The Development of A New Joint Mechanism Based on Human Shoulder Morphology

Nobuo Sakai, Yoshinori Sawae, Teruo Murakami

Dept. of Intelligent Machinery and Systems
Kyushu University
744 Motooka, Nishi-ku, 819-0395 Fukuoka, Japan
sakai@mech.kyushu-u.ac.jp

***Abstract* – The purpose of this study was to develop a new joint system based on human shoulder mechanism. The human shoulder joint has a ball joint mechanism that is surrounded by a number of muscles and is driven by the balance of those forces. The authors thought that the construction could realize 3 degrees of freedom with compact size and lightweight.**

An anatomical skeletal structure had been introduced to the mechanism, especially on the muscle arrangement. Muscles were replaced by wires and humeral head was altered by a ball joint. The movability of the mechanism was evaluated by the relative ratio of the moment arm to the ball radius produced from the wires that surround the ball joint. Several rearrangements in improvement processes enabled the joint to be driven by 6 wires. Inverse kinematics was solved by artificial neural network (NN) that learned the data sets of arm postures and wire displacements. Additional differential outputs were installed in the NN. The principle of virtual work was applied to drive the joint by a feedback control system in the range of 3 degrees of freedom. The movability and capability of the new joint system was satisfactorily demonstrated in this report.

***Index Terms* – Biomimetics, Shoulder, Musculoskeletal Structure, Artificial Neural Network, Joint Mechanism.**

I. Introduction

In 1899, a physical model of a shoulder joint was constructed using artificial materials by Mollier [1], called "Shoulder Organ." This physical model was manipulated by pressing a keyboard, like playing an organ. In this old model, keys were linked to joint part by wires corresponding to contracting muscles. As for the shoulder joint, many shoulder researches were studied for the application of surgical operation of shoulder reconstruction and for specification of design index of the artificial shoulder joint in medical viewpoints [2][3]. The purpose of this study was to develop a new joint system based on human shoulder morphology, which has a ball joint driven by wires.

The human shoulder joint is constrained by a number of muscles and ligaments, which surround the ball joint, and is driven by the balance of those forces. It was thought that the construction of the human shoulder could realize the motion with 3 degrees of freedom with compact size and lightweight in comparison with an industrial robot arm, which was composed of usual pin joints.

Therefore, the authors thought that the new joint mechanism of the robot arm with 3 degrees of freedom should be realized in shoulder mimetic joint mechanism. The moment arm, which was produced by wires, was examined to evaluate the movability of the new joint mechanism. Inverse kinematics was solved by NN, which learned the data sets of arm posture and wire displacement. The additional differential outputs and the consideration of the theory of virtual work balance were applied to a control system to drive the joint in a feedback control system.

The satisfactory movability and capability of the new joint system of the robot arm based on human shoulder mechanism was demonstrated.

II. The Development of New Joint Mechanism

The main part of the human shoulder joint, which is an endoskeletal structure, consists of a ball joint that articulates the scapula with the humerus, and a number of muscles and ligaments. A simplified schematic drawing of the human shoulder organ from [1] is shown in Fig.1. The balance of muscle forces with antagonism drives the Humeral head in 3 degrees of freedom. In this study, we focused on the ball joint mechanism within the shoulder girdle complex.

The purpose of this study was to develop a physical model of the shoulder mechanism. The model was developed by replacing muscles with corresponding wires shown in Fig. 2. In this process, muscle selection and arrangement was important to simplify the physical model from anatomical structure. In this study, we tried to construct the mechanism from anatomical description of Ref. [4], which was written in the viewpoint of medical insight.

In principal theory, the parallel link mechanism with 3 degrees of freedom is driven by a 4 wire system. The authors thought that a 4 wire model did not permit enough movement to gain an effective motion area. So, this study was conducted to construct 5 and 6 wire models. In this paper, we mainly describe the 6 wire model, because the 5 wire model did not have enough moment arms to drive the specified motion area. The aim of motion range was specified in 1/8 of the sphere surface area and the rotation of long axis of the arm in 90 degrees, as shown in Fig. 3. This motion range is the subset of the motion range of the human glenohumeral joint. The human shoulder complex actually extends the motion range by the cooperating actions of the scapula.

