2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Achievement of Twist Squat by Musculoskeletal Humanoid with Screw-Home Mechanism

Yuki Asano, Hironori Mizoguchi, Toyotaka Kozuki, Yotaro Motegi, Junichi Urata,
Yuto Nakanishi, Kei Okada and Masayuki Inaba

***Abstract*— Human knee joint has a yaw-axis rotational DOF and a locking mechanism called screw-home mechanism. We focus on this mechanism and implement it to a musculoskeletal humanoid through hardware design. The importance of developing a knee joint with screw-home mechanism is that such a joint is capable of working yaw-axis properly and generating enough pitch joint torque for supporting whole body motion. In this paper, as an evaluation of our developed knee joint, we first checked the moment arm of the yaw rotational axis of the knee. Moreover, we also checked the yaw angle displacement during squat motion. From these results, we confirmed that the mechanism worked properly. Second, in order to check whether enough pitch joint torque is generated during movement, we conducted several experiments with whole body motions such as squatting. Lastly, as unique and integrated motions that involve the use of yaw DOF derived from the mechanism, we tested knee joint Open-Close, Right-to-Left and whole body twist squat motion. Our results demonstrated the feasibility of musculoskeletal humanoids with screw-home mechanism and showed that we have achieved humanlike twisting motion.**

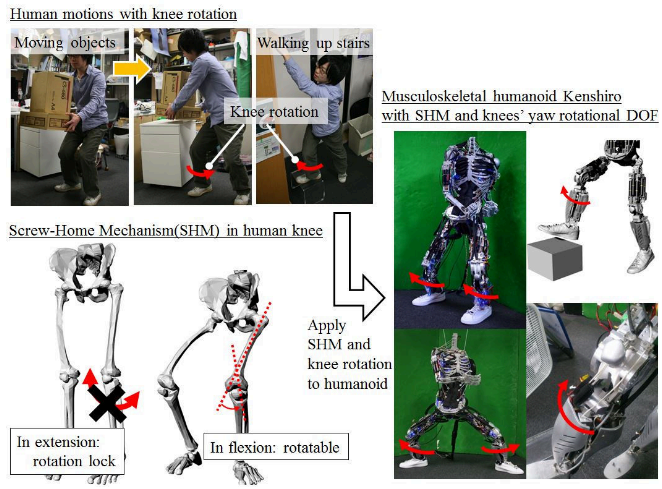

Fig. 1. Humans motions with knee rotation and Kenshiro's motions using rotational DOF in knee joints

I. INTRODUCTION

The human knee is known to have a yaw axis rotational DOF, and it enables humans to perform various motions. For example, upper left of Fig.1 shows the motion of moving objects from one place to another in a squatting position, and also it shows a knee position that uses knee rotation when walking up stairs. As other required features, the knee has to be capable of not only contributing to various motions, but also generating joint torque for withstanding the weight of the whole body. As a result, knees are very important to humans, and there are many studies on knee joint development based on extracting or reproducing functions of the human knee.

Some research studies focus on building humanoid robots with knee joints that are capable of performing with functions found in human knees. For example, there are studies on human mimetic knee joints that focus on mimicking the cruciate ligaments[1] [2]. Also, there are studies on building knee joints that can change between active and passive modes through the use of a clutch mechanism replicating the relaxed condition of the human knee joint[3]. However, yaw rotation has not been considered in these studies. A knee joint with yaw DOF have been developed for training therapists, and this knee joint replicates the rolling-sliding behavior around the flexion/extension axis and the yaw rotation of the knee joint [4]. However, humanoid motion with this knee joint has not been achieved since this knee joint was not built for humanoids. Although there are a lot of studies on human mimetic knee joints, not many focus on yaw rotation of the knee joint or discussion about its feasibility during whole body motion for robots.

Authors are with Department of Mechano-Informatics, Graduate School of Information Science and Technology, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. `[asano, mizoguchi, kozuki, y-motegi, urata, nakanish, k-okada, inaba]@jsk.t.u-tokyo.ac.jp`

Therefore, we are developing a detail musculoskeletal humanoid Kenshiro with Screw-Home Mechanism(SHM), which is provides a yaw rotational DOF and a locking mechanism by mimicking functions of the human knee (Right in Fig.1)[5]. In this paper, as a new attempt in humanoid study, the purpose is to create humanlike motion in Kenshiro through the use of knee joint yaw rotation enabled by SHM. To develop the human mimetic knee joint with SHM, Our design focus mainly on the following two points, and we would like to confirm these points in this paper.

