Realization of Seated Walk by a Musculoskeletal Humanoid with Buttock-Contact Sensors From Human Constrained Teaching

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Abstract— **In this study, seated walk, a movement of walking while sitting on a chair with casters, is realized on a musculoskeletal humanoid from human teaching. The body is balanced by using buttock-contact sensors implemented on the planar interskeletal structure of the human mimetic musculoskeletal robot. Also, we develop a constrained teaching method in which one-dimensional control command, its transition, and a transition condition are described for each state in advance, and a threshold value for each transition condition such as joint angles and foot contact sensor values is determined based on human teaching. Complex behaviors can be easily generated from simple inputs. In the musculoskeletal humanoid MusashiOLegs, forward, backward, and rotational movements of seated walk are realized.**

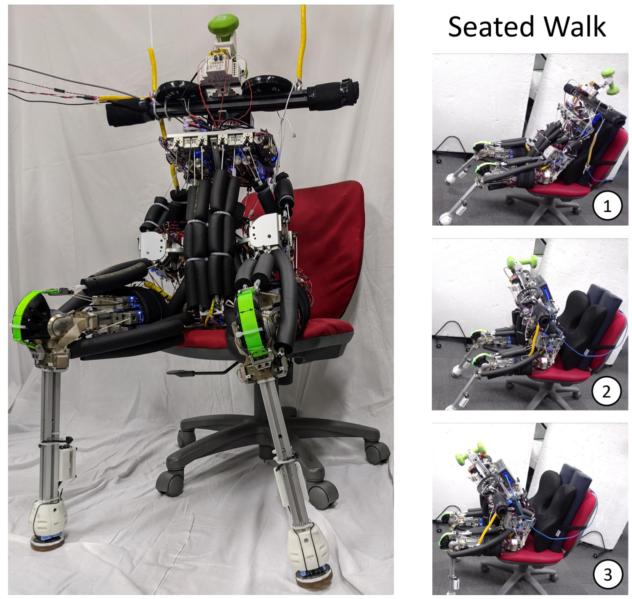

Fig. 1. Seated walk by the musculoskeletal humanoid MusashiOLegs.

I. Introduction

Until now, the field of bipedal humanoids has focused mainly on standing and walking in terms of locomotion [1], [2]. Without the help of the environment, robots walk generally based on theories such as zero moment point [3] and capture point [4]. For robots, locomotion using the environment such as walking upstairs using a handrail [5], [6] is more difficult than the usual walking. On the other hand, for humans, it is easier to move in closer contact with the environment, such as walking while grasping a handrail or moving while crawling [7]. This is due to the errors in recognizing and modeling the environment, the lack of sensors to measure contact with the environment, and the fact that the environment becomes a constraint due to the rigidity of the robot. In this study, we focus on a movement called seated walk, which is an example of a movement with environmental contact, in which a person sits on a chair with casters and moves to pick up documents, phone, etc. (Fig. 1).

Among humanoids, the musculoskeletal humanoid [8]–[10] has a body shape and actuation mechanism that are closer to those of a human, and it has flexibility in its body due to the elongation of muscle wires, nonlinear elastic elements, and soft foam covers. Among these, the newly developed musculoskeletal humanoid MusashiOLegs [11] has planar interskeletal structures all over the body, which enables the realization of environmental contact on a wider surface and stable muscle routes not by using each thin muscle wire but by making the wires planar. Using the planar interskeletal structure of the buttocks of MusashiOLegs, we implement buttock-contact sensors. The purpose of this research is to realize seated walk with MusashiOLegs, a musculoskeletal humanoid that has the same proportions and flexibility as a human and can measure the contact between the body and environment.

In previous researches, motions such as sitting on a chair [12], standing up from a chair, and moving on a desk [13] have been performed. In these cases, the contact force is estimated by using six-axis force sensors and IMUs in the hands and feet, and the motion is generated from the kinematic and dynamic models. However, musculoskeletal humanoids, which have a flexible structure similar to that of humans and are difficult to modelize, need to acquire motions through human teaching and learning. Although there are several teaching methods using a bilaterally controllable device [14], VR device [15] or motion capture [16], these methods require additional devices and, as in the task of seated walk, these methods are not suitable for cases where careful teaching is desirable because the robot cannot be recovered once its balance is lost. Also, there are studies that directly measure the contact force by attaching contact sensors around the whole body and control the movement [17], [18]. On the other hand, in musculoskeletal humanoids, it is difficult to mount a contact sensor on the body surface because the muscles are arranged to wrap around the body. [19] measures the lateral force applied to the muscles as muscle tension, but it cannot separate the contact force from

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the movement of muscles and thus cannot correctly measure the contact between the chair and buttocks.

From these points of view, in this study, we develop a buttock-contact sensor where the planar interskeletal structure of the buttocks of musculoskeletal humanoids is utilized and contact sensors are inserted into it. Using this sensor, we implement a basic balance controller of the body. Also, we develop a constrained teaching method (CTM) in which one-dimensional control command, its transition, and transition condition at each state are described in advance, and only the threshold value of each transition condition such as joint angles and foot contact sensor values are learned from human teaching. By limiting the control command for teaching to one dimension, we can simplify the teaching process and make it possible to teach even complex motions only with a slide bar on the screen. In addition, from the transitions of the control commands during the teaching, we determine the threshold values for the transition conditions and reproduce the motions using these values. Since only the threshold value is learned, the system can only handle quasi-static motions. On the other hand, even in the case of slow and careful teaching, the reproduction speed of the taught motion can be set arbitrarily for each state. Combining these methods, we have realized a seated walk using the musculoskeletal humanoid MusashiOLegs.

