2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Muscle-Tendon Complex Control by "Tension Controlled Muscle" and "Non-linear Spring Ligament" for Real World Musculoskeletal Body Simulator Kenshiro

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Abstract— **This paper presents a control approach to express muscle-tendon complex in a musculoskeletal humanoid robot.**

Kenshiro is a full body tendon driven humanoid robot and is designed from the data of average 14 year old Japanese boy. By winding wires by motors we can express the contraction of muscles, and in this paper we introduce novel actuation system realized by integrating "Tension controlled Muscle(TCM)" and "Non-linear Spring Ligament(NSL)". Combination of active and passive compliance control is explained in this paper to realize the behavior of muscle-tendon complex(MTC).

This enables flexible behavior of Kenshiro, and mimic joint trajectory of human when external force is applied. At the same time the tension data of the load cells can be regarded as muscle tension.

In this way it becomes possible to use musculoskeletal humanoid robots for measuring biological data quantitatively. Application of Kenshiro as actively movable car crash simulation mannequin is illustrated by an example as a future work.

I. INTRODUCTION

For the goal of revealing human biology, there are many research on analyzing human body. Robotic researchers have made robots with anatomical features of human to emulate and understand human body kinematics, control, behaviors etc.

Yoky et al. have constructed anatomically correct model of human hand and have been working on understanding human mechanism and control [1] [2]. Takanishi et al. have clarified the skeletal function of foot arch mechanism by developing a human-like foot arch mechanism with elasticity[3]. Nakashima et al. have built a humanoid robot that can work under water and have evaluated human motion in water during swimming motion[4].

Approaches of using humanoid robot for evaluation of human body has been made, and we believe a life-size robot with detailed human mimetic structure can be of great use in the field. For this goal we have developed a life-size human mimetic musculoskeletal humanoid Kenshiro. Kenshiro is made by tendon driven system, based on the size of an average 13-14 years old Japanese male [5][6][7]. Kenshiro is designed to fulfill the below features.

- Duplicate accurate skeletal and joint structure
- Duplicate accurate muscle arrangements
- Body proportion and weight distribution based on statistical data

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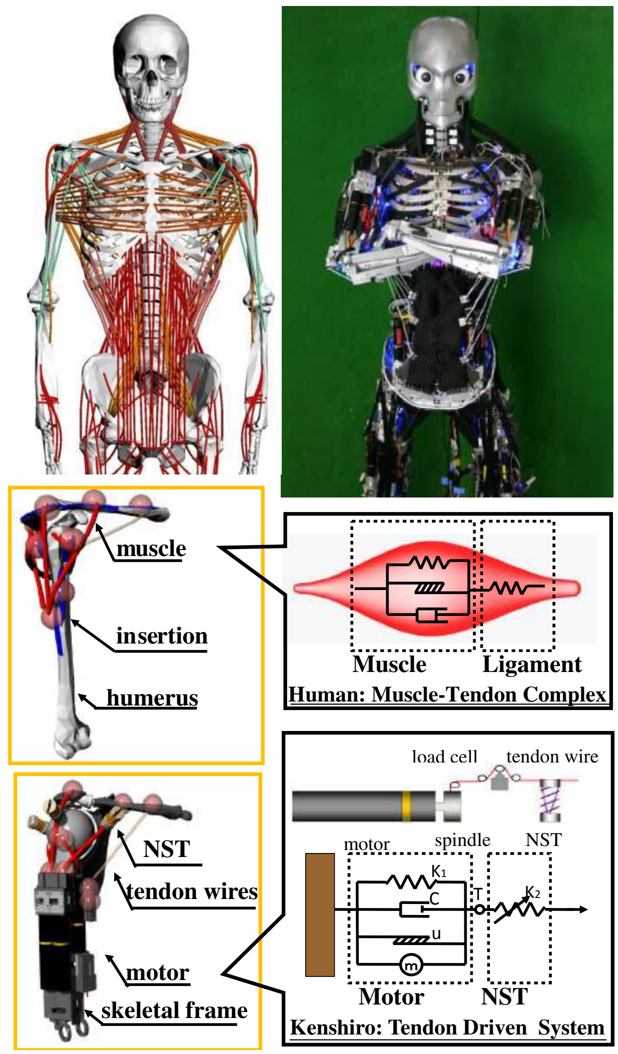

Fig. 1. Strategy of Muscle-Tendon Complex Control by integrated system of "Tension controlled Muscle" and "Non-linear Spring Ligament".