The experimental system shown in Fig.4 consisted of a ball joint unit, pulleys for detecting the wire displacement, a guide plane for measuring and holding a part of the arm, and pulse motors to drive the wires. The arm posture was also detected by a 3-dimensional positioning sensor using an electromagnetic field (Polhemus Incorporated, 3SPACE FASTRAK) in 0.8mmRMS and 0.15degRMS preciseness at 120Hz. The joint portion was composed of an acrylic resin sphere, 50mm in diameter, and a concave polyacetal cup, 51mm in diameter. Flexible stainless steel wires, 0.42mm in diameter, were used for drive wires. The arm, composed of acrylic resin, was 165mm length, 15mm in diameter, and 172g in weight.

As for the evaluation of the movability of the joint system, the instantaneous moment arm around the ball joint was measured by finding the slope of wire excursion against the joint angle, as shown in Fig. 5. This method is useful when the system is complex and a physical model exists [5][6]. The moment arm was normalized to the diameter of the ball joint sphere, so the value of 1 implies a situation such that a specified wire surrounds the most exterior position to the flexing axis. When the normalized

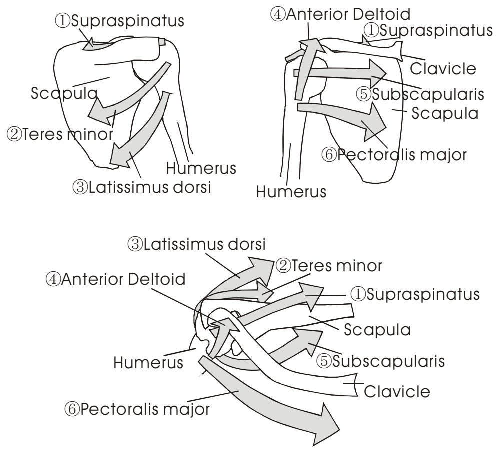

Fig. 1 The Schematic drawing of human shoulder by Kapandji.

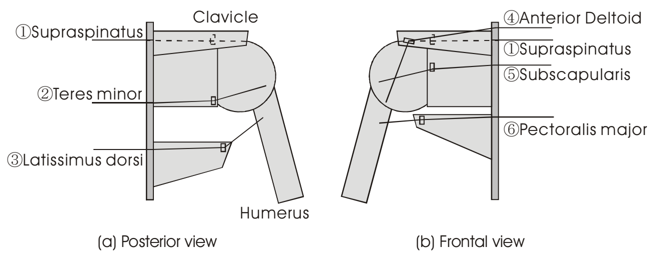

Fig. 2 The joint model based on human shoulder.

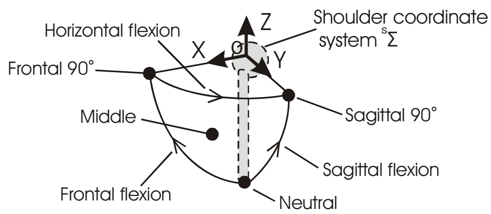

Fig. 3 Specified motion area and definition of motion.

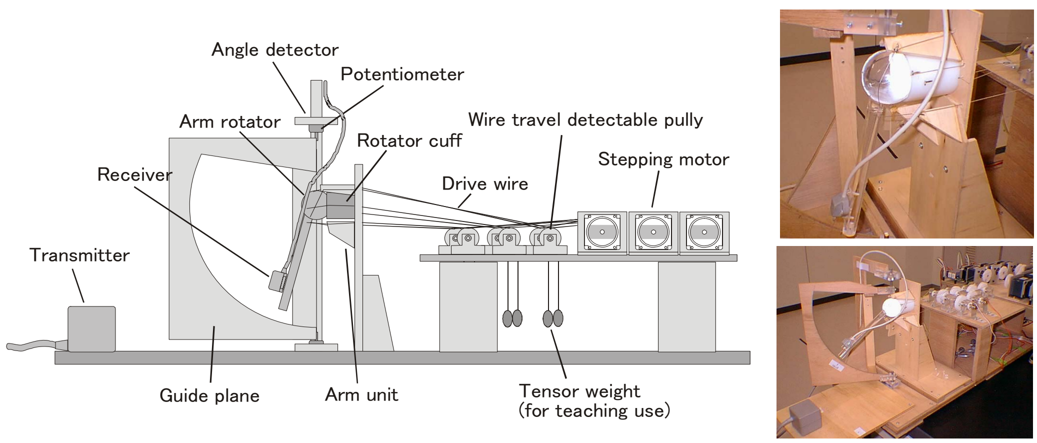

Fig. 4 The schematic drawing and photograph of Experimental model of the new joint mechanism.

moment arm was up to 0.5 in specified motion, we decided that the movability was satisfied to drive the joint mechanism.