The contribution of this research is as follows.

- Development of contact sensors on the planar interskeletal structure of the buttocks and a balance control using them
- Implementation of a constrained teaching method that generates complex motions from simple inputs by learning only the threshold of transition conditions
- Realization of seated walk by a musculoskeletal humanoid

The structure of this research is as follows. In Section II, we introduce the musculoskeletal humanoid MusashiOLegs, its planar interskeletal structure, and the implementation of the buttock-contact sensor. In Section III, we describe the constrained teaching method, the balance control using the buttock-contact sensor, and the whole system. In Section IV, we experiment with forward, backward, and rotational movements, and balance control in seated walking, and show its effectiveness through an integration experiment. In Section V, we discuss the experiments and the limitation of this study, and conclude in Section VI.

II. The Musculoskeletal Humanoid MusashiOLegs and Implementation of Buttock-Contact Sensors

A. Overview of MusashiOLegs

The overall view of the musculoskeletal humanoid MusashiOLegs [11] used in this study is shown in the left figures of Fig. 2. Usually, in musculoskeletal humanoids, muscles are redundantly arranged around the joints. MusashiOLegs uses an electric motor and a pulley to wind the muscle wires, though there are various methods to drive the muscles. Muscle temperature c, muscle tension f, and muscle length l can be measured from the muscle module, which consists of a motor, pulley, circuit, and sensors. In the musculoskeletal structure, although joint angles cannot usually be measured directly due to the presence of the complex spine and spherical joints, etc., joint angles of MusashiOLegs can be directly measured using pseudo ball joints [10]. In MusashiOLegs, only 13 joints are implemented. Each joint is denoted as T-r, T-p, T-y, lH-r, lH-p, lH-y, lK-p, lK-y, rH-r, rH-p, rH-y, rK-p, and rK-y (where T is Torso, H is Hip, K is Knee, $\{l, r\}$ is left and right, and $\{r, p, y\}$ is roll, pitch, and yaw). The joint angle of *joint* is represented by θ_{joint}. Four loadcells are distributed at the tip of each foot to measure the contact force. In this study, $F_{\{lfoot,rfoot\}}$ is the sum of the values of the loadcells of each foot, and F_{foot} is $F_{lfoot} + F_{rfoot}$. Since the muscle wires are made of Dyneema®, an abrasion resistant synthetic fiber, and are surrounded by a soft foam cover, their elasticity provides the flexibility of the body. By learning the relationship between muscle length, muscle tension, and joint angle, it is possible to control the joint angle [20]–[22]. However, due to the effects of friction and hysteresis, it is not always possible to control the joint angle accurately enough. Therefore, the measured or estimated joint angle and the commanded joint angle are often different, and the expression θ_{joint} in this study refers to the commanded joint angle.

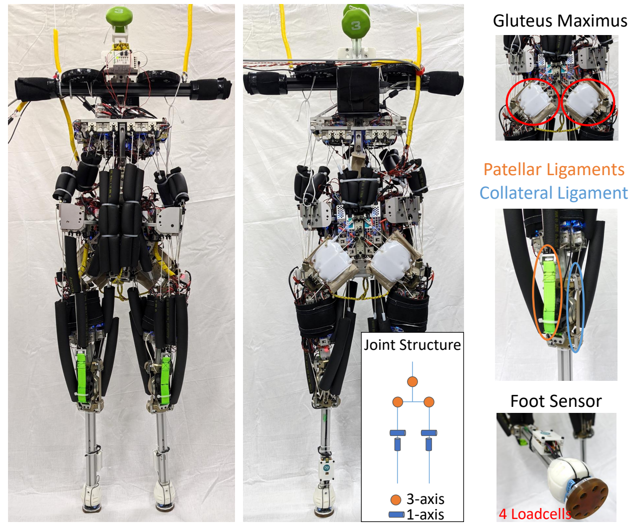

Fig. 2. The musculoskeletal humanoid MusashiOLegs [11] with various planar interskeletal structures.

We describe the planar interskeletal structure, which is a unique feature of MusashiOLegs. Normally, muscles are driven by thin wires in musculoskeletal humanoids, but in MusashiOLegs, the planar interskeletal structure is adopted at several points. As shown in the right figures of Fig. 2, the collateral ligament and patellar ligament of the knee are constructed in a planar structure, which realizes a screw home mechanism and a large moment arm. In addition, the gluteus maximus muscle is implemented by a planar structure that runs through multiple wires, ensuring a large moment arm and flexibility in environmental contact.

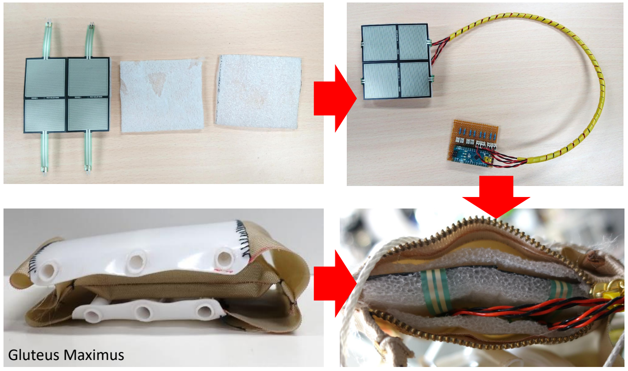

Fig. 3. The implementation of buttock-contact sensors in the planar interskeletal structure of gluteus maximus.

