanoid is wearing assistive device and standing by maintaining its balance. Assistive device supports target joints of robot.
2) Without activating servo controller at joint i, turn on the assistive device and start supporting the joint to reach the target joint angle by manual operation. The robot can maintain the posture with its zero joint torque because of the supported torque from assistive device. Applying $\tau_{Joint,i} = 0$ when the robot joint coordinates are $\boldsymbol{\theta}^{(1)}$ in Eq. (1) leads to:

$$\tau_{G,i}(\boldsymbol{\theta}^{(1)}) = \tau^{(1)}_{Assist,i} \tag{2}$$

3) Activate the joint i without changing stationary torque of Eq. (2) by keeping current position with PD control. Along the decreasing supportive torque, the joint torque increases. Applying $\tau_{Assist,i} = 0$ when robot joint coordinates are $\boldsymbol{\theta}^{(2)}$ in Eq. (1) leads to:

$$\tau_{G,i}(\boldsymbol{\theta}^{(2)}) = \tau^{(2)}_{Joint,i} \tag{3}$$

4) The supportive torque can be estimated as the torque currently generated at the joint i. Assuming that the difference of joint positions between steps 2 and 3 are negligible and the stationary torque keeps unchanged, from Eqs. (2) and (3) with $\boldsymbol{\theta}^{(1)} \approx \boldsymbol{\theta}^{(2)}$, the following relation is derived:

$$\tau^{(1)}_{Assist,i} = \tau^{(2)}_{Joint,i} \tag{4}$$

The stationary torque is consist of only the supportive torque in Eq. (2) at step 2; on the other hand, it is replaced with the joint torque in Eq. (3) at step 3. Since the stationary torque keeps the same value at step 2 and 3, Eq. (4) at step 4 holds: the supportive torque $\tau_{Assist,i}$. is to be equivalent to the joint torque $\tau_{Joint,i}$ measured by the robot sensor.

III. EXPERIMENTS

In this section, we investigate the feasibility of this new method using a full-size humanoid "HRP-4" and pneumatic exoskeleton suit "Muscle Suit".

A. Active Supportive Device "Muscle Suit"

The "Muscle suit for lower back" (Fig.3) has been developed by Kobayashi et al. [3], [4] and commercialized by Innophys Co., Ltd. [14]. This device helps human lift heavy loads by using McKibben artificial muscles.

Fig.4 shows the mechanism of "Muscle Suit". The artificial muscle arranged on the backside generates strong compressing linear force when the air is supplied to lift the upper body of the user. It is designed to put on and take off easily like a backpack, and fixed to the user's body by a belt at the shoulders and by soft pads at the thighs.

The torso joint of the Muscle Suit is designed with two joints to allow the natural motions during its usage. The user can control the air supply to activate and deactivate the actuators with a touch switch, or an exhalation switch, or an exhalation switch when the both hands are unavailable during such tasks like transferring elderly people.

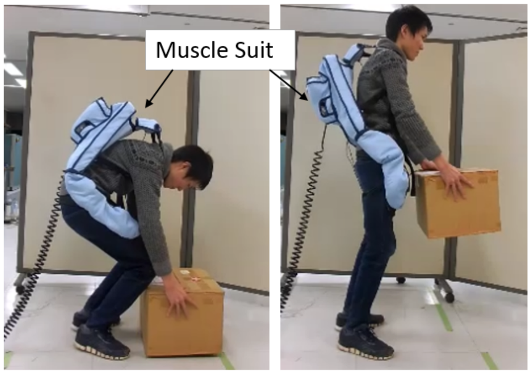

Fig. 3. Muscle Suit for Lower Back

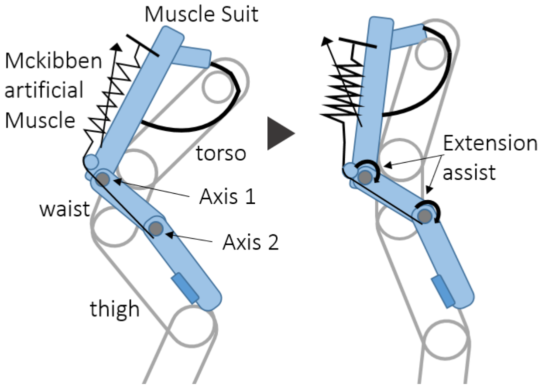

Fig. 4. Structure of Muscle Suit

B. Experimental Setup

In this research, we use the humanoid platform HRP-4[12] as shown in Fig. 5. This robot mimics the human structure to perform human-like motions. This humanoid has total 37 Degrees of Freedom (DOFs), each leg with 7 DOFs (hip joint: 3, knee: 1, ankle: 2, toe: 1), each arm with 9 DOFs (shoulder joint: 3, elbow: 1, wrist: 3, hand: 2), torso with 3 DOF, neck with 2 DOFs.