Fig. 6 shows example data in the motion of sagittal flexion. The wire representing ④Anterior Deltoid worked to generate the moment arm for sagittal flexion motion. In sagittal extension, ③Latissimus dorsi plays as an antagonistic wire for ④Anterior Deltoid. This result indicated that the moment arm in sagittal plane existed in both flexion and extension motion. While two wires worked in sagittal motion, the moment arm of ⑥Pectralis major generated flexion moment arm until 35deg. After 35deg of the flexion, ⑥Pectralis major produced the moment arm for sagittal extension contrary. This result was consistent with the apparent coordination of the living body of human. As a result of improvement processes, the effective movability was ascertained in a specified movable area in only the 6 wire model.

Each muscle worked in each motion, and each motion was generated by a number of muscles. Table 1 shows which wires were effective in generating each motion. Each motion had effective wires both flexion and extension (or spination and pronation), while each wire worked in several motions. Fig 7 shows the details of the 6 wire model.

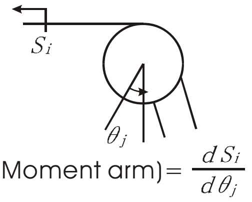

Fig. 5 The method of estimation of moment arm.

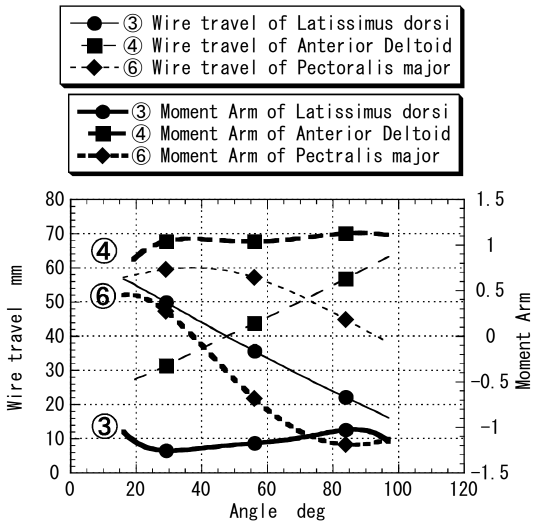

Fig. 6 Evaluation of the motion of the sagittal flexion.

Table 1 The effective index of the wire and its relationship in each motion.
Each marks shows how much moment arm was generated by each wires.
(◎:>0.75, ○:>0.5, △:<0.5, —: 0)

	Frontal		Sagittal		Horizontal		Middle		Neutral		Frontal90		Sagittal90	
	flex.	ext.	flex.	ext.	flex.	ext.	pron.	spin.	pron.	spin.	pron.	spin.	pron.	spin.
①Supraspinatus	◎	—	△	—	—	—	△	—	—	—	○	—	◎	—
②Teres minor	—	—	—	—	—	○	—	◎	—	◎	—	◎	—	◎
③Latissimus dorsi	—	○	—	◎	—	○	—	—	—	—	—	—	—	—
④Anterior Deltoid	○	—	◎	—	○	—	—	—	—	—	—	△	—	—
⑤Subscapularis	△	—	—	—	—	—	◎	—	◎	—	◎	—	○	—
⑥Pectoralis major	—	◎	△	○	◎	—	—	—	—	—	—	—	—	—