In this paper we introduce Muscle-Tendon Complex(MTC) Control, the control system based on the behavior of muscle-tendon complex based on knowledge of human anatomy. The key for developing this system is the integration of the two compliance control approaches.

One is "Tension Controlled Muscle(TCM)". The behavior of the motor control can be modeled by spring-mass-damper system mimicking muscle features.

The other is "Non-linear Spring Ligament(NSL)". The non linear specification of the Non-linear spring tensioner(NST) resembles the characteristic of the ligament that works as elastic element in human.

Combination of TCM and NSL enables Kenshiro to be actuated based on human muscle-tendon complex, behave compliantly like human. Thus by realizing a human mimetic musculoskeletal humanoid, we believe Kenshiro can be used as a real world musculoskeletal body simulator. Sensory data from robots with human like body structures and control can tell us the internal body information that would otherwise be impossible to measure without being invasive.

In this paper we introduce our novel approach of realizing muscle-tendon complex in robots. Total prospect of the system is shown in Fig.1 . In Section II, we will focus on how human muscle can be expressed with viscoelasticity, and how compliance have been implemented in robotics. Section III will explain the overall actuation system developed in this paper. In Section IV we will make evaluation on the proposed actuation system. Finally the last section presents our conclusion and opportunities for future work.

II. Compliant behaviors in Human and Robots

Human are able to make flexible motions by the viscoelasticity in musculoskeletal structure. In this section, we look into some researches to understand viscoelasticity in human, and how compliance is developed in the field of robotics.

Human body are known to have viscoelasticity in all kinds of tissues. Especially muscle, which is one of the main element when generating human body motions, are known to have viscoelasticity and there have been many approaches in examining parameters of viscosity modulus and elastic modulus[8][9]. Hill muscle model in Fig.2 is a well known model expressing the muscle behaviors and have often been referred to when considering human musculoskeletal behaviors[10][2] .

Fig.2 shows one example of muscle model which is mechanically equivalent to Hill muscle model. CE is the contractile component, SEC stands for Series Elastic Component, and PEC stands for Parallel Elastic Component. SEC1 derives from myosin molecule with stretch rate of 0.5-1.0%, and SEC2 derives from connective tissues like ligaments with stretch rate up to 10% in some muscles, PEC generates force passively when being stretched. These components are said to be depending on tensions, length and contraction speed etc. can be expressed by non-linear function.

These non-linear features are known to be essential in controlling human joints stiffness in antagonist muscles. There has been some research of inserting mechanical unit to rigid wire for tension adjuster[11][12][13] to control joint stiffness.

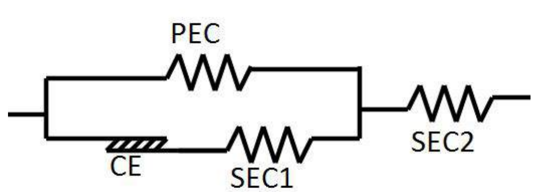

Fig. 2. Hill muscle model. Generally expressed as elasticity in parallel and series.

Looking into other approaches of controlling joint stiffness in humanoid robots, it had been a traditional approach in robotics to design interface between actuator and its structure very stiff, but for multiple reasons such as shock reduction, safe contact with environment, energy storage or accurate force control etc. There are many researches that can embed viscoelasticity in robots[14][15], and these approaches are very effective in the view point of control and compliant behavior in robots. But these approaches have low relation with human control and do not lead to human like joint stiffness when applied to redundant and antagonistic musculoskeletal structures.

McKibben actuator often referred to as Pneumatic artificial actuator does have viscoelasticity, that can be regarded as parallel elastic element like human muscle, but inescapably have a certain stiffness at any postures since it needs certain level of pressure for controlling the length.

