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

Design of Upper limb by Adhesion of Muscles and Bones -Detail Human Mimetic Musculoskeletal Humanoid Kenshiro-

Toyotaka Kozuki, Yotaro Motegi, Takuma Shirai, Yuki Asano,
Junichi Urata, Yuto Nakanishi, Kei Okada, Masayuki Inaba

Abstract— **This paper presents a design methodology for humanoid upper limb based on human anatomy. Kenshiro is a full body tendon driven humanoid robot and is designed from the data of average 14 year old Japanese boy. The design of his upper limb is realizing detail features of muscles, bones and the adhesive relation of the two. Human mimetic design is realized by focusing on the fact that joints are being stabled by muscles winding around the bones, and by accurately mimicking the bone shape this was enabled. In this paper we also introduce details of mechanical specifications of the upper limb.**

By having muscles, bones, and joint structures based on human anatomy, Kenshiro can move flexibly. The use as human body simulator can be expected by measuring sensor data which can correspond to biological data.

I. INTRODUCTION

There are many research on design approaches for humanoid robots. Tendon driven system is a method which is often used to mimic the biological features of muscle and is a prevalent way for emulating human body structures [1][2][3]. For the purpose of revealing the human biology and dynamism we develop 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 [4].

By realizing a human mimetic musculoskeletal humanoid, we believe Kenshiro can be used as a human body simulator. Qualitative evaluation of human motion can be done with a robot, on condition that it has the same body structure as a human. Approaches of using humanoid robot for evaluation of human body has been made[5][6], and we believe the human mimetic structure of Kenshiro can be of great use in the field. For example by measuring the tension of each tendon, we are able to measure the load applied to each muscles.

To develop a life-size humanoid robot, our research group has made research on robots with spines and blade bones like Kojiro[7] and Kenzo[8] on the thought that the musculoskeletal structure is a very important element for a humanoid robot to move flexibly like human. But looking at these robots, we can see that they have been simplified from human to avoid complicated mechanism and is far from being anthropomorphic in some points. They have little in common with human body in that the muscle arrangements, skeletal frameworks, nor the range of motion is different from that of human. Therefore we set following concept to design Kenshiro.

Graduate School of Information Science and Technology, Department of Mechano-Infomatics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan kozuki@jsk.t.u-tokyo.ac.jp,

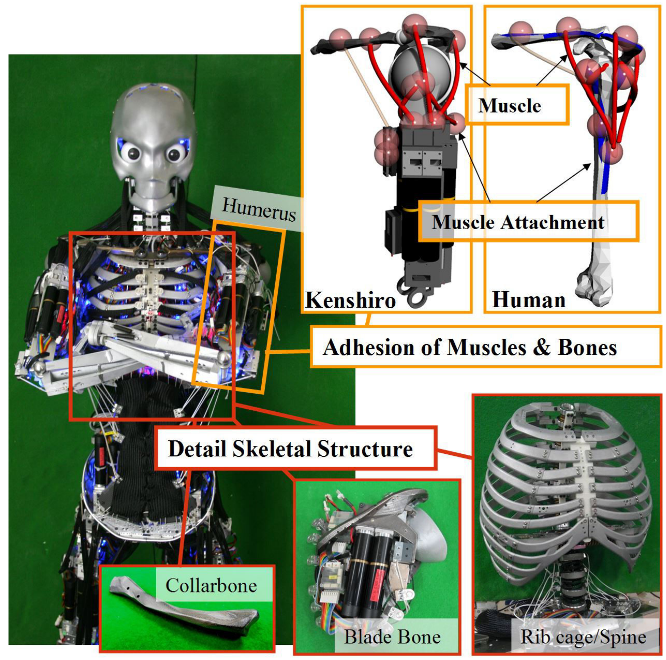

Fig. 1. 'Kenshiro' The Human Mimetic Musculoskeletal Humanoid

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

Especially the upper limb is a part of the body that is one of the most complex, and is a part that is difficult to mechanically design under the conditions above. We have made basic mechanical experiments [9] to actuate a musculoskeletal shoulder that leads to realizing such structures, and here in this paper we present the refined structural approach that fulfills the above conditions, based on focusing on adhesive relation of muscles and bones.

Fig.1 shows the picture of the latest Kenshiro developed in this research. In this paper we propose a design methodology for Kenshiro's mechanical key points for upper limb. The first section introduces the approach we take. SectionII explains the design concepts of the upper limb. SectionIII explains specifications of mechanical structures. SectionIV shows experiments to show the capability of the design developed. Finally the last section will conclude the design that has been achieved in this research.