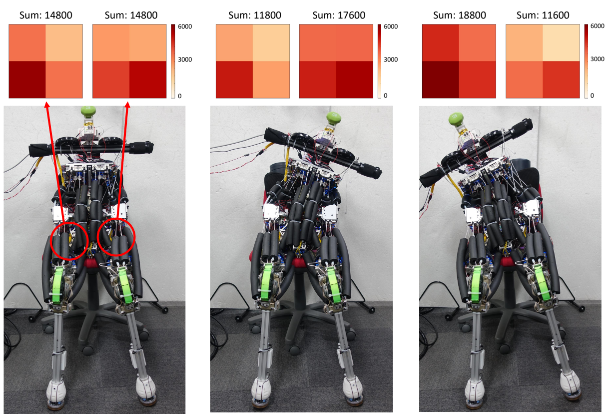

Fig. 4. The difference in buttock-contact forces with various ways of sitting.

B. Buttock-Contact Sensor

The implementation of the buttock-contact sensor is shown in Fig. 3. Three thin sheets of foam material are prepared, and four large pressure sensors FSR®406 are attached to one of them. It is sandwiched between the other two sheets and inserted into the planar interskeletal structure of the gluteus maximus muscle. The cable passes through the pubic symphysis and the analog value is measured by Arudino near the sacrum. Since the sensitivity of FSR is nonlinear and the larger the force, the smaller the potential difference becomes, we use the corrected value as $\exp(A/100)$. Here, A is a 10-bit analog value, and the pressure sensor has a wide contact surface, so the exact magnitude of the force cannot be measured. $F_{\{lhip,rhip\}}$ is the sum of the four contact sensor values for each left or right buttock. As shown in Fig. 4, we can see that there is a difference in the values of the buttock-contact sensors depending on how the robot sits on the chair. In parallel with CTM generating the overall motion, the body balance is controlled by using the buttock-contact sensors.

III. Seated Walk with Constrained Teaching Method and Buttock-Contact Balancer

A. Constrained Teaching Method

We describe a constrained teaching method (CTM). This method differs from the usual teaching method in that the following assumptions are made on the behavior. Here, i is the current transition state, u is the one-dimensional control command, s is some sensor state for transition condition, C^{thre} is the threshold of the sensor state, and $\{u, s, C^{thre}\}_i$ denotes $\{u, s, C^{thre}\}$ at i.

- There is an explicit state transition in the behavior and each control command u_i can only be given in one dimension.
- The transition condition is expressed by the relationship between s_i and C^{thre}_i, and s_i must change depending on u_i.
- the behavior can be reproduced by learning only C^{thre}.

With these assumptions, Fig. 5 shows how preparation, teaching, and reproduction are executed.

First, the preparation before teaching is as follows.

- Register the initial posture $\boldsymbol{p}^{init}$.
- Register the control function $f_i(u_i)$ and the transition condition function $g_i(s_i, C^{thre}_i)$ $(1 \leq i \leq N^{state})$.

Here, N^{state} is the number of states. For example, f_i may move the pitch axis of the torso or specify the x-coordinate position in three-dimensional space for inverse kinematics. Let g_i be a condition such as $s_i \geq C^{thre}_i$ or $s_i \leq C^{thre}_i$, which returns True when satisfied. This preparation are made by humans while considering the target task.

Next, the teaching procedure is as follows

1) Transition to the initial posture $\boldsymbol{p}^{init}$.
2) u_i is manipulated from the teaching panel.
3) Stop changing u_i at the desired position and transition to $i+1$.

Here, the learning process of determining the parameter C^{thre}_i takes place. The value of s_i is registered as C^{thre}_i when the state is moved from i to $i+1$.

Finally, the reproduction procedure is as follows.

1) Determine the change in control command Δu_i.
2) Transition to the initial posture $\boldsymbol{p}^{init}$.
3) Repeat $u_i \leftarrow u_i + \Delta u_i$ to change u_i.
4) Move to $i+1$ when the transition condition is satisfied.
5) Repeat 3) – 4).

Although this is a very simple teaching method, it is powerful for certain behaviors where the motion can be quasi-statically described only by transitions of one-dimensional control commands. The only term to be learned is the threshold value of C^{thre}_i, and Δu_i is arbitrarily set for each state before reproduction. Therefore, it is possible to operate the robot slowly and carefully so as not to lose its balance, and then reproduce it at a fast speed.

B. Buttock-Contact Balancer

We use buttock-contact sensors for balancing. Because the back of the chair is behind the robot, it is difficult to lose the front-back balance. On the other hand, the problem in seated walk is the misalignment of the left and right balance. In order to solve this problem, the following PI control is

