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Shoulder Mechanism Design of an Exoskeleton Robot for Stroke Patient Rehabilitation

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Abstract—**Shoulder girdle movement is critical for stabilizing and orientating the arm during daily activities. During robotic arm rehabilitation with stroke patients, the robot must assist movements of the shoulder girdle. Shoulder girdle movement is characterized by a highly nonlinear function of the humeral orientation, which is different for each person. Hence it is improper to use pre-calculated shoulder girdle movement. If an exoskeleton robot cannot mimic the patient's shoulder girdle movement well, the robot axes will not coincide with the patient's, which brings reduced range of motion (ROM) and discomfort to the patients. A number of exoskeleton robots have been developed to assist shoulder girdle movement. The shoulder mechanism of these robots, along with the advantages and disadvantages, are introduced. In this paper, a novel shoulder mechanism design of exoskeleton robot is proposed, which can fully mimic the patient's shoulder girdle movement in real time.**

***Keywords-** Exoskeleton, Rehabilitation Robot, Arm Rehabilitation, Shoulder Girdle, Shoulder Complex, Shoulder Mechanism*

I. INTRODUCTION

The aim of the stroke patient rehabilitation is to recover a motor function to perform activities of daily life. Conventional therapeutic exercises are performed directly by the therapist to move the patient's body; however, this costs a lot of labor and money. Recently, to meet the intensive, repetitive, and task-oriented training, a number of robots were developed that can provide continuous training and quantitative measures [1].

Arm rehabilitation robots can be divided into the end-effector type and the exoskeleton type. End-effector type robot has contact with patient's hands or forearm. Some examples are the MIT-MANUS [2], the ARM Guide [3], and the REHAROB [4]. On the other hand, the exoskeleton type robot resembles the human anatomy to mimic the human movement. Some examples are the CADEN7 [5], the RUPERT [6], the MGA Exoskeleton [7,8], the ARMin [9,10], the IntelliArm [11], and the MEDARM [12,13]. Although it has a more complicated structure, this type of robots has many advantages as it can provide training and measurements for each joint with larger workspace.

In the exoskeleton type, the robot's rotation axes must be aligned with the patient's anatomical rotation axes. The early versions of the arm rehabilitation robot used ball and socket joint which provided only 3 degrees of freedom (DOF) because the human shoulder was considered to consist just of the glenohumeral joint.

However, the center of glenohumeral joint (CGH) shifts according to different humerus orientations which is caused by shoulder girdle movements. Therefore, shoulder girdle movement must be considered in the kinematics of the robot shoulder mechanism. Without such consideration, misalignment between the robot and patient's shoulder rotation axes will result in not only limited workspace for rehabilitation but also discomfort to the patients [14]. To account for these problems, recently, robots have been developed considering the shoulder girdle movements; however, the shoulder mechanism of these robots have some problems in mimicking shoulder girdle movements and reduced range of motion (ROM) for rehabilitation. This paper proposes a novel shoulder mechanism of an exoskeleton robot for stroke patient arm rehabilitation.

The paper is organized as follows. Section II describes the anatomical structure and movement of shoulder complex that consists of shoulder and shoulder girdle. Section III describes shoulder mechanism of exoskeleton robots of previous research. Then a novel shoulder mechanism is proposed in Section IV. The final section provides a comparison with previous research and the conclusion.

II. BIOMECHANICAL PROPERTIES OF THE SHOULDER COMPLEX

A. Structure of the shoulder complex

The shoulder complex consists of the shoulder and the shoulder girdle. The shoulder girdle comprises of the sternoclavicular joint (SC), the acromioclavicular joint (AC), and the scapulothoracic joint (ST) (fig. 1). The sternoclavicular and the acromioclavicular joints have 3 DOF for each while the scapulothoracic joint has 5 DOF. The movement of these three joints shifts the center of glenohumeral joint (CGH) [15]. Because these three joints make a closed kinematic chain, each