- How to implement yaw rotation DOF with SHM
- Ability to do whole body motions

Section I was about the goal and motivation of this paper. paper. Section II is about the development of SHM and its evaluation. Section III is about whole body motions for testing knee performance. Section IV is on the achievement of twist squat motion through the use of yaw rotational DOF of the knee joint. Section V is on conclusion and future work.

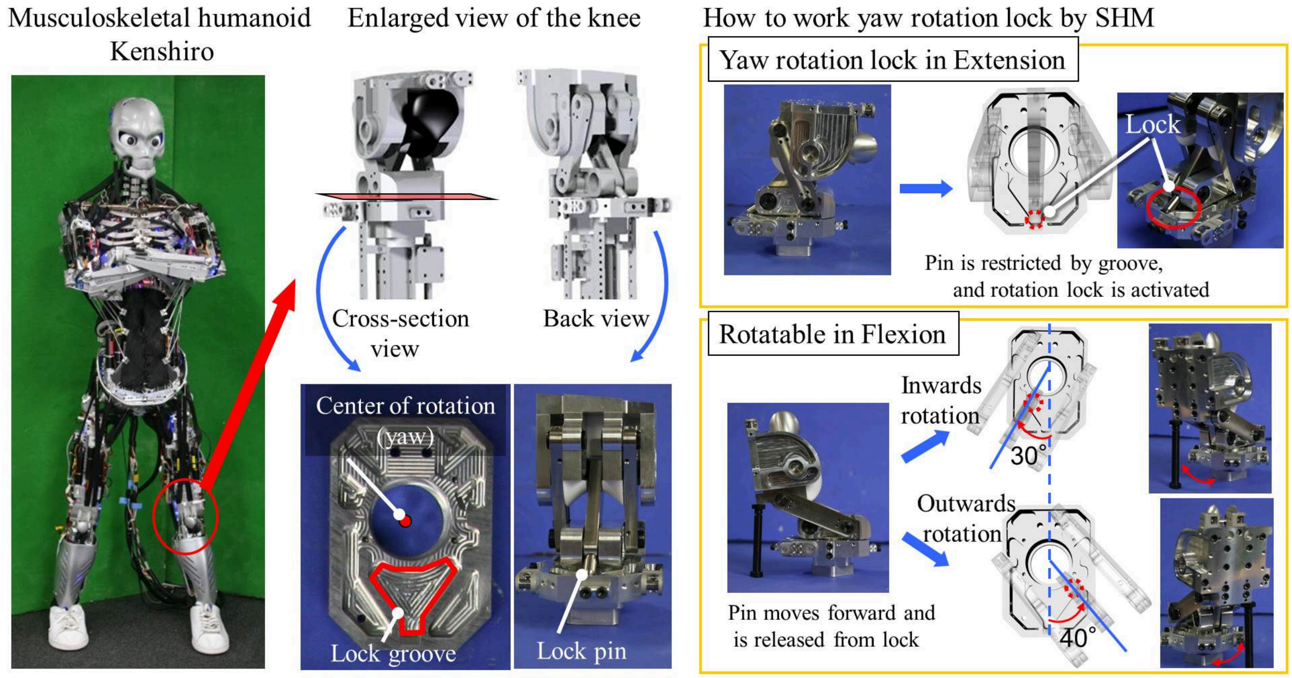

Fig. 2. Design concept of Screw-Home Mechanism(SHM).

II. Development and Evaluation of SHM

A. The Importance of SHM

When we think about expanding the variation of humanlike motion which can be done by musculoskeletal humanoids by adding yaw rotation to the knee joint, joint constraint is a crucial problem. To elaborate on this, if we just add a rotational DOF to musculoskeletal humanoid without enough consideration, it would result in joint instability. It could cause lack of constraint force, from the change of moment arm along with body posture, which is a problem unique in musculoskeletal humanoid.

Focusing on the human knee, although there is yaw rotation DOF of a knee in the flexion position, the DOF becomes locked by passive rotational movement as the knee extends. The mechanism composed of the yaw rotational DOF and its locking is called SHM. This Mechanism is enabled by the slack in cruciate ligaments, muscle constraint and bone shape. It contributes to the relieve of torsional load at the knee when changing direction.