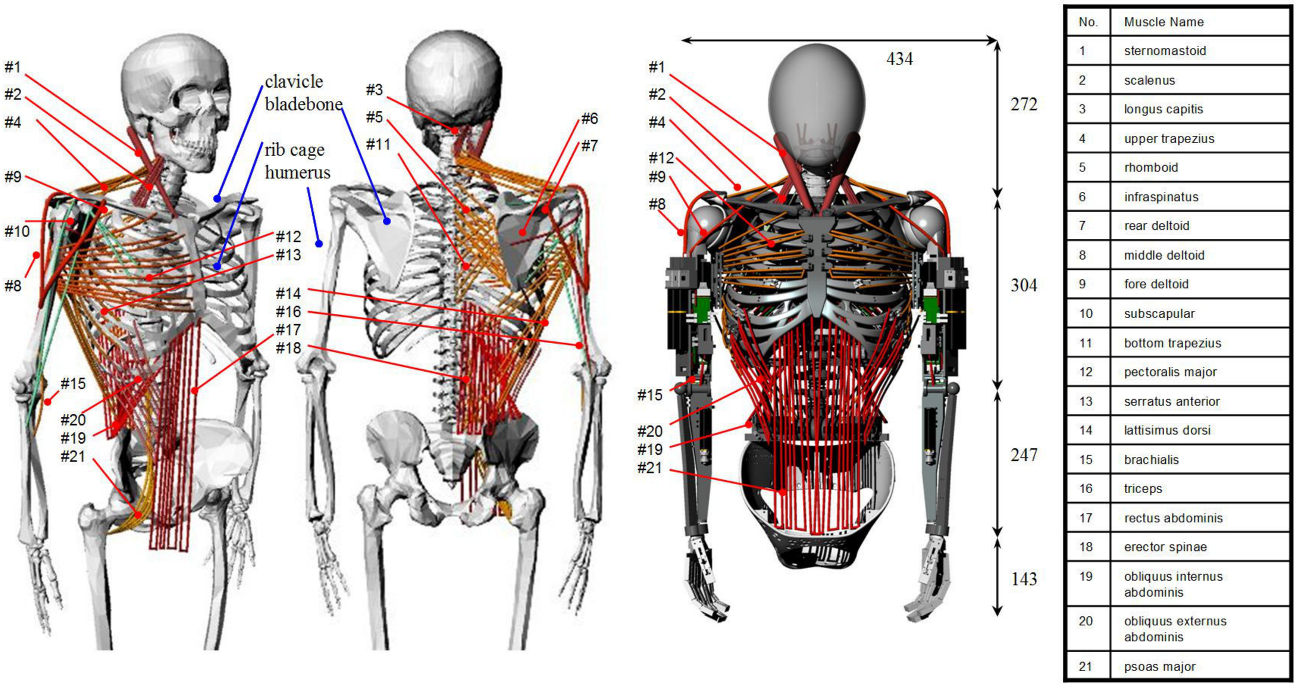

Fig. 2. Musculoskeletal structure of human body and Kenshiro. The figure indicates high relationship of Kenshiro's body configuration with human body.

II. Design Approach Focused on Adhesive Relation of Muscles and Bones

When we look at existing approaches of designing an upper limb for musculoskeletal humanoid robots [10][11][12], designing detail human structure has been a difficult goal to achieve. It is difficult for the robot to actuate with redundant skeletal, joint, and muscle structures, having the same range of motion as human, with certain strength.

To enable this, as a result, many designs of musculoskeletal structures have led to low correlation with actual human body. To solve the challenges mentioned above and realize a truly human like upper limb, we take approaches listed below.

1) Set concepts as a whole robot (introduced in Section.I).
2) Focus on the adhesive relation of muscles and bones.

The upper limb explained in this paper is designed to fulfill the concepts. Fig.2 is a simple CAD model of human body and Kenshiro. By comparing human(left) and Kenshiro(right) we can see that Kenshiro is designed to duplicate most of the agonist muscles for the upper limb. The structure was designed based on knowledge of anatomy[13]. Some muscles were united to other muscles with close insertion areas. The blue lines are muscles which was not adopted in Kenshiro. We were not able to implement these muscles for spatial constraints(levator scapulae, pectoralis minor, coracobrachialis, etc).