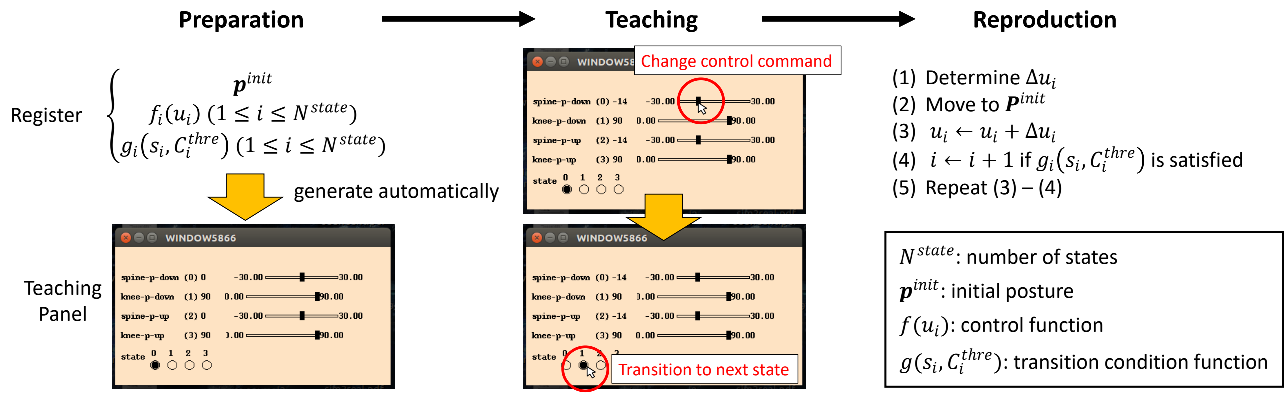

Fig. 5. The procedures of constrained teaching method: preparation, teaching, and reproduction.

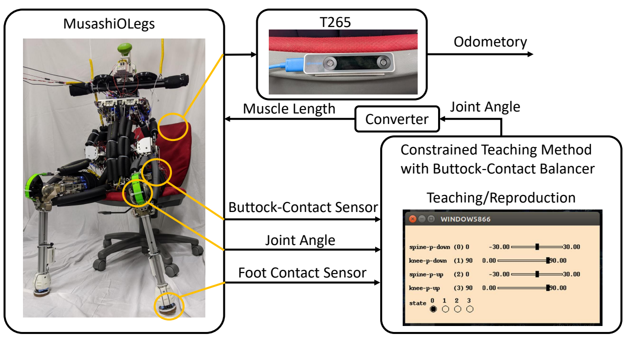

Fig. 6. The whole system of the constrained teaching method and buttock-contact balancer.

applied to control the tactile balance of the buttocks.

$$d = F_{lhip} - F_{rhip} \quad (1)$$

$$D \leftarrow D + d \quad (2)$$

$$\theta_{T-r} = C_{pgain} d + C_{igain} D \quad (3)$$

Here, $C_{\{pgain, igain\}}$ is the gain of the PI control. In this study, $C_{pgain} = 5.0$ and C_{igain} is set to $C_{igain} = 0.3$ for forward and backward motions and $C_{igain} = 0.03$ for rotational motions.

C. Whole System For Seated Walk

The whole system of this study is shown in Fig. 6. MusashiOLegs sits on a chair with casters and a swivel seat, and target motion is taught and reproduced by CTM. During the movement, the buttock-contact balance control is run simultaneously. In order to quantitatively observe the movement, Intel Realsense T265 is attached to the back of the chair and the motion trajectory is measured by visual SLAM. The joint angles are converted into muscle lengths by [21] and sent to the actual robot. The period of the CTM and balance control is set to 5 Hz.

The control and transition condition functions to be registered in CTM and their transitions for motions of Move-Forward, Move-Backward, Rotate-Left, and Rotate-Right of seated walk are shown below.

Move-Forward is as follows.

1) $f_1(u_1) : \theta_{T-p} = u_1,\ g_1(s_1 = F_{foot}, C_1^{thre}) : s_1 \le C_1^{thre}$
2) $f_2(u_2) : \theta_{K-p} = u_2,\ g_2(s_2 = \theta_{lK-p}, C_2^{thre}) : s_2 \le C_2^{thre}$
3) $f_3(u_3) : \theta_{T-p} = u_3,\ g_3(s_3 = F_{foot}, C_3^{thre}) : s_3 \ge C_3^{thre}$
4) $f_4(u_4) : \theta_{K-p} = u_4,\ g_4(s_4 = \theta_{lK-p}, C_4^{thre}) : s_4 \ge C_4^{thre}$

Note that $\theta_{K-p} = u$ means that $\theta_{lK-p} = u$ and $\theta_{rK-p} = u$ are performed simultaneously. The motion is to bend at the waist, raise the legs, round at the waist to put the weight on the legs, and bend the knees to move forward. We set $\Delta u = \{u_1, u_2, \cdots, u_{N^{state}}\} = \{-2, -3, 2, 1\}$ [deg].

Move-Backward is as follows.

1) $f_1(u_1) : \theta_{T-p} = u_1,\ g_1(s_1 = F_{foot}, C_1^{thre}) : s_1 \le C_1^{thre}$
2) $f_2(u_2) : \theta_{K-p} = u_2,\ g_2(s_2 = \theta_{K-p}, C_2^{thre}) : s_2 \ge C_2^{thre}$
3) $f_3(u_3) : \theta_{T-p} = u_3,\ g_3(s_3 = F_{foot}, C_3^{thre}) : s_3 \ge C_3^{thre}$
4) $f_4(u_4) : \theta_{K-p} = u_4,\ g_4(s_4 = \theta_{K-p}, C_4^{thre}) : s_4 \le C_4^{thre}$

The motion is to bend at the waist, lower the legs, round at the waist to put the weight on the legs, and raise the knees to move backward. We set $\Delta u = \{-2, 3, 2, -1\}$ [deg].

Rotate-Left is as follows.