B. Design and Implementation of SHM

We can consider two methods to constrain joints of musculoskeletal humanoid. First is a hardware approach analogous to skeleton structure and ligaments. The other is a software approach analogous to muscle control. In this paper, we try to implement the mechanism by a hardware design approach analogous to skeleton and ligament. The biggest reason to why there has not ever been humanoids with SHM and why there are few humanoid motions achieved using knee joint yaw rotation is that if we use a complex knee joint, it becomes difficult to move or control the whole body since the knee joints have to withstand large loads. Moreover, we have to avoid increasing the difficulty in motion control due to the pursuit of human function mimicry. We have to extract human joint function properly considering feasibility since it is difficult to replicate all functions of the complex human knee, such as friction between the joints, or constraint by flexible ligaments or muscles. Therefore, our design priorities have mainly two points as shown below.

- It should be a joint mechanism that can work properly as a joint and can withstand humanoid motion.
- Engineering replication based on extracting human joint functions.

SHM contributes to stability and joint constrain in standing by locking yaw rotational DOF. The human knee joint can rotate outwards 40 degrees and inwards 30 degrees in flexion by enabling the DOF [6]. Based on the human structure, we designed SHM to achieve such movable range when the knee joint is in 100 degrees flexion. The mechanism is composed of a lock pin and a lock groove at the cross-section of the tibia as shown in Fig.2. When the knee joint is in extension, rotation is locked by constraining the pin with the groove. On the other hand, when the joint is in flexion, the pin is released from the groove and the DOF is enabled. Furthermore, the DOF is actuated and constrained by the Biceps Femoris Longus and the Semimembranosus/Semitendinosus belonging to the hamstrings as shown in Fig.3. Fig.4 shows how to work the mechanism manually.

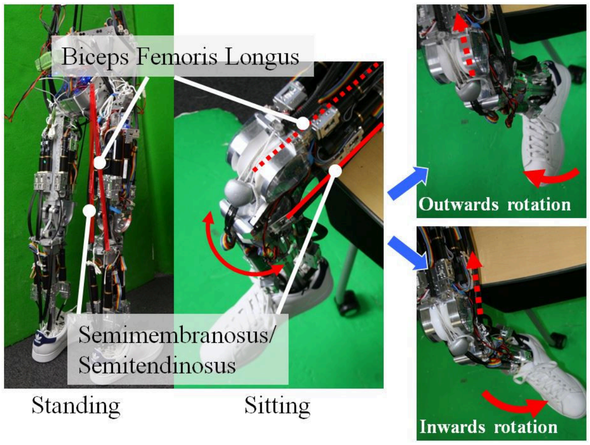

Fig. 3. Bi-articular muscles(hamstrings) that plays knee rotation. Semimembranosus/Semitendinosus is for inwards rotation. Biceps Femoris Longus is for outwards rotation.

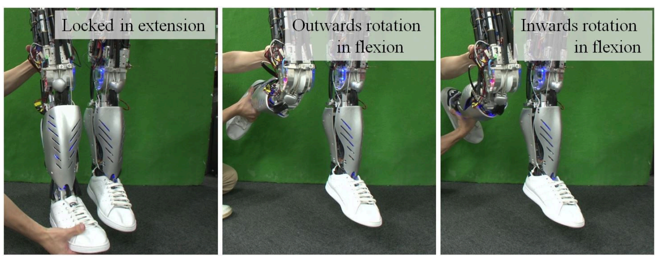

Fig. 4. The behavior of SHM built in Kenshiro. Left: rotation locking condition in extension, Center: Outwards rotation in flexion, Right: Inwards rotation in flexion.

C. Relationship Between Rotational Moment Arm of Knee Joint and SHM

We discuss the relationship between moment arm contributing to yaw rotation and SHM. Joint torque and constraint force are dependent on the moment arms of the muscles responsible for inwards/outwards rotation for the knee joint. When these moment arms are small, it becomes difficult to constrain the joints. As a verification of the moment arms' behaviors, Fig.5 shows the relationship between the moment arms and knee flexion angles. The vertical axis shows the moment arms around the yaw axis of the knee. The horizontal axis shows the knee flexion angle.