III. Set up for Muscle-tendon complex Control in Kenshiro

In this section we explain the basic composition of Kenshiro upper limb, and how the MTC control can be implemented in the wire-driven system.

The contraction of the muscles are expressed by winding tendon wires with motors, and by implementing viscoelasticity both actively(TCM) and passively(NSL), the characteristics of MTC can be realized in the actuation.

A. Kenshiro with human mimetic musculoskeletal structure

As a main feature of Kenshiro, it is designed to have the same body structures as human body. As can be seen in Fig.3 it has muscle insertion based on human and the whole joint structures and limb length are designed based on anatomy. To express muscle contraction we adopted 100W MAXON brush-less DC motor for high power weight ratio, and each motor is capable of generating 0.3 - 0.35[kgfm] continuously by the gears(gear ratio 29:1 to 128:1) and spindles we adopted. This means a single muscle, actuated by a motor can theoretically generate tension of 50.0 - 58.3[kgf] value depending on the limit of the gear strength. The reduction ratio of the gears were decided to have close speed between the antagonist muscles, so as not to disturb each other's movement at maximum speed. The motors were set to the skeletal frame to preserve human like endoskeletal shapes, and this enabled body weight contribution based on statistical human data, the center of gravity was not necessarily duplicated in each limbs.

B. TCM: Active compliance control by Motor

This section explains TCM which is active compliance control implemented in Kenshiro. As explained in Section III-A, the contraction of muscle is expressed by the tendon wire winded by the spindle placed on the gear head. Each motor has potentiometers and load cell units to observe change in muscle length and tension. By constructing a model using spring, damper, and mass shown in Fig.4 , and

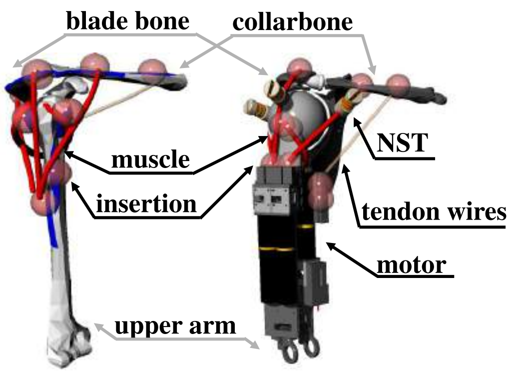

Fig. 3. Musculoskeletal structure of human and Kenshiro in comparison. It can be seen that accurate proportion and muscle insertion is emulated.The muscles depicted here is fore, middle, rear deltoids(three muscles mainly measured in later experiments), ifraspinatus and subscapular.

using potentiometers, tension data for input, TCM can be implemented.

Based on the model shown in Fig.4 , the motor output can be decided by the equation shown below.

PID:PID controller
ω:motor speed to define dynamic friction
ω_{ref}:desired value for motor speed
ω_0:threshhold motor speed
K_1:elasticity modulus for spring in muscle model
T:tension measured from load cell
T_{ref}: Desirable basic tension
J_m:modeled inertia converted from m in Fig.4
L_{ref}:muscle length for reference in control order
L:muscle length from motor potentiometers
F_{max}:threshold for friction= Dynamic friction force

$$output = \mathrm{PID}(\omega - \omega_{ref}) \quad (1)$$

$$\omega_{ref} = \int \frac{d\omega}{dt} dt \quad (2)$$

$$J_m \frac{d\omega}{dt} + fric + \max\{0, K_1(L - L_{ref})\} = T - T_{ref} \quad (3)$$

$$(\omega < \omega_0) fric = \min[F_{max}, abs(T - T_{ref})] * \mathrm{sign}(\omega) \quad (4)$$

$$(\omega > \omega_0) fric = F_{max} * \mathrm{sign}(\omega) \quad (5)$$

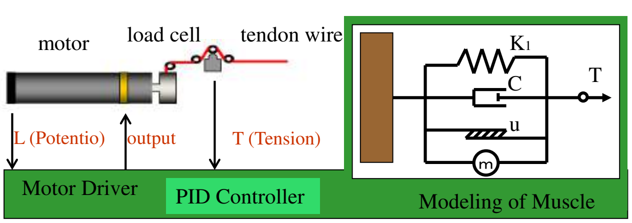

Fig. 4. TCM control system by muscle model for control.(K_1:elasticity modulus in muscle,C:friction modulus in muscle,u:contractile force,m:mass of muscle model,T:Tension measured on load cell