This abbreviation in muscular system was decided by preferentially adopting agonist muscles which has large cross-sectional area, based on the fact that muscle with larger cross-sectional area contributes more joint torques.

The body mass is also considered important element for actuation, and is made to weigh close to body proportion[4] based on the statistical data.

TABLE I
Weight distribution of the upper body. Trunk includes thorax and the muscles around blade bone. (*:due to unfinished body parts)

who	upper arm [kg]	trunk [kg]	upper arm [mm]	width [mm]	total [mm]	total [kg]
human	1.5	17	316	417	159.5	50
Kenshiro	1.8	15.4	304	434	159.3	*

In traditional tendon driven robots, the wire paths that express the muscles were in straight line, while human muscles are not in that way. For the robots to have the same range of motion as human, the muscles needed longer moment arm that led to longer skeletal frames for muscle attachment. This resulted in musculoskeletal robot with low relationship with human body in that it has different muscle arrangement, different bone shapes, and forms from human. As an example, Fig.3 shows how the humerus of Kenshiro has been developed. Based on human anatomy we take approach of introducing "Adhesive relation of muscles and bones", with muscles winding around the bones. By adopting appropriate shaping technologies and materials for this goal, accurate muscle attachment and bone shape was designed. Comparing the structure with traditional robots as shown in Fig.4 , you can see that Kenshiro is designed to highly mimic human body structure.

III. Mechanical Specification to Design Musculoskeletal Upper Limb

In this section we explain the key mechanics of Kenshiro upper limb based on human anatomy. From the experience of

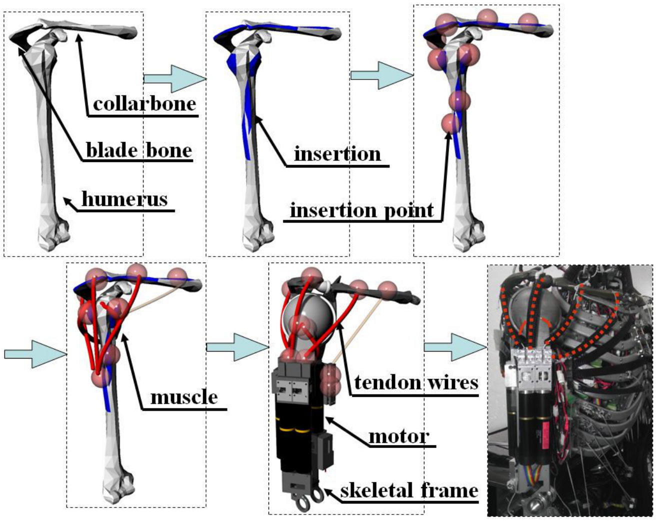

Fig. 3. The figure shows the step of how Kenshiro is being designed from human bones and insertions.

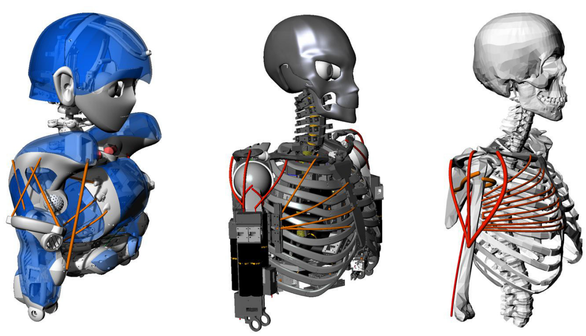

Fig. 4. Kojiro(left), Kenshiro(center) and human(right). Adhesion of muscles and bones can be seen in the shoulder of Kenshiro. In Kojiro, traditional tendon driven robots, the muscles were placed straight, whereas in Kenshiro and human the muscles are winding around the bones.

building a prototype by ABS plastics and nyron, we decided to adopt aluminum or steel as a basic material for skeletal frames. When we compare density and Youngs modulus between nyron and aluminum (nyron:1.15[g/cm^3],7GPa, aluminum:2.79[g/cm^3],29GPa), using metal material can make the design compact and lighter which enables complex form of human bone with strength.

Each body parts are designed to realize detail human mimetic body structure as explained in Section.II, with high mechanical strength, and the actuation mechanism is calculated to maximize joint speed characteristics with joint torque sufficient to move within the motion range.

A. Humerus that enables muscle-bone adhesion

Scapulohumerical joint(joint between blade bone and humerus) is a very important joint that is related to all kinds of daily life motion by the wide range of motion and its flexibility. The challenge in duplicating the joint begins from understanding the bone shape of humerus.