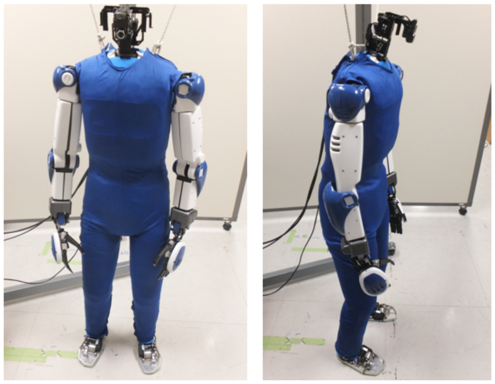

Fig. 5. humanoid HRP-4 with Soft cover

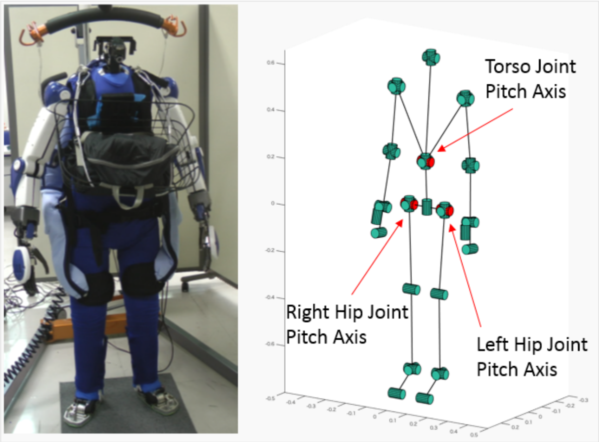

Fig. 6. Experimental setup and joint position of torso pitch joint and hip pitch joint

It measures 155cm and weighs 40kg, and its link length and size is designed to be within 10% of average Japanese women based on database. A soft outer cover is employed instead of the original hard plastic one so that it can wear various supportive devices. As can be seen in Fig. 6, this robot can wear Muscle Suite like a human user without any hardware modifications. In addition to this advantage, the humanoid can maintain its balance with the suit for evaluation under a scenario of its usage close to the reality.

C. Supportive Torque Estimation

In the experiments, we measure the supportive torque of torso joint and hip joints, which are supported by Muscle Suit. As mentioned earlier, the supportive torque can be estimated using Eq.(4). Since the joint angles of the robot are position-controlled with a servo control system, the joint torque $\tau_{Joint,i}$ can be obtained as follows:

$$\tau_{Joint,torso} = K_c(\theta^{ref}_{torso} - \theta_{torso}) \tag{5}$$

where

- K_c is the gain of servo control system
- θ^{ref}_{torso} is the reference joint angle of torso joint to keep the posture
- θ_{torso} is the current joint angle of torso joint

As a typical task with Muscle Suite, we measured load-lifting motions of a human wearing it with 5kg and 10kg weight and without weight. The measured motions were then converted to humanoid motions by using motion retargeting method in II-A.

The humanoid wears Muscle Suit in the same way as a human for the experiment. A basket is also attached to hold the weight of 5kg or 10kg as shown in the left-hand side of Fig. 6. In this experiment, we measure the supportive torque of torso pitch joint and hip pitch joints as illustrated in the right-hand side of Fig. 6.

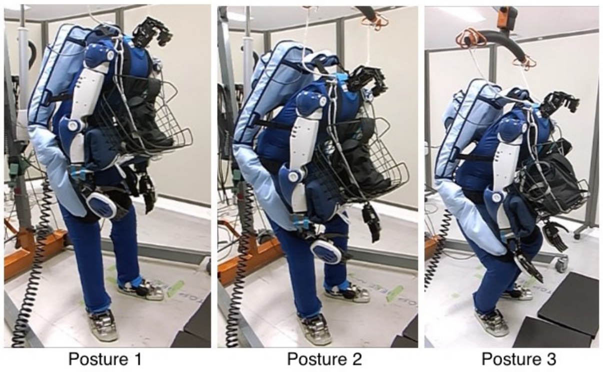
Posture 1 Posture 2 Posture 3

Fig. 7. Three types of posture (weight: 5kg)

D. Experiment of Supportive Torque Measurement

Three distinct it postures are extracted from each converted humanoid motion. Figure 7 shows those postures in the case of lifting 5kg. The supportive torques are measured using the humanoid as described in Section II with those static postures, when lifting 5kg and 10kg weight and without weight. It should be noted that the converted motions of humanoid for each weight are slightly different since the original human motions are not exactly the same.