The maximum moment arms are measured at about 90 degree in flexion, the minimum moment arms are measured at approximately 0 degree in extension. This shows that the developed knee joint has similar characteristic to a human knee joint in terms of yaw moment arms, since human knee joints can generate less constraint force around rotational axis in flexion[7] due to the positional relation between muscle attachment points and rotational axis. This characteristic of the human knee means that it is difficult to generate knee joint torque around rotational axis in its extension position, like standing, because of the human musculoskeletal structure, but when the knee joint is in flexion, like squatting pose, it is possible to constrain knee joint stably because of longer moment arms. Therefore, in order to support an unstabilized knee in standing position, rotational locking mechanism by SHM is important, and the mechanism is reasonable for human musculoskeletal structure. This means SHM contributes to joint stability, and this is the effect of the mechanism.

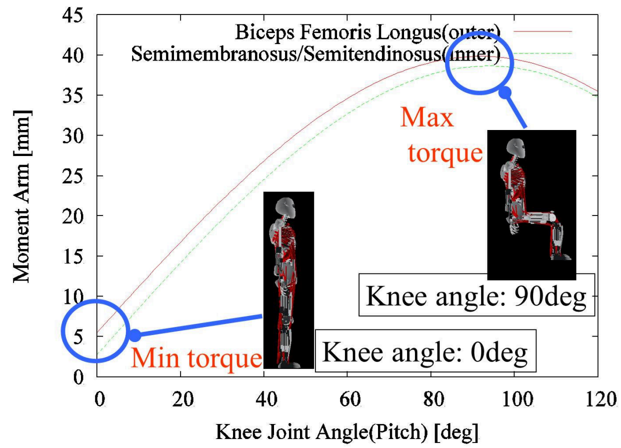

Fig. 5. Moment arm of knee joint around yaw axis rotation. Biceps Femoris Longus and Semimembranosus/Semitendinosus contribute to the knee rotation.

D. Relationship Between SHM and Rotational Angle Displacement During Squatting

For the leg part, it is important to check motion or its performance with its landing condition because the legs have to work on ground in a lot of real life situation. Squat is suitable for checking leg performance because it is fundamental human motion which moves all the joints in the legs. Therefore, we conduct the evaluation of SHM with angular displacement around knee joint yaw axis during squatting motion. During the experiment, squatting motion is generated based on position control by sending joint angle sequentially. Each joint angle is generated by mapping muscle lengths to joint position. The deepest knee angle during squat is 45 degrees, and we perform ten repetitions. Motion commands are only for the flexion axis, while move in the yaw direction is passively made. We conducted experiment in two conditions shown below. In both experiments, we sent the same control command and measured angle displacement around the yaw axis of knee joint.

1) without SHM (possible for free rotation around yaw axis)
2) with SHM (possible for yaw rotation, but there is constraint)

Fig.6 shows a squat in condition 1. Left of Fig.7 is a graph of the knees' yaw rotation angle displacements for condition 1, and Right of Fig.7 is for condition 2. In each graph, the vertical axis show the angle displacement around the rotational axis of the knee joint, which begins at the starting position of the squat. The horizontal axis shows time. In Condition 1, a knee yaw rotation of about 12 degrees occurred during squat, and displacement from initial position also occurred after the motion. In Condition 2, less knee yaw rotation, about 8 degrees, than in Condition 1 occurred, and yaw rotation angle displacement returned to the initial position after the motion. This implies that SHM worked in this squatting motion. As a result, it can be inferred that a twisting load at the knees' cross-section derived from joint sliding has occurred due to the angle displacement around yaw axis during the squat. Therefore, an effect of SHM is the contribution to relieving twisting load and supporting joint constraint by returning the knee joint angle displacement to its initial position.