C. NSL: Passive Compliance control by NST

In contrast to TCM active compliance control, NSL is expressed by passive compliance control by mechanical element. Here we adopt Non-linear Spring Tensioner(NST[12]) for NSL. This series elastic element can be comparable with human ligament, as NST set to the wires of antagonistic muscles, can modify joint stiffness in the same mechanism as human. When the NST is loaded small force it has low stiffness, whereas when large force is applied its stiffness becomes high. In Fig.5 mechanism of NST is shown together with experimental set up. In order to choose appropriate elasticity when generating various motions in Kenshiro, springs of wide range in length and elasticity as in Table.I were examined. 8 types of different springs were examined. Fig.6 shows the resultant behaviors of each spring on NST.

As tendon wire, we adopted Dyneema [1] (DB-100, breaking strength 350 [kgf] (some DB-50, 170 [kgf]).) As we also conduced a test on DB-100 dyneema, linear characteristic with 6.7-6.9% stretch under the conditions of 50 [kgf] tension.

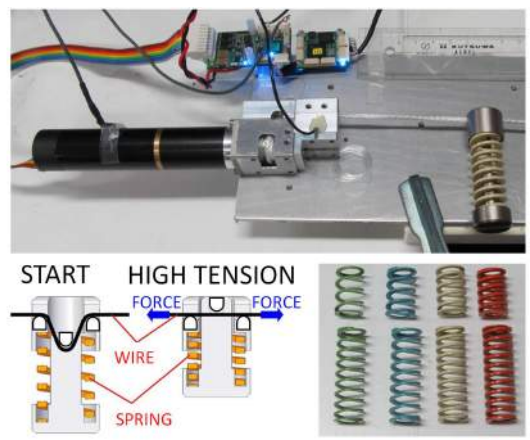

Fig. 5. Mechanism of Non-linear Spring Tensioner as elastic element for controlling mechanical stiffness. Springs were examined its specifications for appropriate control.

TABLE I
LENGTH AND ELASTICITY OF THE SPRING IN CHOICE

spring type	1	2	3	4	5	6	7	8
length $[mm]$	25	25	25	25	50	50	50	50
elasticity $[kgf/mm]$	5.6	9.8	15.7	29.4	2.8	4.9	7.9	14.7

Result from Fig.6 shows NST has various stiffness curve depending on the choice of springs. In theory the curve has non-linear curve throughout the range, though in reality, undesirable feature of linear range was observed. To have the motors wind wires long distance leads to slow response when varying joint stiffness.

[1] $http://www.hayami.co.jp/hamilon_english$

Also from the previous experiments[6] of generating motions in Kenshiro upper limb, it is not preferable to have the muscle stiffness change under 10$[kgf]$, since when generating motion it is very easy for the wire tension to go beyond 10$[kgf]$. As a result, spring appropriate for Kenshiro would be spring4 and spring3. Comparing these two, spring4 would be the best choice as it has non-linear property in wide range of tension.

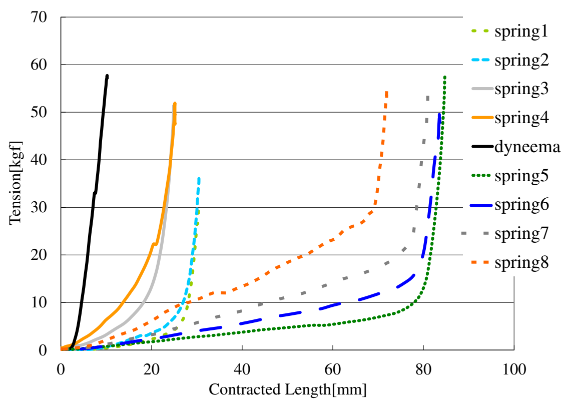

Fig. 6. Measured Mechanical specification of NST with various springs. Dyneema itself was also tested. Distance of the exposed setup was set to 1500$[mm]$. Actual experimental results show NST does not follow theoretical curve of the variable stiffness. Caused by stretch of dyneema during experiment and mechanical friction.