1) $f_1(u_1) : \theta_{lH-p} = u_1,\ g_1(s_1 = F_{lfoot}, C_1^{thre}) : s_1 \le C_1^{thre}$
2) $f_2(u_2) : \theta_{H-r} = u_2,\ g_2(s_2 = \theta_{lH-r}, C_2^{thre}) : s_2 \ge C_2^{thre}$
3) $f_3(u_3) : \theta_{lH-p} = u_3,\ g_3(s_3 = F_{lfoot}, C_3^{thre}) : s_3 \ge C_3^{thre}$
4) $f_4(u_4) : \theta_{rH-p} = u_4,\ g_4(s_4 = F_{rfoot}, C_4^{thre}) : s_4 \le C_4^{thre}$
5) $f_5(u_5) : \theta_{H-r} = u_5,\ g_5(s_5 = \theta_{lH-r}, C_5^{thre}) : s_5 \le C_5^{thre}$
6) $f_6(u_6) : \theta_{rH-p} = u_6,\ g_6(s_6 = F_{rfoot}, C_6^{thre}) : s_6 \ge C_6^{thre}$

Note that $\theta_{H-r} = u$ means that $\theta_{lH-r} = u$ and $\theta_{rH-r} = -u$ are performed simultaneously. The motion is to raise the left leg, open the crotch for left rotation, lower the left leg, raise the right leg, close the crotch, and lower the right leg. We set $\Delta u = \{-2, 2, 2, -2, -2, 2\}$ [deg].

Rotate-Right is as follows.

1) $f_1(u_1) : \theta_{rH-p} = u_1,\ g_1(s_1 = F_{rfoot}, C_1^{thre}) : s_1 \le C_1^{thre}$
2) $f_2(u_2) : \theta_{H-r} = u_2,\ g_2(s_2 = \theta_{lH-r}, C_2^{thre}) : s_2 \ge C_2^{thre}$
3) $f_3(u_3) : \theta_{rH-p} = u_3,\ g_3(s_3 = F_{rfoot}, C_3^{thre}) : s_3 \ge C_3^{thre}$
4) $f_4(u_4) : \theta_{lH-p} = u_4,\ g_4(s_4 = F_{lfoot}, C_4^{thre}) : s_4 \le C_4^{thre}$
5) $f_5(u_5) : \theta_{H-r} = u_5,\ g_5(s_5 = \theta_{lH-r}, C_5^{thre}) : s_5 \le C_5^{thre}$
6) $f_6(u_6) : \theta_{lH-p} = u_6,\ g_6(s_6 = F_{lfoot}, C_6^{thre}) : s_6 \ge C_6^{thre}$

The motion is to raise the right leg, open the crotch for right rotation, lower the right leg, raise the left leg, close the crotch, and lower the left leg. We set $\Delta u = \{-2, 2, 2, -2, -2, 2\}$ [deg].