The result from our experimental model in the past-Fig.6 indicated the lack of moment arm with muscles winding around humerus during flexion and horizontal flexion. This was caused by lack of preciseness in duplicating

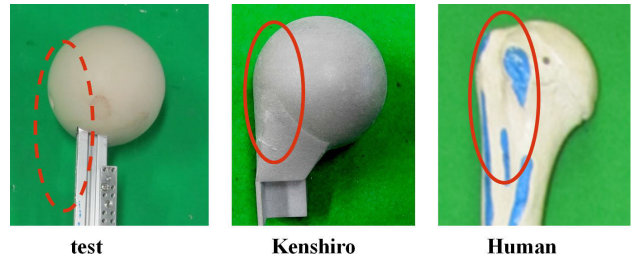

Fig. 5. Head of humerus for the test model, developed humerus, and human humerus. The crest of tubercle that was not adopted in the test model is adopted in Kenshiro for muscle adhesion with bones..

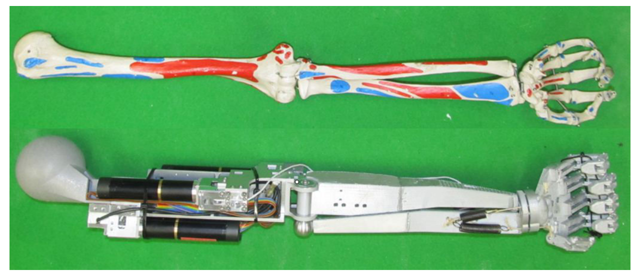

Fig. 6. Design of the arm compared with human. You can see the arm has endoskeletal framework with human proportion.

the shape of humerus. It had a very thin humerus to gain wide range of motion in the scapulohumerical joint. This model failed to mimic the structure of "Adhesive relation of muscles and bones", in this case, muscles did not wind around the crest of tubercle to keep moment arm at various body positions. Thus we developed the tubercle as showed in Fig.5 which has more accurate bone shape. In human, humerus works as a frame for the upper arm and at the same time the hemisphere of the ball joint is attached to the crest of tubercle. The design shown in Fig.5 is designed to have these features, and by implementing the close relationship of the bones and the muscles, the wire expressing the muscle is able to wind around the crest of tubercle enabling high level duplication of human body structure and range of motion in the scapulohumerical joint.

By this design we solve the challenges and problems mentioned in Section.II and are able to design the upper limb in close form as human. Fig.6 is the arm developed. It can be seen to have high relation with human body in the sense of bone shape and length proportion.

B. Blade bone for many Insertions

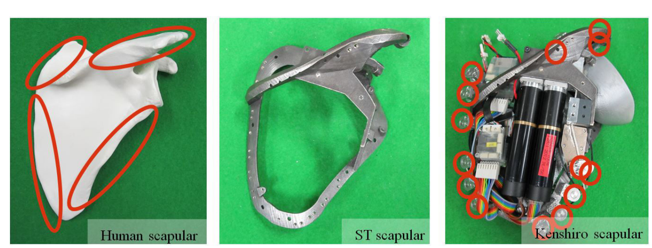

Fig. 7. Design of blade bone compared with human. It can be seen that the 3 dimensional shape for insertion is realized by the design.

The blade bone which is a bone that connects to many muscles and has a 3 dimensional complex shape, we adopt stainless steel(ST) 3D print technology(420 SS, Bronze(40%)). Developed blade bone is shown in Fig.7 . This material allows the complex shape of the design, and at the same time a shape that could withstand force applied by insertions on the bone. As we adopt planar muscle mechanism(Section.III-D) to imitate human muscles around the blade bone, many insertions were necessary in the blade bone.

Open sphere joint in the scapulohumerical joint helps wide range of motion in the shoulder, as approximately 120 degrees of range of motion in scapulohumerical joint is enabled by the glenoid cavity of the blade bone being very small compared to the head of humerus. Though we have very small glenoid cavity, the reason why our shoulder does not dislocate easily is because muscles wind around the joint contributes to the stability of the joint, and this mechanism is implemented in the design. The glenoid cavity of the blade bone was designed to be shallow open sphere joint with 42% coverage of the socket. Combination of this socket along with the humerus ball joint compose the scapulohumerical joint with wide range of motion.