D. MTC Control: Integration of TCM and NSL

The configuration of setting of TCM and NSL in series can be named Muscle-Tendon Complex control(MTC control), since MTC is "human muscle" and "human ligament" in series.

IV. EXPERIMENTS

As a demonstration of the proposed control configuration, this section shows three experiments. First impact test on shoulder to compare each control modes are made. Second, abduction motion is made with two control modes to see the load distributions between redundant muscles. And Finally impact tests with two different conditions of MTC control are made and joint angles are measured. Observing the tension results, joint angles of Kenshiro enables the feasibility of Kenshiro to be utilized as a human body simulator.

A. Evaluation of Control during impact on shoulder

In this section, to see the effect of each compliant actuation of muscles on the joint stiffness, we conducted an experiment of dropping a 2.5$[kg]$ weight from 100$[mm]$ height on the end effector of Kenshiro arm with the scapulohumerical joint 90°, as shown in Fig.7 . The experiment was conducted varying control method as shown below. Here, "Length control" has no tension data input for the control, with PID control over the muscle excursion.

- (A)Length control
- (B)Length control +NSL
- (C)TCM
- (D)TCM +NSL (MTC control)

Fig.8 shows the result of tension data of middle deltoid, which is the muscle that had the highest tension in the experiment. From the result, at Time=1.2$[sec]$ the peak tension can be seen to decrease with NST when comparing the same control approach(A)to(B) and (C)to(D). After dropping the weight (C)(D) has lower tension than (A)(B).

From this result it can be said that the proposed method of combination of TCM and NSL can decrease peak force against impact force and also can decrease necessary force to make certain postures, as TCM works to distribute force between other muscles when force is loaded.

Fig. 7. Drop test of 2.5$[kg]$, 10$[mm]$ to arm end position at scapulohumerical joint abduction angle 90deg.

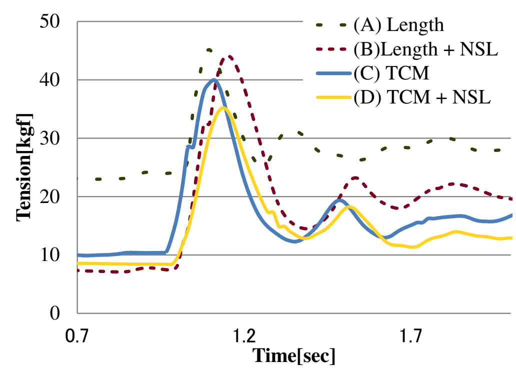

Fig. 8. Tension result of middle deltoid muscle. Maximum tension in (A) (D) is 45.2, 44.0, 40.0, 37.1 $[kgf]$. NST can be said to have decreased the peak tension in the middle deltoid muscle.

B. Evaluation of Biological Data during Abduction

To compare the compliant behavior of the proposed method, we compare the tension data of motions made by 2 approaches. By calculating the length of muscles from simulation model, we gain the amount of distance δL that the muscles need to be contracted or stretched. One control was made by using this value for (A)Length control, the other by (D)MTC control.

Fig.9 show the resultant tension of middle deltoid muscle during abduction of the scapulohumerical joint. By seeing Fig.9 and Fig.10 the concentration of force can be seen to have occurred with (A) whereas proposed control (D) had less tension as force being distributed between the muscles. It can be said that this was enabled as fore, middle, rear deltoids

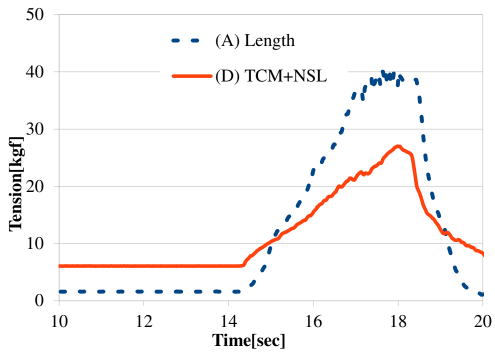

Fig. 9. Tension data of deltoid middle muscle during abduction 60 [deg] motion. The proposed method can be seen to have lower tension.