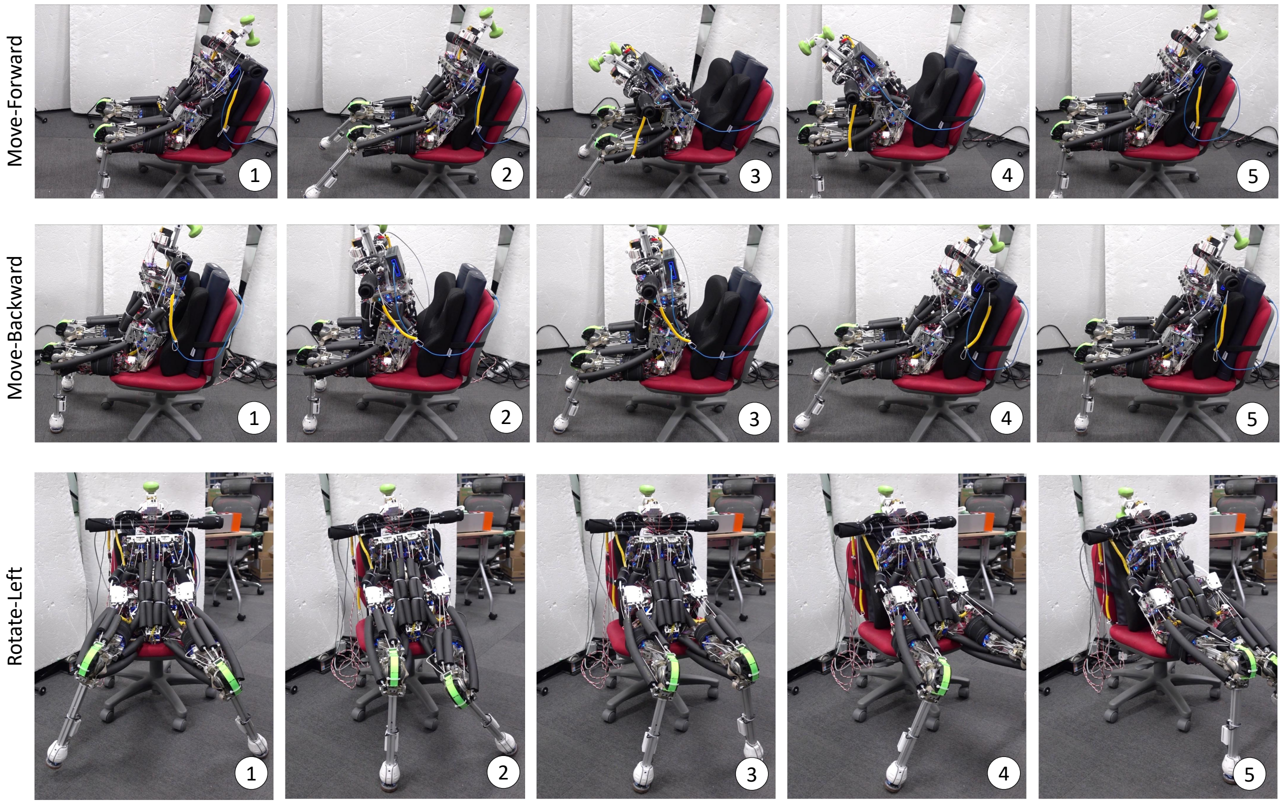

Fig. 7. Experiments of Move-Forward, Move-Backward, and Rotate-Left of seated walk by MusashiOLegs.

IV. Experiments

A. Forward, Backward, and Rotational Movements

We show the experimental results of seated walk by MusashiOLegs. We performed Move-Forward, Move-Backward, and Rotate-Left (only Rotate-Left was performed because the left and right rotations were symmetrical) in the order of teaching and reproduction. Each motion is shown in Fig. 7. By learning only the threshold of the transition condition, each motion was successfully performed. The measurement by visual SLAM showed that the robot moved forward by 0.20 m, backward by 0.15 m, and rotated by 23 deg in one state transition loop.

The thresholds of the transition conditions obtained were $C_0^{thre} = 0$ [N], $C_1^{thre} = 51.3$ [deg], $C_2^{thre} = 75.8$ [N], and $C_3^{thre} = 90$ [deg] for Move-Forward. The motion of bending backward at the waist until the legs are completely apart from the ground, extending the knees, bending forward at the waist until a force of 76 N is applied to both legs, and bending the knees to move forward was reproduced. In Move-Backward, $C_0^{thre} = 0$ [N], $C_1^{thre} = 90$ [deg], $C_2^{thre} = 6.3$ [N], and $C_3^{thre} = 46.8$ [deg]. It was possible to move backward by applying a force of only 6.3 N to both legs, which is much smaller than that for Move-Forward. In Move-Forward, when $C_2^{thre} = 38.0$ [N], the foot slipped and it was not possible to move forward. In Rotate-Left, $C_0^{thre} = 0$ [N], $C_1^{thre} = 30.4$ [deg], $C_2^{thre} = 1.92$ [N], $C_3^{thre} = 0.0$ [deg], $C_4^{thre} = 4.0$ [deg], and $C_5^{thre} = 5.24$ [N].

The motion durations of teaching and reproduction were 47 [sec] → 17 [sec] for Move-Forward, 42 [sec] → 16 [sec] for Move-Backward, and 63 [sec] → 17 [sec] for Rotate-Left. This shows the advantage of learning only the threshold of the transition condition and being able to change the execution time arbitrarily.

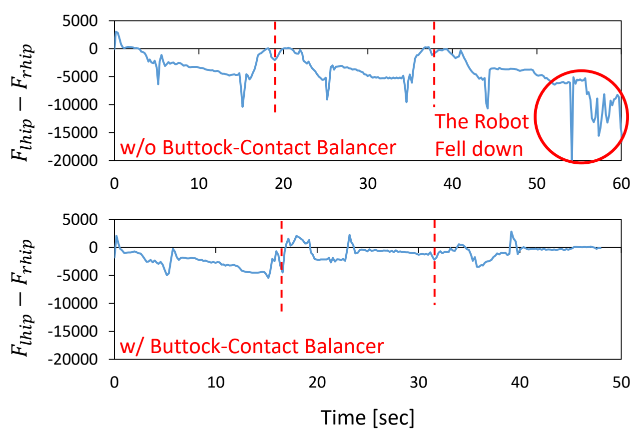

Fig. 8. Transition of $F_{lhip} - F_{rhip}$ when moving forward by seated walk with and without buttock-contact balancer.

B. Buttock-Contact Balancer

We show the difference in translational and rotational motions with and without the buttock-contact balancer. Fig. 8 shows $F_{lhip} - F_{rhip}$ in Move-Forward, and Fig. 9 shows $F_{lhip} - F_{rhip}$ in Rotate-Left. Each experiment represents the results of the same motions performed three times consecutively.

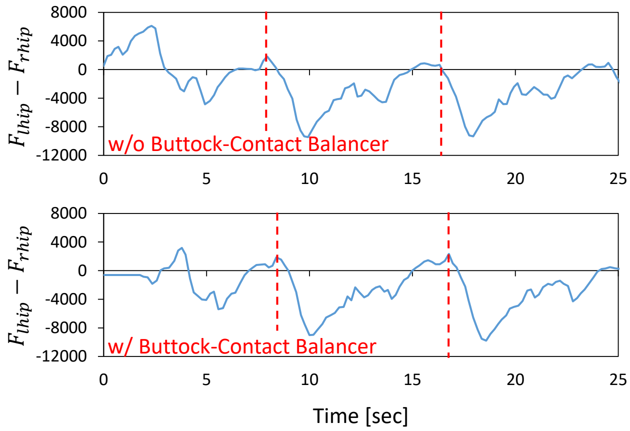

Fig. 9. Transition of $F_{lhip} - F_{rhip}$ when rotating left by seated walk with and without buttock-contact balancer.