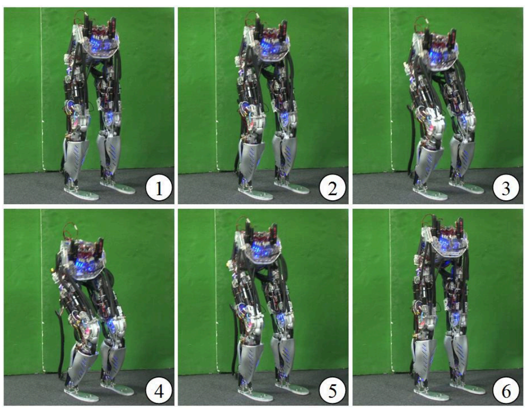

Fig. 6. Squat motion sequence

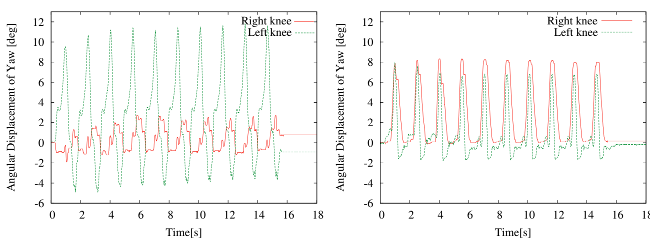

Fig. 7. Rotational(yaw) angle displacement in knee joint during squat motions. Left:WITHOUT SHM, Right:WITH SHM.

III. ACHIEVEMENT OF WHOLE BODY MOTION THROUGH MUSCLE LENGTH CONTROL

In order to confirm the capabilities of Kenshiro and its knee joints, we worked on achieving whole body motion through muscle length control. In this section, we explain about motion generation methods of Kenshiro and test ability to do whole body motions.

A. Joint Torque Improvement in Kenshiro

Our previous musculoskeletal humanoid Kojiro[8] had difficulty in withstanding whole body weight since it could not generate sufficient joint torque or speed. We adopted higher power 100W blushless motors to Kenshiro as muscle actuators in place of previous 40W motors. Also, we use nine motors for each knee joint. This is a more redundant muscle arrangement than the one in Kojiro which used four motors for each knee joint. As a result, Kenshiro has improved joint torque and speed capabilities.

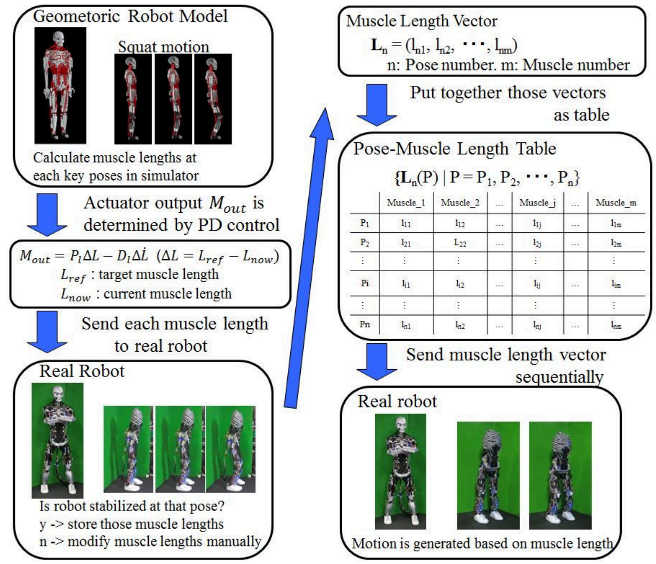

Fig. 8. Motion generation methods based on muscle length.

B. Motion Generation Method Based on Muscle Length Control

We describe the motion generation method based on muscle length control . The procedure is shown Fig.8.

1) In PC simulation environment, muscle lengths correspond to joint angles. We generate postures of a geometric robot model according to a time series of the target motion. Then, each muscle length is calculated.
2) Actual sending muscle lengths are determined by PD control based on target muscle lengths calculated by the value of the rotary encoder built in each muscle actuator. Muscles are actuated according to calculated actuator output M_{out}.
3) We send the calculated muscle lengths to the real robot. If the robot does not fall down at that posture, we store that set of muscle lengths as muscle length vector $L_n = (l_{n1}, l_{n2}, \cdots, l_{nm})$ (n: Pose number, m: Muscle number) which is composed of each muscle length (l_m) at that time. If it fall down, we modify the pose by adjusting each muscle length manually to obtain a stable pose, and then we store the set of muscle lengths at that pose. For the set of motions, we store muscle length vectors at several keyposes for each target motion and put together those vectors as a pose-muscle length table $\{L_n(P)|P = P_1, P_2, \cdots, P_n\}$.
4) The robot motion is generated by sending the vectors from the table sequentially. The commands are not sent according to feedback based on sensor values, but using feedforward. We think that this balancing control should be improved because this open loop control leads unstable condition.