As can be seen from Fig.2 , the upper limb is composed of thorax, clavicle, blade bone, humerus and fore arm, each connected with 3,3,3,1 DOF joint. But at the same time the blade bone and the thorax can be seen as a false joint(FCS-joint:joint of Facies Costalis Scapulae) in that they are always in close position due to constraint of muscles. This FCS-joint is a joint which blade bone slides on the free-form surface of the rib cage softly by having subscapular muscle and scarratus anterior muscle as a muscle cushion in-between. This structure leads to the flexibility and the great range of motion in the shoulder joint. We take the approach of adopting a urethane material to express this joint and by doing this the blade bone which is the basis for the humerus helps the range of motion of the upper limb by rotation, abduction, adduction, depression and elevation. For example when we raise our hands in the air, the scapula outer rotates about 60 degrees and the humerus 120 degrees.

C. Rib cage with smooth surface for blade bone

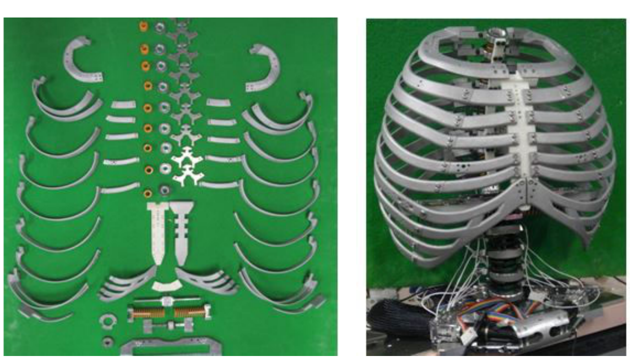

Fig. 8. Designed parts of the rib cage. It can be seen that accurate bone shape was realized which is important physical feature when the blade bone slides on its surface.

In a complex structure of the upper limb in human, the rib cage works as a smooth surface in the FCS-joint for the blade bone to slide with muscle cushion in between. Thus the smooth surface composed by the combination of each ribs is geometrically important to replicate the muscles and bones in the FCS-joint. Moreover, the individual ribs will enable the structure of individual thoracic spines that leads to movable S-curve spine that leads to human flexibility in body postures. For this reason the ribs in Kenshiro were aimed to copy the shape of human ribs in detail as shown in Fig.8 , enabling Kenshiro to truly resemble the skeletal structure.

The shape of the ribs were based on human skeletal structure, and was designed by Rhinoceros(NURBS modeling). The material used to shape the ribs are aluminum(AC4C) and is made by lost wax casting process. This manufacturing process was the most appropriate to realize the complex shape of the ribs considering the cost, stability, total weight contribution, etc in making Kenshiro thorax. The ribs are designed to connect to sterunum and thoracic spine based on human body.

D. Specification in Actuation Method

This section explains the actuation method used in Kenshiro. The actuation method used to express the contraction of muscle is shown in Fig.9 . The contraction of muscle is expressed by the wire winded by the spindle on the motor. Traditional actuation method which is called “linear muscle” using one line of wire. We have also applied “planar muscle”[14] mechanism to some muscles. In planar muscle, wire is bended back many times which results in high reduction ratio. It can

- Express the width and exterior softness of the muscle
- Simplify hardware composition and control

Also, comparing the two cases below which is the same reduction ratio as a total, (i)Using high gear reduction ratio motor composing linear muscle, (ii)Using low gear reduction ratio motor composing planar muscle, using the planar muscle mechanism is better in energy efficiency [15], which can be said as another advantage for applying the “planar muscle” mechanism.

We adopted 100W MAXON brush-less DC motor for high power weight ratio, and each motor is capable of generating 3 - 3.5Nm continuously by the gears(gear ratio 29:1 to 128:1) we adopted. This means a single muscle, actuated by a motor can theoretically generate tension of 50.0 - 58.3 [kgf](more than 100[kgf] in planar-muscle), value dependent on the limit of the gear strength. The reduction ratio of the gears and planar muscle was decided to have close speed between the antagonist muscles, so as not to disturb each other’s movement. 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 shown in Table.I .

Thus the joint speed of upper limb realized in Kenshiro is shown in Table.II .