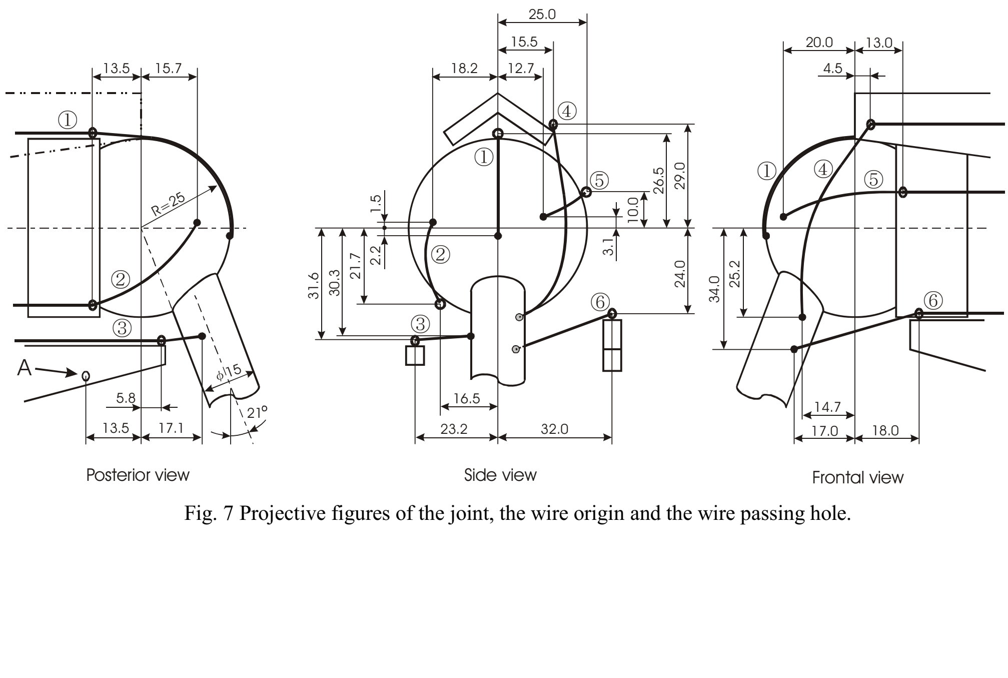

Fig. 7 Projective figures of the joint, the wire origin and the wire passing hole.

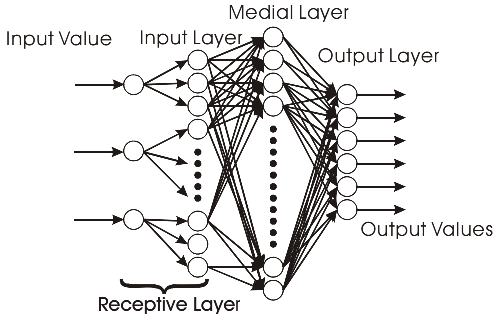

Fig. 8 Artificial Neural Network for learning inverse kinematics.

III. THE METHOD TO CONTROL THE MECHANISM

A study of the inverse kinematics becomes necessary when the joint is driven actually as a robot arm. In the present study, the geometrical inverse kinematics about the relationship between posture and wire excursion in the joint system was learned by NN. The data on the relationship between the postures vs. wire excursions for learning of NN were acquired from experimental physical model directory by detecting wire displacement and arm flexion angle. In the geometric consideration for Parallel Link Mechanism, the system was a complete geometrical constraint type mechanism. So the wire displacements were based only on the posture of the joint when the elastic expansions of wires were not accounted.

NN had to learn inverse kinematics accurately and interpolate the set of data, while NN learns functional relationship without over-learning problems. So, the Receptive Layer was composed for pre-process of the input value in front of NN (Fig. 8). The Receptive Layer enabled both the improvement of the pattern recognition by the binary input and compatibility with the continuity of the analog input. Firstly, the input value θ was normalized. For assigning it to the Input Layer that was described as

$$(x_1, \cdots, x_m, \cdots, x_t, x_{t+1}, \cdots, x_n) \quad \cdots\cdots(1)$$

, the corresponding input position with θ was chosen by using following formula

$$\begin{cases} \tilde{x}_t = \dfrac{t-1}{n-1} \\ \tilde{x}_{t+1} = \dfrac{t}{n-1} \end{cases} \quad \cdots(2)$$

, where the value to the Input Layer was determined by

$$\begin{cases} x_t = (n-1)(\tilde{x}_{t+1} - \theta) \\ x_{t+1} = (n-1)(\theta - \tilde{x}_t) \end{cases} \quad (\tilde{x}_t < \theta < \tilde{x}_{t+1}) \quad \cdots(3)$$
$$x_m = 0 \qquad (\theta : other)$$

For a feedback control, the differential output was calculated by the chain rule principle of differentiation. In receptive layer, the differentials were written in the following equation as

$$\begin{cases} dx_t = -(n-1)d\theta \\ dx_{t+1} = (n-1)d\theta \\ dx_m = 0 \end{cases} \quad \cdots\cdots(4)$$

In internal of NN, the chain rule was also applied continuously as following equations,

$$\begin{aligned} ds1_i &= wt1_{t,i} \cdot dx_t + wt1_{t+1,i} \cdot dx_{t+1} \\ dy1_i &= sigmoid'(s1_i) \cdot ds1_i \\ ds2_j &= \sum wt2_{i,j} \cdot dy1_i \\ dy2_j &= sigmoid'(s2_j) \cdot ds2_i \end{aligned} \quad \cdots\cdots(5)$$

Finally, input differentials and output differentials were clearly connected. This method regenerated differentials by using learned weight data in NN, and extra learning processes were unnecessary. Fig. 9 shows an example of output data of NN in the subscapularis wire in 2-dimensional intersection. Output values were internal values. So, this graph was useful only when we confirmed that differential outputs were correct or not. The differentials were successfully acquired in each direction from this method. Actual NN learned the relationship between 6 wire excursions and 3 input values representing the arm posture. Each output value of wire excursion had 3 differentials for each direction.