C. Whole Body Motion Achievement

1) Squat Motion with Rib Bones: We generate squat motion and send the motion to Kenshiro's body with legs and rib bones. The weight of Kenshiro in this motion is 30.9kg (upper body 9.4kg, lower body 21.5kg). The upper body was unactuated, and muscle lengths of the upper body were tighten to proper length before motion. The bottom pose of the squat motion was set to 40 deg at the knee joints, 20 deg at the hip joints and 20 deg at the ankle joints. We got and stored 9 poses from 0 deg to 40 deg for knee joint at interval of 5 deg.We achieved 10 times squat motion continuously in the condition of 100ms transition speed between each pose. One of the squat motions is shown in Fig.9.

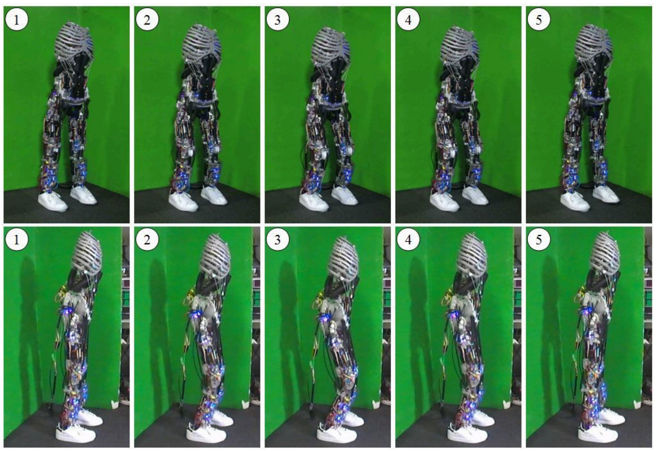

Fig. 9. Squat motion by Kenshiro with rib cage. Upper: front view. Lower: side view.

2) Squat Motion with Upper Body: We also generate squat motion and send the motion to Kenshiro with whole upper body. The weight of Kenshiro in this motion is about 41.5kg (upper body is about 20kg, lower body 21.5kg). The bottom pose of the squat motion was set to 30 deg at the knee joints and we made a seven-pose table from 0 deg to 30 deg at an interval of 5 deg.We achieved squat motion with whole body in the condition of 200ms transition speed between each pose. The squat motion is shown in Fig.10.Through this test, we confirmed joint torque feasibility of Kenshiro by achieving squat motion with whole upper body, which was impossible for our previous musculoskeletal humanoid.

3) One Step Motion: One-Step Motion: We worked on one-step motion which needs instantaneous power in the form of joint speed and torque. Although Kenshiro fell down after landing, we achieved the motion of lifting one foot off the ground with whole body weight. The one-step motion is shown in Fig.11.

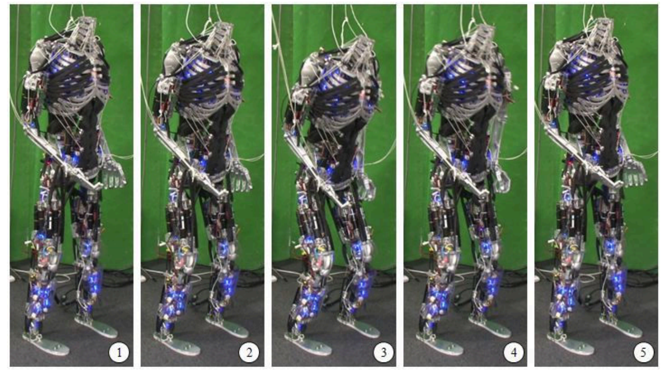

Fig. 10. Squat motion by whole body Kenshiro without human balance support.

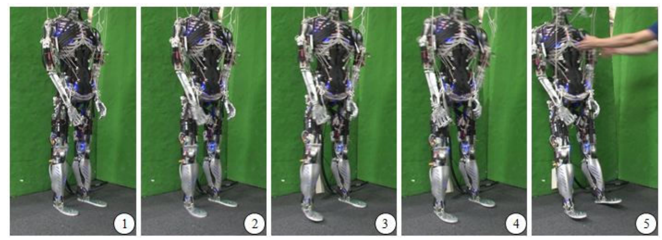

Fig. 11. One-step motion by Kenshiro. After landing, Kenshiro fell down.