Fig. 8 shows the result of measured torque of the torso joint with posture 2 and 5kg weight. As Fig. 8 indicates, during the first period of 5 seconds, the humanoid keeps the posture by the supportive torque of Muscle Suit, which results in the torque of 0Nm at the torso joint. We start reducing the supportive torque of Muscle Suite from $t =$ 5sec, until it does not produce any supportive force. Finally at $t =$ 10sec, torso joint torque became stable at around 40Nm. This result shows that the supportive torque of Muscle Suit is 40Nm at the torso joint from Eq. (4).

The same observation applies to right and left hip joints torque as shown in Fig. 9. The supportive torque is measured as 25.6Nm in right hip joint and 22.3Nm in left hip joint. Those results clearly show that Muscle Suit generate significant supportive torque at each of the joints.

With other postures and weights, we conducted the experiments and measured the supportive torque at the torso and hip joints in the same way. The measurement was performed three times for each combination of the posture and weight. Table I summarizes the measured supportive torque from all the conditions with the average and the standard deviation. In all of the experiment, the humanoid stood by its own power maintaining the balance with the postures retargeted from the human motions.

The positive direction of supportive torque is defined as the direction opposite to the torque generated by the gravity. It should be noted that the supportive torque of Muscle Suit measured in this experiment is below its maximum mechanical capacity.

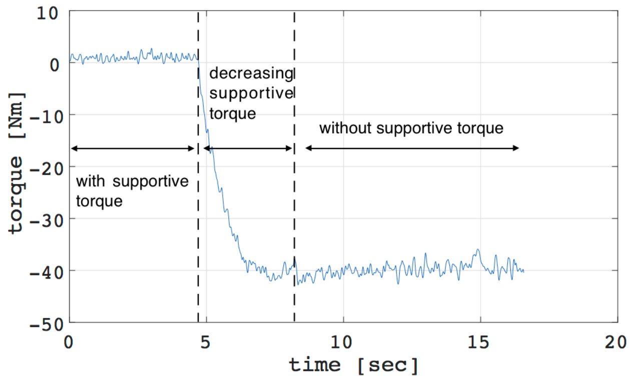

Fig. 8. Measured Torque of Torso Joint (Posture 2, weight: 5kg)

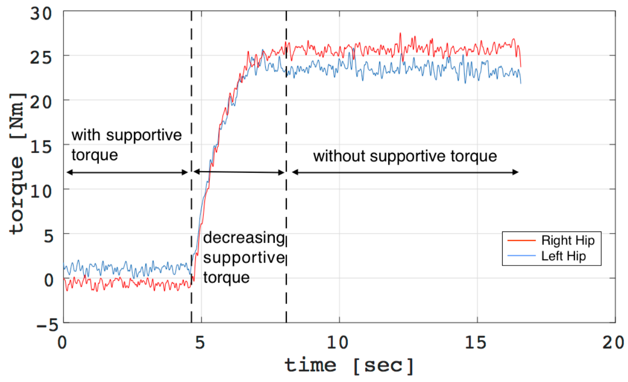

Fig. 9. Measured Torque of Hip Joints (Posture 2, weight: 5kg)

IV. DISCUSSIONS ON EXPERIMENTAL RESULTS

A. Supportive Torque at Torso Joint

Table I indicates that the supportive torque of torso joint increases as the weight becomes heavier for the same posture. The fact that the supportive torque of torso joint increases when the lifted weight increases matches our expectation.

On the other hand, comparing with the same weight, the maximum supportive torque of the torso joint is observed at posture 2 for 0kg and 5kg weight, whereas it was at posture 3 for 10kg weight. This result can be explained in the following way. From our intuition, we may believe that the supportive torque becomes maximum when the upper body and the hands are the lowest position like posture 3. However, the maximum supportive torque is observed with posture 2 when lifting 0kg and 5kg weight. This is because the angle between the vertical axis and the torso is the largest (51°) at posture 2 with 5kg weight as shown in Fig. 10, which leads to the largest moment arm. As mentioned earlier, the postures are not exactly the same depending on the weight. Actually, the angle of the torso is maximum at posture 3 (64°) in the case of 10kg weight as illustrated in Fig. 11. This can well explain the supportive torque is the greatest at posture 3 for 10kg weight.

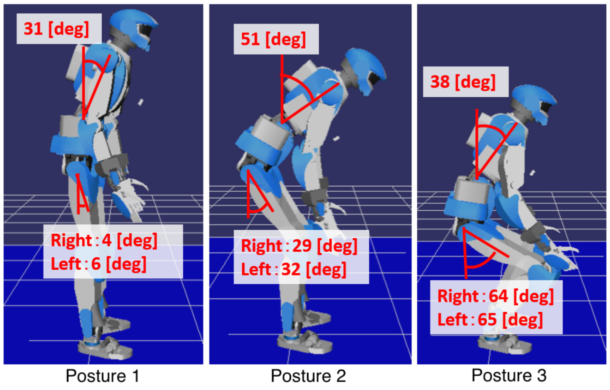

Fig. 10. The torso joint angles of each posture (weight: 5kg)

B. Supportive Torque at Hip Joint

At hip joints in Table I, a large variance up to 10Nm is observed between right and left supportive torques like at posture 2 with 5kg and posture 3 with 10kg. This problem is caused by a slight difference in feet positions may affect greatly the results. We also notice that estimation of the supportive torque at the hip joints is an indeterministic problem due to the closed loop formed between the both legs of the humanoid and the floor. These issues will be addressed in our future work.