When a motion is done successively about a ball joint system, the conjunct rotation called CODMAN'S PARADOX happens. This is the nature in which the arm has 3 degrees of freedom in single joint [7]. So, in considering a center of rotation range about arm long axis, the temporary

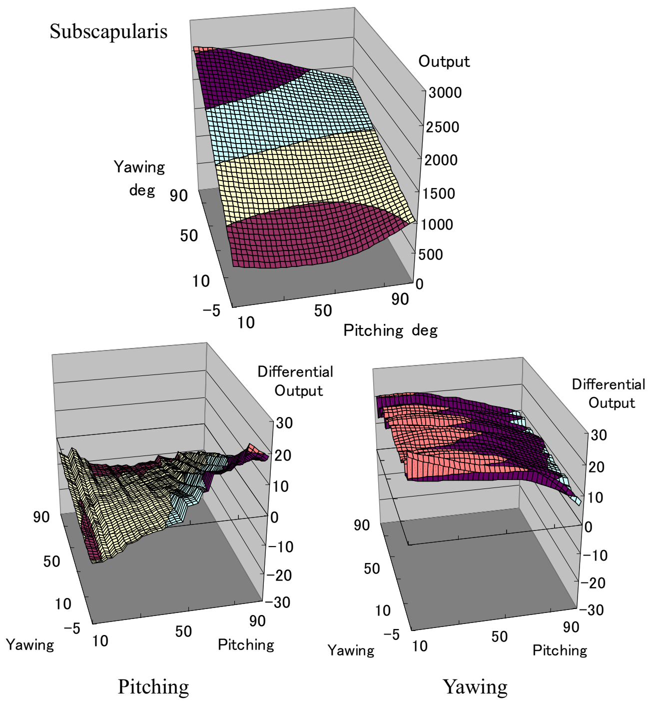

Fig. 9 Output of NN and differentials in each direction.

coordinate system was introduced, which separated a rotation about arm long axis from an arm position.

The additional differential outputs installed in learned NN and the consideration of a theory of virtual work balance were introduced to apply a force control method to the joint. We utilized pulse motors to drive wires. So, wire tensions were produced by extra driving from initial wire length of theoretical one in geometrically constraint mechanism. Approximate length of each wire was measured in advance to produce each wire tensions correctly. Tension control ability was confirmed in another experiment, but wire tensions were not monitored in this joint system.

Arm posture was monitored by a 3-dimensional positioning sensor for feedback control. The method enabled to compensate a displacement for gravity forces, and a common task coordinate feedback could be applied to control the arm trajectory in the range of 3 degrees of freedom. Redundancy problem of wire numbers were solved as follows. Each wire was concerned in each motions (Table 1). In fig. 5, differential output of NN was equal to moment arm itself. In this paper, we controlled wire tensions to produce the tensional distribution in proportional to 3rd power of moment arm of each wire.

IV. Experimental Result

The driving experiment was conducted in the actual machine to confirm movability as a robot arm joint mechanism. The experimental trajectory of circle pathway of the arm end point was applied in a period of T=10s. Fig. 10-12 show the experimental results. Fig. 10 shows the result of open loop. The arm trajectory was displaced in the direction of gravitational force because of the stretching of wires. Fig. 11 shows the effect of the compensation only for gravitational force. In fig. 11, it was considered that the displacement was mainly caused by the friction of wire pathways, occurring particularly when the direction of the motion was changed extremely. The result in applying the control method both gravity compensation and positioning control was shown in Fig. 12. The performance of follow-up ability to the destination trajectory was quite improved in feedback control. This joint mechanism moves about 3 degrees of freedom. Therefore, a powder can be scooped up with a spoon, and moved in another cup by the single joint, as shown in Fig. 13.