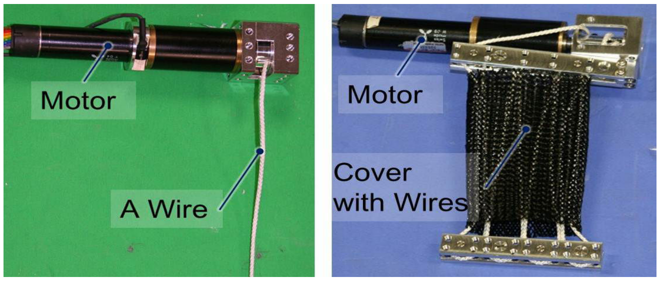

Fig. 9. Linear muscle(left) and Planar muscle(Right). Linear muscle only winds a wire, while wire of planar muscle is winded many times by pulleys for higher reduction ratio. Soft outer skin like muscle is also realized. This mechanism can generate 100[kgf] when the planar muscle's reduction ratio is 2:1.

TABLE II

ANGLE VELOCITY OF JOINTS

Joint	motion	Speed[π/sec]
Elbow	flexion, extension	12.5
Shoulder	horizontal flexion, extension	3.6
	abduction, adduction	2.2

E. Series elastic element

Also series elastic element[16], mechanism explained in Fig.10 , which acts as variable stiffness is mounted on the muscles for elbow joint. This enables compliant behavior of the joint not only by software based control of the motor, but also mechanically. Human too has longer ligaments at the distal portion of the body and we plan to adopt more of this structure.

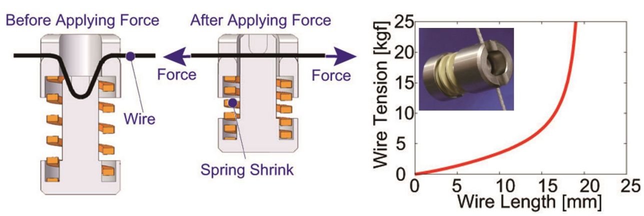

Fig. 10. Mechanism of Non Linear Spring unit as elastic element for controlling mechanical stiffness.

IV. EXPERIMENTS FOR UPPER LIMB

As a demonstration to show the physical capability of the proposed mechanical structure based on human anatomy, we examined the range of motion of the shoulder. Table.III shows the result of range of motion, and Fig.11 is the image of each movements.

The joint is composed of sternoclavicular joint, acromioclavicular joint, and scapulohumerical joint and the posture is enabled by the skeletal structure and 11 actuators expressing the muscle contraction.

The result shows, the problem of lack in range of motion in the experimental model[9] has being improved. This was enabled by adhesion of muscles and bones by the design refine of humerus. The muscles were able to wind around the humerus(the part mimicking crest of tubercle) keeping the moment arm to make the posture. Joint dislocation of the scapulohumerical joint did not happen within the motion range. This was examined up to π [rad/sec] of abduction, and can be said that the muscle's adhesion to the humerus worked to stable the joint.

By comparing the range of motion with other research on musculoskeletal upper limb, the developed structure can be said to have the feasibility to be a model approaches, as the design is also realizing highly human mimetic features in many senses.

TABLE III

RANGE OF MOTION OF THE DEVELOPED UPPER LIMB IN COMPARISON WITH HUMAN AND OTHER ROBOTS.[DEG]

	human	Kenshiro	Kojiro[7]	other[12]
Abduction	180	170	90	170
Adduction	0	10	10	0
Flexion	180	180	170	170
Extension	50	45	80	0
Horizontal flexion	135	135	-	80
Horizontal extention	30	30	-	0