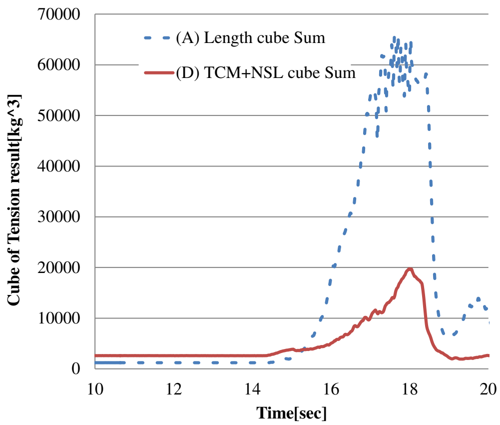

Fig. 10. The sum of square of tension data in fore, middle, back deltoid. Double or cube of tension data can be used to compare the magnitude relation of the energy consumption between the control approaches.

were all place in a row working as antigravity muscles in this experiment.

The difference occur based on motor control strategy. The proposed method based on human muscle control realize more power distributed actuation as a result of implementing compliance. This can be seen from Fig.10 . The sum of the cube of the tension in fore, middle, back deltoid was seen to decrease in the proposed method. This means the load had been distributed between the muscles and not transferred to other muscles.

C. Evaluation of joint angle during impact on neck

As a demonstration for measurement and evaluation of joint angles when under external force, in this subsection we conduct an impact experiment on Kenshiro neck. Under 2 different conditions the experiment is conducted, the parameters in MTC control was varied to modify joint stiffness around the cervical vertebrae.

As experimental set up, the impact on neck was made by medicine ball of 5$[kg]$ of 2.2$[m/s]$ directed towards the center of the head. The head was covered with aluminum frame box to protect the outer shell. The mass of the head was 2.68$[kg]$, the cervical vertebrae was 0.38$[kg]$.

In this experiment, the two different stiffness of the MTC control was made by modifying T_{ref}. The muscles involved in this experiment is shown in Table.II. T_{ref} was set to 2.0,2.0,2.0,2.0,5.0 in low stiffness and 10.0,10.0,7.0,2.0,12.0 in high stiffness arbitrary, as the high value of these parameters mean strong antagonistic activity of the muscle. The Thorax was stabled to measure the angle displacement of the neck independently.

Successive pictures of Fig.11 shows the moment of impact, and Fig.12 follows the change in joint angle of the cervical vertebrae. The change in pitch angle of the neck was, high stiffness maximum -19.1$[deg]$, while low stiffness -35.4$[deg]$. The high stiffness mode was observed to suppress change in joint angle compared to low stiffness mode. As can be seen from these results the condition of joint stiffness could be modified by changing the parameters in antagonistic muscles in the proposed MTC control.

TABLE II

MUSCLE NAME INVOLVED IN IMPACT ON NECK.

ID	Muscle name	ID	Muscle name
#1	Longus colli	#3	Scalenus
#2	Sternocleidomastoid	#4	Trapezius
		#5	Splenius capitis

V. CONCLUSION

By integrating TCM and NSL we have introduced MTC control which is a novel system that resembles the behavior of muscle-tendon complex in human body.

Kenshiro with this MTC control was observed to behave compliantly against impulsive force, as force distribution between muscle was observed in the experiment.

The control approach is highly based on human anatomy, and this approach applied to redundant actuators in musculoskeletal humanoid robot enables compliant behavior in the overall joint behavior. The change in parameters in the proposed control was capable of modifying joint stiffness in Kenshiro.