IV. MOTION ACHIEVEMENT USING YAW ROTATIONAL DOFS

A. Knee Transition Motion Using Yaw DOF in Knee

We conducted performance test on the rotational DOF in the knee joints. As motions that use knee joint rotational DOF, Open-Close motion and Right-to-Left motion could be selected. By considering the relationship between human body and these motions, achieving these motions means that it is possible to actuate and constrain yaw rotational DOF using muscles. If it is not enough to constrain the knee joints, humanoid will fall down by its weight. Therefore, achieving these motions is equivalent to passing actuation test on the knees' yaw rotational DOF of the musculoskeletal humanoid with SHM developed in this paper, and is equivalent to achieving flexible motion using the knees' yaw DOF in humanoids. The knee joints' initial position are at 45 deg flexion. Both motions were generated from motion command for ± 25 deg rotation about the knee and the hip joints. Open-Close motion is shown in above of Fig.12, Right-to-Left motion is shown in below of Fig.12.

B. Whole Body Twist Squat Motion

Leg motion is only one element in achieving whole body motion. Humans can achieve several complex motions by integration of these kind of elements. We try to achieve integrated natural motion like humans by coordinating each joint of Kenshiro, which has humanlike joint structure.Kenshiro has human mimetic multi-DOF joints. Especially, rotational DOF of multiple spine, hip and knee are unique characteristic which are often not seen other humanoids. As a motion utilizing whole body rotational DOFs based on human-like hardware, we try to achieve a twist squat motion by rotating the spine, knee and hip joint at the bottom position.

In the experiment, we apply SHM to the knee and Kenshiro was supported by human in all directions without falling down. As a result, we achieved twist squat with

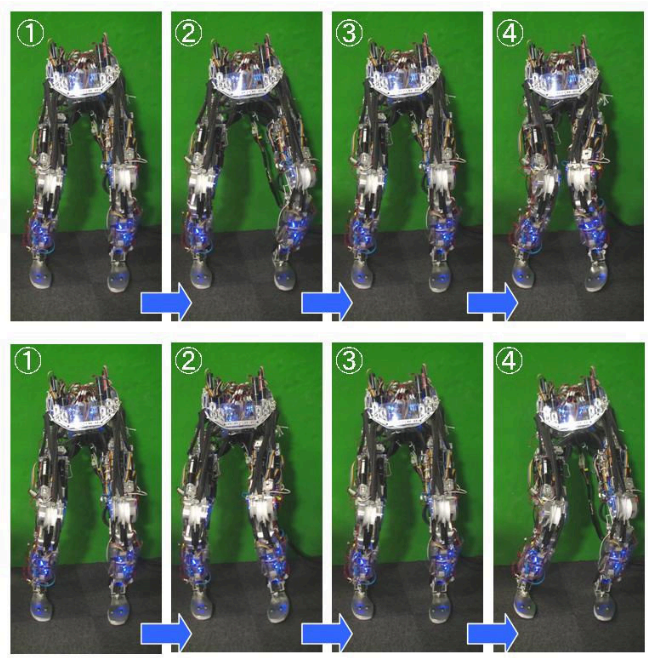

Fig. 12. Knee transition motions of using yaw DOF in knee. Upper: Open-Close motion. Lower: Right-to-Left motion.