Note that the time taken for each motion is different because of only looking at the threshold of the sensor. In Move-Forward, the pressure difference between the left and right buttocks was kept constant with buttock-contact balancer, while the pressure difference increased gradually without it, and the robot fell down in the third movement. For Rotate-Left, there was no significant difference in the pressure transition.

C. Carrying a Bag by MusashiOLegs

Finally, we conducted an experiment in which a bag was delivered by combining translational and rotational movments. The threshold values of the transition conditions were obtained by human teaching in advance. The experiment is shown in Fig. 10. The robot successfully delivered the blue bag by moving forward four times, rotating to the right once, and moving forward twice. The trajectory of the robot is shown in Fig. 11, and the robot was able to move 1.14 m in the x direction and -0.18 m in the y direction in 145 seconds. By combining the motions generated by our method, more complex motions are possible.

V. Discussion

From the experiments in this study, we found that the constrained teaching method can realize the forward, backward, and rotational movements of seated walk, and that the reproduced motion can be executed much faster than the taught motion depending on the control speed setting. In addition, it was found that the buttock-contact balance control is significantly important for the translational direction of forward and backward movements, but did not make a significant difference for the rotational movement. It was also found that the robot can move in arbitrary directions by combining the taught motions of seated walk. Although there are no good examples of three-dimensional walking in flexible musculoskeletal humanoids, the seated walk enables the robot to greatly expand the range of movement.

On the other hand, there are many limitations in this research, especially in the constrained teaching method. First of all, the control and transition condition functions must be written down by humans, which takes more time to prepare than the ordinary teaching. We would like to develop a method that estimates and extracts explicit state transitions from human teaching, and obtains sensor values to be used as control commands and sensor thresholds in each state. Second, we assume that only quasi-static states can be handled and that the control command is only one-dimensional. Of course, dynamic motions are not the focus of this research, but it would be interesting to mix some of ordinary teaching methods with this research, because this research cannot be applied to the motions where the robot needs to move dynamically even for a moment or move multiple joints in different ways. Finally, in this study, odometry information is only used for the evaluation of experiments. In the future, it will be more practical if we can find out how to reach a target position on the map by combining the taught actions, and if we can parameterize the taught actions themselves and adjust the magnitude of the movements.

VI. Conclusion

In this study, we described a method to achieve seated walk, which has not been realized so far, by using musculoskeletal humanoids that are more human-like and difficult to modelize. By implementing a buttock-contact sensor on the planar interskeletal structure that mimics the gluteus maximus muscle, the robot can measure the pressure between the buttocks and the chair and execute balance control. In addition, we have developed a constrained teaching method and have succeeded in realizing forward, backward, and rotational movements by learning the threshold of the transition condition from human teaching. By narrowing down the control command to one dimension and providing the control and transition condition functions in advance, only the threshold value is learned and the execution speed of reproduction can be arbitrarily changed from human teaching. For the first time, we succeeded in the seated walk motion and showed that it is possible for musculoskeletal humanoids to carry objects by combining translation and rotation. In the future, we would like to extend this research further and construct a whole system that integrates manipulation by upper limbs and navigation with this study.

References

[1] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, “The 3D linear inverted pendulum mode: a simple modeling for a biped walking pattern generation,” in *Proceedings of the 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2001, pp. 239–246.

[2] M. Hirose and K. Ogawa, “Honda humanoid robots development,” *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 365, no. 1850, pp. 11–19, 2007.

[3] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, “Biped walking pattern generation by using preview control of zero-moment point,” in *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*, 2003, pp. 1620–1626.

[4] J. Pratt, J. Carff, S. Drakunov, and A. Goswami, “Capture Point: A Step toward Humanoid Push Recovery,” in *Proceedings of the 2006 IEEE-RAS International Conference on Humanoid Robots*, 2006, pp. 200–207.

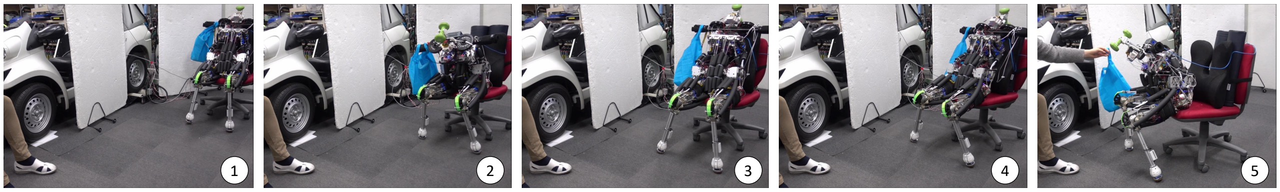

Fig. 10. An experiment of carrying a bag by seated walk.

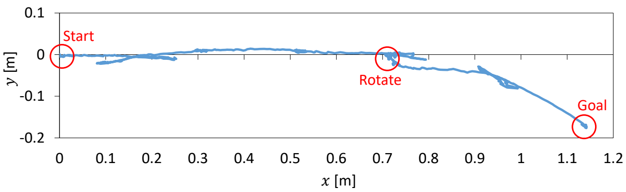

Fig. 11. The trajectory of the robot when carrying a bag by seated walk.

[5] K. Harada, H. Hirukawa, F. Kanehiro, K. Fujiwara, K. Kaneko, S. Kajita, and M. Nakamura, "Dynamical balance of a humanoid robot grasping an environment," in *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2004, pp. 1167–1173.