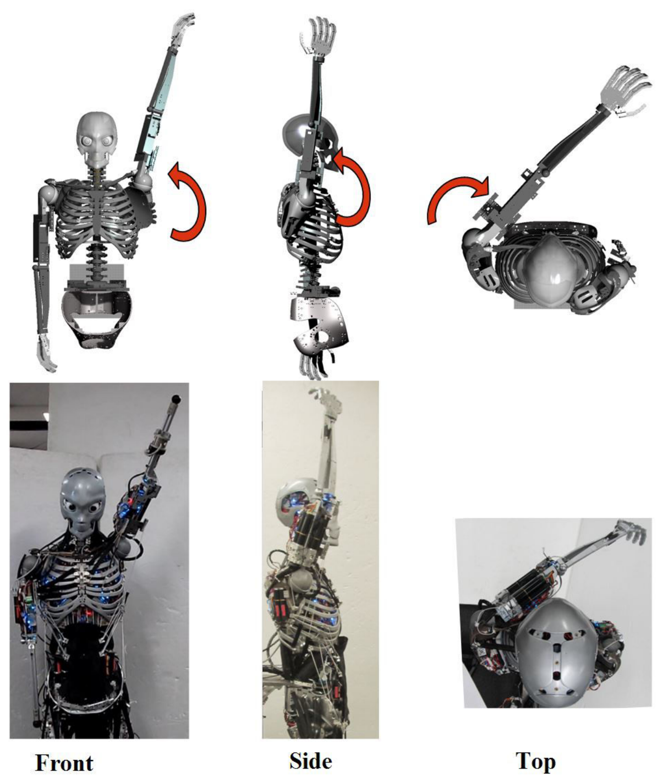

Fig. 11. The CAD and actual photo image showing the range of motion. Kenshiro seen from Front(abduction), side(flexion) and top(horizontal extension).

By mimicking the accurate musculoskelatal structure from human, we believe Kenshiro may have the capability of making motions using body properties such as wide range of motion by multiple joints, antagonist muscles to stiffen or relax joints, elasticity of the muscles, or body weights.

As an example of motion involving some physical properties we carried out an experiment of throwing a ball. With the elastic element in the elbow joint, Kenshiro is expected to store energy by the acceleration of the arm when generating the motion. But as a result this resulted in less distance in

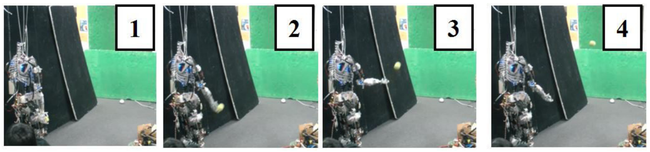

Fig. 12. Under throw pitching motion using 10 DOFs.

throwing the ball. This was caused by the elastic element working as a shock absorber rather than for storing energy as a spring, since distance thrown with elasticity was 2.3[m] while throwing without elastic unit was 2.9[m]. To use the elastic element to accelerate the swing speed of the motion, further research on elements that has influence to the motion must be dealt, such as the mass of each limbs and balls; the elastic constant, the speed of each joints, active levels of antagonist muscles.

Fig.12 shows the throwing motion made by Kenshiro(with elasticity). Fig.13 is the tension data of major muscles during the motion. The accurate duplication of the body structure enables analysis of such movements, for example tension data of wires can be said to have relation with human muscle tensions, and this could lead to indirect measurement of biological data under actual physical environment.

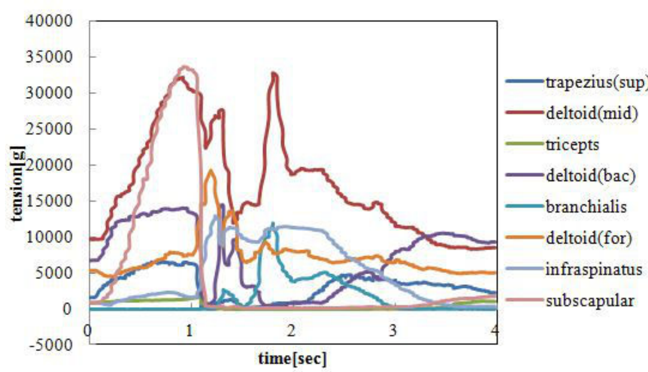

Fig. 13. Tension data of major muscles during throwing motion. By comparing muscles from Fig.2 the activity of the actuator can directly be compared to the human muscles.

V. Conclusion

In this paper we focused on design approach and its mechanical specifications for musculoskeletal upper limb of Kenshiro. The design focus was on realizing the human body structure of muscles winding around the bone adhesively. As a result, Kenshiro upper limb showed the capability of moving in wide range of motion flexibly. The design of accurate bones were achieved by choosing different design techniques respectively. By a ball throwing motion and measuring muscle tension data Kenshiro showed possibility of a robot that can be used for measuring the inner human body information with its high relationship with human body.

As our next challenge, we are interested in making motions involving more body parts such as trunk, or elastic elements to make more dynamic motions. We believe the design of the upper limb of Kenshiro is a progress in developing a musculoskeletal humanoid robot, and we hope to make further experiments with Kenshiro as human motion simulator as a future research.

References

[1] Hugo Gravato Marques, MichaelJ¨ antsc, Steffen Wittmeier, Owen Holland, Cristiano Alessandro, Alan Diamond, Max Lungarella, Rob Knight. Ecce1: the first of a series of anthropomimetic musculoskelal upper torsos. In *IEEE-RAS International Conference on Humanoid Robots*, 2010.