The goal of actuating human mimetic musculoskeletal humanoid Kenshiro by proposed method , is to realize a real world musculoskeletal body simulator. Quantitative evaluation of human body can be made by regarding sensory data in Kenshiro as biological information. Muscle tensions are not always necessarily measurable in human, especially with experiments with high damage to our body such as car crash situations. Joint angles and stiffness resembling human features enables accurate emulation of various environments which is otherwise difficult to simulate. By utilizing humanoids designed and controlled based on human anatomy, we propose a real world musculoskeletal body simulator for assisting development of safe products through measurement and evaluation of sensor data.

Fig.13 illustrates the experimental set up of for Kenshiro car driving experiment and car crash experiment for future work.

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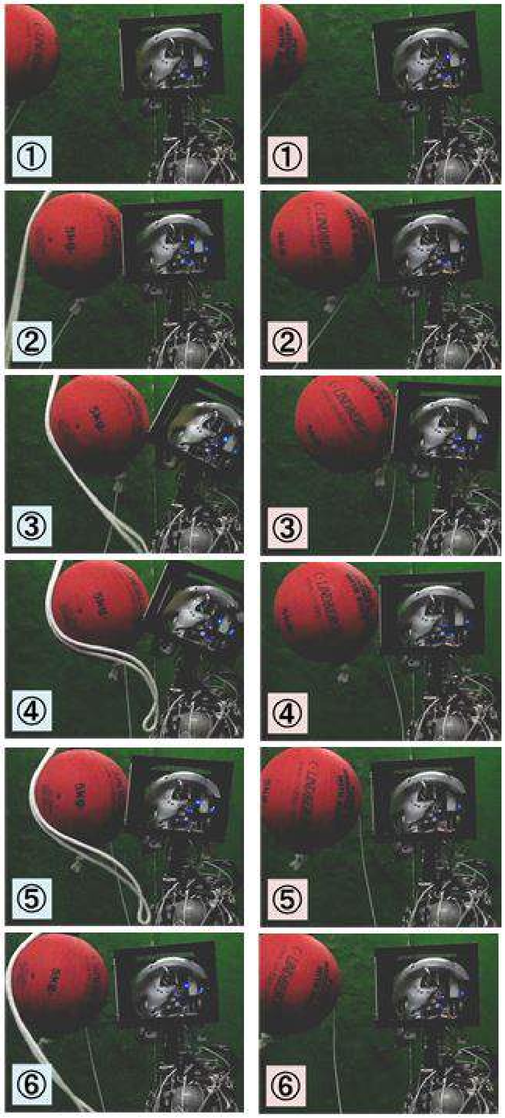

Fig. 11. Impact on cervical vertebrae(neck). Left: MTC with low stiffness mode. Right: MTC with high stiffness mode. Impact was made from a medicine ball of 5.0$[kg]$, 2.2$[m/s]$.

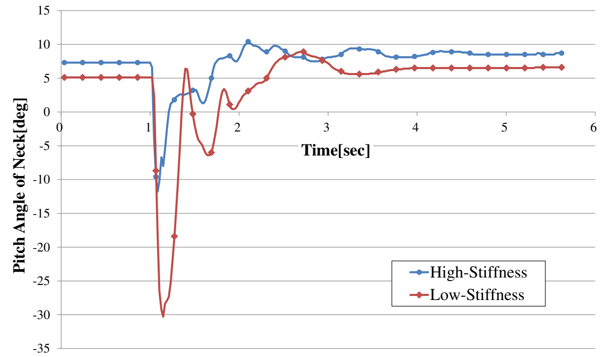

Fig. 12. Measurement and comparison of Pitch angle of Neck during impact. High stiffness with maximum -19.1$[deg]$, while low stiffness -35.4$[deg]$.

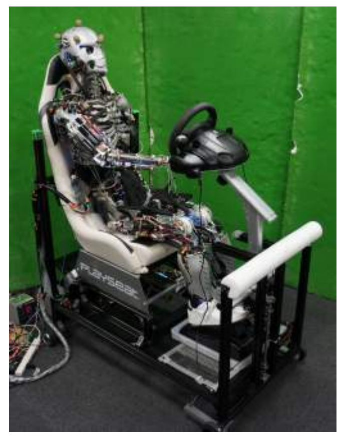

Fig. 13. Kenshiro on car as a demonstration of future work.

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