V. CONCLUSIONS

In this paper, we presented a new quantitative evaluation method called stationary torque replacement for active wearable assistive devices using a humanoid robot reproducing human motions using a retargeting method. The static supportive torque can be estimated by measuring the torque of humanoid robot wearing the device by activating their actuators in turn. This novel evaluation method has such advantageous as reproduction of real device usage with a humanoid performing human-like postures wearing the device, and also no need for heavy procedures of human subject experiments.

The proposed method is applied to the active wearable device “Muscle Suit” actuated by air artificial muscles using the humanoid platform HRP-4 to validate the effectiveness of the proposed method. Motions of humans wearing the device is first measured and converted to the humanoid to

TABLE I

THE RESULT OF SUPPORTIVE TORQUE

weight	joint	Posture 1	Posture 2	Posture 3
0kg	Torso	10.5 ±2.2	19.6 ±0.2	14.4 ±3.6
	R Hip	10.3 ±2.5	12.6 ±1.8	12.2 ±1.1
	L Hip	11.4 ±2.4	17.0 ±2.7	11.6 ±2.1
5kg	Torso	22.0 ±0.3	41.1 ±2.4	24.9 ±0.8
	R Hip	9.3 ±1.5	20.5 ±2.5	13.9 ±1.2
	L Hip	16.4 ±0.6	29.1 ±3.1	10.2 ±0.5
10kg	Torso	33.4 ±0.6	49.2 ±1.5	53.0 ±2.6
	R Hip	10.1 ±0.8	29.5 ±0.5	40.6 ±1.9
	L Hip	16.8 ±0.6	26.1 ±3.0	31.1 ±2.9

(Unit : Nm)

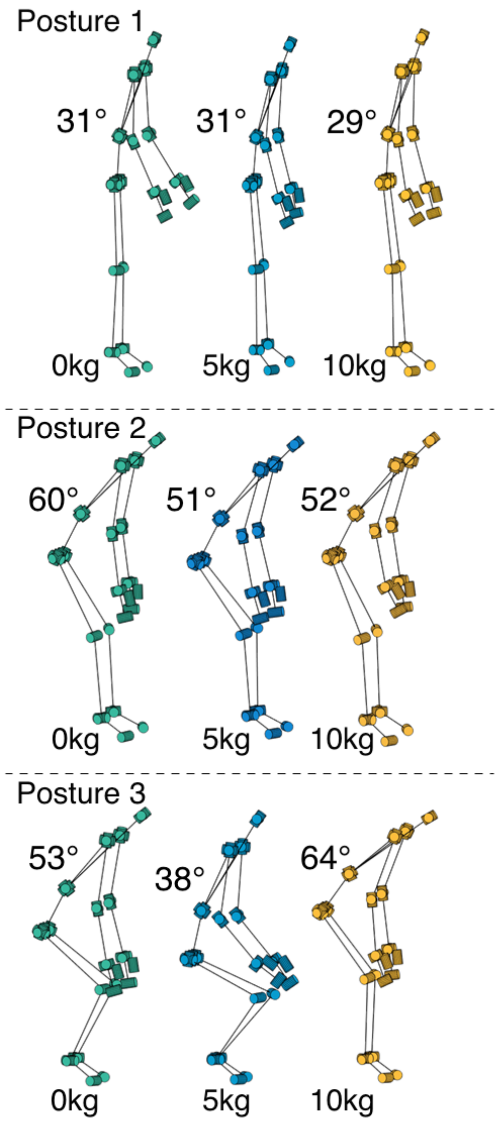

Fig. 11. Extracted postures for all weights (the angles are torso joint angles from the vertical axis base line.)

extract several typical postures. Supportive torque at torso and hip joints are estimated with those static postures with different weights to lift. The experiment first revealed that Muscle Suit generate significant supportive torque up to 50Nm at torso and 40Nm at hip joints although this is still below its maximum mechanical capacity. These results are encouraging because it is substantially difficult to directly measure such quantitative supportive effect with human experiments.

Future work includes extension of the proposed scheme towards evaluation of supportive effects for dynamical motions. This requires a humanoid control system that allows reproducing human motions to adapt to the output force of active devices. For this purpose, we will investigate a human-like control system through torque-based control scheme and a retargeting method reproducing not only the motion trajectory but also interaction with the external force of humans.

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