[6] A. Werner, B. Henze, D. A. Rodriguez, J. Gabaret, O. Porges, and M. A. Roa, "Multi-contact planning and control for a torque-controlled humanoid robot," in *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2016, pp. 5708–5715.

[7] K. E. Adolph, I. B. Bennett, S. M. Boker, E. C. Goldfield, and E. J. Gibson., "Learning in the Development of Infant Locomotion," *Monographs of the Society for Research in Child Development*, vol. 62, no. 3, pp. 1–162, 1997.

[8] H. G. Marques, M. Jäntsh, S. Wittmeier, O. Holland, C. Alessandro, A. Diamond, M. Lungarella, and R. Knight, "ECCE1: the first of a series of anthropomimetic musculoskeletal upper torsos," in *Proceedings of the 2010 IEEE-RAS International Conference on Humanoid Robots*, 2010, pp. 391–396.

[9] Y. Nakanishi, S. Ohta, T. Shirai, Y. Asano, T. Kozuki, Y. Kakehashi, H. Mizoguchi, T. Kurotobi, Y. Motegi, K. Sasabuchi, J. Urata, K. Okada, I. Mizuuchi, and M. Inaba, "Design Approach of Biologically-Inspired Musculoskeletal Humanoids," *International Journal of Advanced Robotic Systems*, vol. 10, no. 4, pp. 216–228, 2013.

[10] K. Kawaharazuka, S. Makino, K. Tsuzuki, M. Onitsuka, Y. Nagamatsu, K. Shinjo, T. Makabe, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Component Modularized Design of Musculoskeletal Humanoid Platform Musashi to Investigate Learning Control Systems," in *Proceedings of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2019, pp. 7294–7301.

[11] M. Onitsuka, M. Nishiura, K. Kawaharazuka, K. Tsuzuki, Y. Toshimitsu, Y. Omura, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Development of Musculoskeletal Legs with Planar Interskeletal Structures to Realize Human Comparable Moving Function," in *Proceedings of the 2020 IEEE-RAS International Conference on Humanoid Robots*, 2021, pp. 17–24.

[12] S. Noda, S. Nozawa, Y. Kakiuchi, K. Okada, and M. Inaba, "Contact involving whole-body behavior generation based on contact transition strategies switching," in *Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2015, pp. 2787–2794.

[13] K. Fukazawa, N. Hiraoka, K. Kojima, S. Noda, M. Bando, K. Okada, and M. Inaba, "Online System for Dynamic Multi-contact Motion with Impact Force Based on Contact Wrench Estimation and Current-Based Torque Control," in *Proceedings of the 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2020, pp. 7601–7608.

[14] Y. Ishiguro, T. Makabe, Y. Nagamatsu, Y. Kojio, K. Kojima, F. Sugai, Y. Kakiuchi, K. Okada, and M. Inaba, "Bilateral Humanoid Teleoperation System Using Whole-Body Exoskeleton Cockpit TABLIS," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6419–6426, 2020.

[15] T. Zhang, Z. McCarthy, O. Jow, D. Lee, X. Chen, K. Goldberg, and P. Abbeel, "Deep Imitation Learning for Complex Manipulation Tasks from Virtual Reality Teleoperation," in *Proceedings of the 2018 IEEE International Conference on Robotics and Automation*, 2018, pp. 5628–5635.

[16] C. Stanton, A. Bogdanovych, and E. Ratanasena, "Teleoperation of a humanoid robot using full-body motion capture, example movements, and machine learning," in *Proceedings of the 2012 Australasian Conference on Robotics and Automation*, 2012.

[17] Y. Ohmura and Y. Kuniyoshi, "Humanoid robot which can lift a 30kg box by whole body contact and tactile feedback," in *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2007, pp. 1136–1141.

[18] I. Kumagai, K. Kobayashi, S. Nozawa, Y. Kakiuchi, T. Yoshikai, K. Okada, and M. Inaba, "Development of a full body multi-axis soft tactile sensor suit for life sized humanoid robot and an algorithm to detect contact states," in *Proceedings of the 2012 IEEE-RAS International Conference on Humanoid Robots*, 2012, pp. 526–531.

[19] M. Osada, H. Mizoguchi, Y. Asano, T. Kozuki, J. Urata, Y. Nakanishi, K. Okada, and M. Inaba, "Application of "Planar Muscle" with Soft Skin-Like Outer Function Suitable for Musculoskeletal Humanoid," *Journal of Robotics and Mechatronics*, vol. 24, no. 6, pp. 1080–1088, 2012.

[20] K. Kawaharazuka, S. Makino, M. Kawamura, Y. Asano, K. Okada, and M. Inaba, "Online Learning of Joint-Muscle Mapping using Vision in Tendon-driven Musculoskeletal Humanoids," *IEEE Robotics and Automation Letters*, vol. 3, no. 2, pp. 772–779, 2018.

[21] K. Kawaharazuka, K. Tsuzuki, S. Makino, M. Onitsuka, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Long-time Self-body Image Acquisition and its Application to the Control of Musculoskeletal Structures," *IEEE Robotics and Automation Letters*, vol. 4, no. 3, pp. 2965–2972, 2019.

[22] K. Kawaharazuka, K. Tsuzuki, M. Onitsuka, Y. Asano, K. Okada, K. Kawasaki, and M. Inaba, "Musculoskeletal AutoEncoder: A Unified Online Acquisition Method of Intersensory Networks for State Estimation, Control, and Simulation of Musculoskeletal Humanoids," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2411–2418, 2020.