[2] Ravi Balasubramanian and Yoky Matsuoka. Biological stiffness control strategies for the anatomically correct testbed(act) hand. In *In Proceesings of the IEEE International Conference on Robotics and Automation*, pp. 737–742, 2008.

[3] Ryuma Niiyama, Satoshi Nishikawa, and Yasuo Kuniyoshi. Athlete robot with applied human muscle activation patterns for bipedal running. In *Proc. IEEE-RAS Int. Conf. on Humanoid Robots (Humanoids 2010)*, pp. 498–503, Nashville, Tennessee USA, Dec. 2010.

[4] AIST Digital Human Research Center. Aist human proportion database. In *Database*, 2011.

[5] K. Hashimoto, Y. Takezaki, K. Hattori, H. Kondo, T. Takashima, and A. Takanishi. A study of function of foot's medial longitudinal arch using biped humanoid robot. In *Proceedings of the IEEE/RSJ international conference on Intelligent Robots and Systems*, 2010.

[6] Changhyun Chung and Motomu Nakashima. Development of the upper body of an underwater humanoid robot for research of unsteady fluid forces acting on a swimmer. In *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*, pp. 701–706. IEEE, 2012.

[7] I. Mizuuchiand Y. Nakanishi, Y. Sodeyama, Y. Namiki, T. Nishino, N. Muramatsu, J. Urata, K. Hongoand T. Yoshikai, , and M. Inaba. An advanced musculoskeletal humanoid kojiro. In *IEEE-RAS International Conference on Humanoid Robots*, 2007.

[8] Yuto Nakanihs, Tamon Izawa, Masahiko Osada, Nobuyuki Ito, Shigeki Oht, Junichi Urata, and Masayuki Inaba. Development of musculoskeletal humanoid kenzo with mechanical compliance changeable tendons by nonlinear spring unit. In *Proceedings of The 2011 IEEE International Conference on Robotics and Biomimetics -IEEE-ROBIO2011-*, 2011.

[9] Toyotaka Kozuki, Hironori Mizoguchi, Yuki Asano, Masahiko Osada, Takuma Shirai, Urata Junichi, Yuto Nakanishi, Kei Okada, and Masayuki Inaba. Design methodology for the thorax and shoulder of human mimetic musculoskeletal humanoid kenshiro -a thorax structure with rib like surface -. In *Proceedings of the IEEE/RSJ international conference on Intelligent Robots and Systems*, 2012.

[10] Yoshinao Sodeyama, Tamaki Nishino, Yuto Nakanishi, Ikuo Mizuuchi, and Masayuki Inaba. The design and Motion of a Shoulder Structure with a Spherical Thorax, Scapulas and Collarbones for Humanoid "Kojiro". In *IEEE/RSJ International Conference on Intelligent Robot and Systems*, 2008.

[11] Michael Jantsh, Steffen Wittmeier, Konstantinos Dalamagkidis, and Alois Knoll. Computed muscle control for and anthropomimetic elbow joint. In *IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS)*, pp. 2192–2197, 2012.

[12] Shuhei Ikemoto, Fumiya Kannou, and Koh Hosoda. Humanlike shoulder complex for musculoskeletal robot arms. In *IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS)*, pp. 4892–4987, 2012.

[13] Donald A. Neumann. Kinesiology of the musculoskeletal system. In *Ishiyaku Publishers, Inc.*, 2006.

[14] Masahiko.O, Toyotaka Kozuki, Hironori Mizoguchi, Yuki Asano, Yuto Nakanishi, Kei Okada, and Masayuki Inaba. "design of human body trunk with multiple spine structure"and "planar-muscle-dirven sysytem" for achievement of humanlike powerful and lithe motion. In *IEEE Internatonal Conference on Robotics and Biomimetics 2011*, 2011.

[15] Michiki Nakano, Masafumi Okada, and Yoshihiko Nakamura. Design of wire driven ankle mechanism with high backdrivability. In *JSME Robotics and Mechatronics Conference*, 2004.

[16] Masahiko Osada, Nobuyuki ito, Yuto Nakanishi, and Masayuki Inaba. Realization of flexible motion by musculoskeletal humanoid" kojiro" with add-on nonlinear spring units. In *Humanoid Robots (Humanoids), 2010 10th IEEE-RAS International Conference on*, pp. 174–179. IEEE, 2010.