V. Discussion

The experimental driving test of a new joint mechanism based on human shoulder morphology was shown in this paper. The joint mechanism could be controlled in the

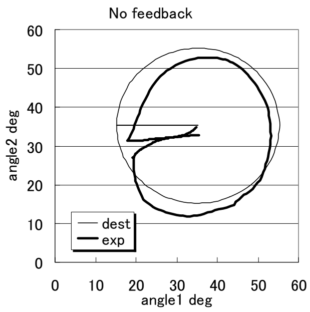

Fig. 10 Trajectory of arm **without** feedback and gravity compensation.

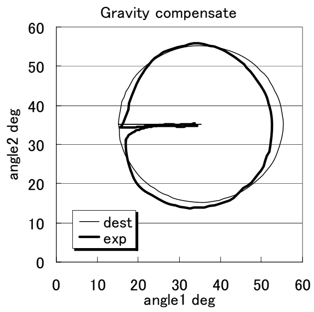

Fig. 11 Trajectory of arm with gravity compensation without feedback.

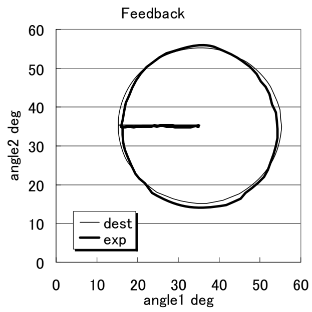

Fig. 12 Trajectory of arm **with** feedback and gravity compensation.

Fig. 13 Photograph of the task in which the powder was scooped up with the spoon, and moved to another cup.

motion of 3 degrees of freedom by the cooperative driving of wires. However, we must study further to determine the optimal wire arrangement. If the aim of the design was to mimic the human shoulder morphology, the objective function of the optimal processes was arbitrarily configured to form a similar shape to the human shoulder. The nature of the problem might be found where the human shoulder was truly optimal. This problem is beyond the scope of this paper in the standpoint of present development.

We realized that this report was one in a series of our study. One of our interests is to find rationality and reasonability of shoulder joint mechanism, which should be utilized in the field of clinical applications. To study these problems, authors are now attempting to describe another computer model including mobile wire pathway by numerical formula expression.

Another notable problem was selection of materials related to each part and function, which was mainly concentrated in the problem of friction. The articulation of cup and ball had to sustain all forces of wire tensions to drive the joint. The same problem concerning friction was found in the wire passing hole and wire bending parts. We thought that it was important problem to actually construct the biomimetic articular joint, because the anatomical joint employs the forces by surface articulation in contrast to pin joint, which is commonly used in a robot arm joint mechanism. Synovial joints of the human body realize extreme low friction (μ <0.01) and endurance [8]. Therefore, we scheduled to apply materials with improved friction and wear, e.g. UHMWPE (Ultra High Molecular Weight Polyethylene), for the articulation.

VI. CONCLUSION

In this study, we proposed a new joint mechanism based on human shoulder morphology. The movability of the joint was evaluated by estimating the moment arm produced by wires around a ball joint. The Inverse kinematics was learned by NN, and the joint mechanism was driven by a feedback control system in the range of 3 degrees of freedom. Thus, the movability and capability of the new joint system of a robot arm based on human shoulder mechanism was satisfactorily demonstrated in this paper.

REFERENCES

[1] van der Helm, F. C. T., "A finite musculoskeletal model of the shoulder mechanism", *J. Biomechanics*, 27, 551-569, 1994.

[2] Karlsson, D. and Peterson, B., "Towards a model for force prediction in the human shoulder", *J. Biomechanics*, 25, 189-199, 1992.

[3] Novotny, J. E., Beynnon, B. D., Nichols, C. E., "Modeling the stability of the human glenohumeral joint during external rotation", *J. Biomechanics*, 33, 345-354, 2000.

[4] Kapandji, I. A., "The phisiology of the joint", Churchill livingstone, 1982.

[5] An, K. N., Takahashi, K., Harrigan, T. P., Chao, E. Y., "Determination of muscle orientation and moment arms", *Trans. ASME J. Biomech. Eng.*, 106, 280-282, 1984.

[6] Hughes, R. E., Niebur, G., Liu, J., An, K. N., "Comparison of two methods for computing abduction moment arm s of the rotator cuff", *J. Biomechanics*, 31, 157-160, 1998.

[7] Grood, E. S., Suntay, W. J., "Comment on justification of triaxial goniometer for the measureing of joint rotation", *J. Biomechanics*, 14, 653-655, 1980.

[8] Teruo, M. "The lubrication in natural synovial joints and joint prosthesis", JSME Int. J. Ser. III, 33, 465-474, 1990.