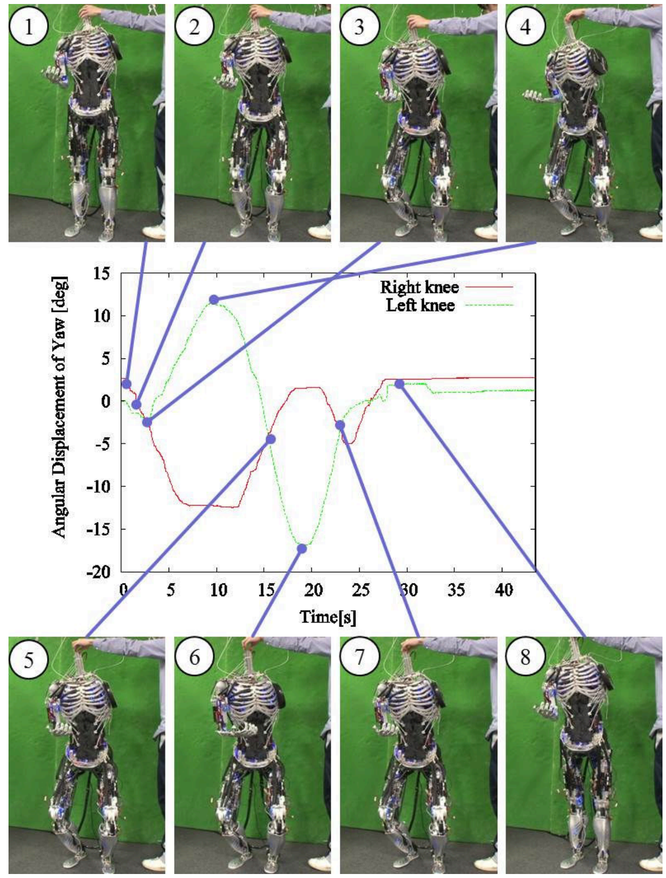

Fig. 13. Twist squat by rotating spine, knee and hip joint at bottom position and angle displacement around rotational(yaw) axis of knee during the motion

whole body. Fig.13 shows twist squat motion and angle displacement of knee joint rotational DOF during the motion. We confirmed the presence of joint constraint due to SHM because there is yaw angle displacement during motion, and it is almost zero at motion start/stop time.

V. Conclusion

In this paper, we designed a musculoskeletal humanoid knee joint with SHM as a human function mimetic joint and achieved humanlike motion. By showing the role and effect of SHM, we discussed the superiority in human body structure from the viewpoints of yaw rotational moment arm of the knee and rotational angle displacement during squats. This indicates the importance of SHM for locking the joint in extension position where muscle constraint force is decreased. We showed several motion achievements of musculoskeletal humanoid Kenshiro with whole body in order to check that it has enough pitch joint torque to move its body weight. We achieved humanlike twist squat motion using rotational DOFs of spine, hip and knee. As a result, we confirmed the feasibility of Kenshiro to do humanlike motion.

Our future work will include discussing the meaning or mechanism of human structure, which is not yet well-understood. In order to do this, we have to perform more experiments on humanlike motions of Kenshiro with joint coordination of not only rotational DOFs, but also more multi-DOFs in whole body such as head or arm. Therefore, we have to build control systems that are able to achieve motions while balancing autonomously.

References

[1] A. C. Etoundi, R. Vaidyanathan, and S. C. Burgess, "A bio-inspired condylar hinge joint for mobile robots," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 4042–4047.

[2] A. Hamon and Y. Aoustin, "Cross four-bar linkage for the knees of a planar bipedal robot," in *IEEE-RAS International Conference on Humanoid Robots*, 2010, pp. 379–384.

[3] M. OKADA, T. SHINOHARA, T. GOTOH, S. BAN, and Y. NAKAMURA, "Double spherical joint and backlash clutch for lower limbs of humanoids," in *IEEE International Conference on Robotics and Automation*, 2003, pp. 491–496.

[4] Y. Morita, Y. Kawai, Y. Hayashi, T. Hirano, H. Ukai, K. Sanaka, H. Nakamuta, and K. , Takao, "Development of knee joint robot for students becoming therapist - design of prototype and fundamental experiments," in *International Conference on Control Automation and Systems (ICCAS)*, 2010.

[5] Y. Asano, H. Mizoguchi, T. Kozuki, Y. Motegi, M. Osada, J. Urata, Y. Nakanishi, K. Okada, and M. Inaba, "Lower thigh design of detailed musculoskeletal humanoid "kenshiro"," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 4367–4372.

[6] I.A.KAPANDJI, *PHYSIOLOGIE ARTICULAIRE*, 5th ed. Ishiyaku Pub,Inc., 1987, vol. 2.

[7] D. A. Neumann, *KINESIOLOGY of the MUSCULOSKELETAL SYSTEM*. Ishiyaku Pub,Inc., 2005.

[8] I. Mizuuchi, Y. Nakanishi, Y. Sodeyama, Y. Namiki, T. Nishino, N. Muramatsu, J. Urata, K. Hongo, T. Yoshikai, and M. Inaba, "An advanced musculoskeletal humanoid kojiro," in *IEEE-RAS International Conference on Humanoid Robots*, 2007, pp. 294–299.