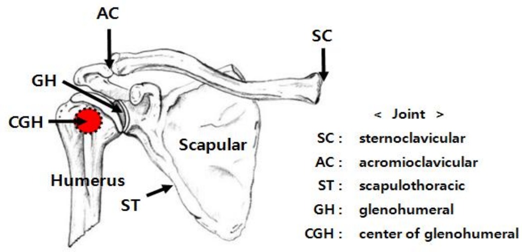


Figure 1. Structure of the shoulder complex

joint cannot move independently. So the real physical therapy on the shoulder girdle is performed by moving the humerus which consequently leads to shoulder girdle movement. If the exoskeleton robot can describe humerus orientation (3 DOF) as well as the central position of the glenohumeral joint (3 DOF), it can also perform training like physical therapists do.

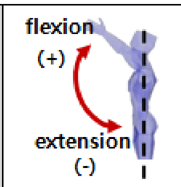
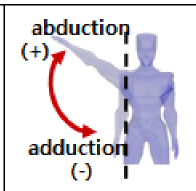
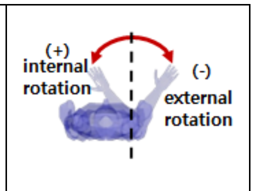
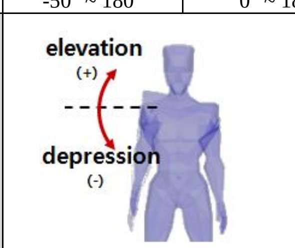
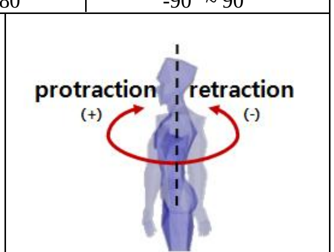
B. *Movements of the shoulder complex*

The movements of the shoulder complex are as described below table I. The ROM of each motion differs from each book and author, so we will use the commonly used value [16,17,18]. Shoulder joint commonly means glenohumeral joint; it takes 3 DOF. So we can describe it with 3 DOF ball and socket joint for shoulder movements. Shoulder girdle has four movements, but only elevation/depression, and protraction/retraction are dominant so these two pairs are sufficient to describe movements effectively [13].

C. *Scapulohumeral rhythm*

The movement of the humerus causes the scapular to move also; this joint movement is called scapulohumeral rhythm (fig. 2). When the humerus is fully flexed (180°) or abducted, the real upward rotation angle of the humerus will be 120° while the remaining 60° is flexed by the help of the scapular. This means that the humerus versus scapular movement ratio is approximately 2:1 [18]. However, this ratio becomes highly nonlinear, ranging between 0.71~7.29, when the humerus moves[19].

TABLE I. MOVEMENTS OF THE SHOULDER COMPLEX

SHOULDER			
ROM	-50° ~ 180°	0° ~ 180°	-90° ~ 90°
SHOULDER GIRDLE			
ROM	-10° ~ 20°	-20° ~ 20°	

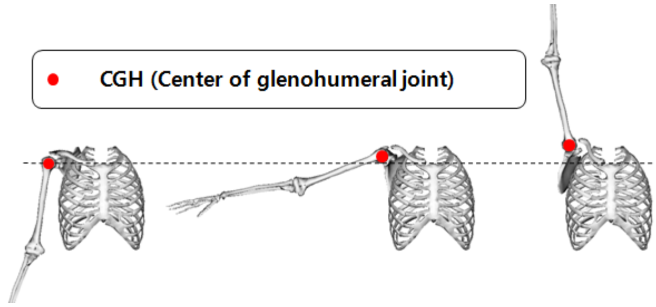


Figure 2. Scapulohumeral rhythm

Scapulohumeral rhythm also changes with different planes of humeral elevation [20] (fig. 3-a,b), The rhythm is different when there is a difference between the angle of shoulder's internal or external rotation [21] (fig. 3-c,d). Furthermore these properties differ from person to person so we need to sense this movement in real time.

D. *Importance of implementing shoulder girdle movements in exoskeleton robot.*

If the exoskeleton robot's shoulder is modeled with only 3 DOF ball and socket joint, there will be a misalignment between the robot and the patient's rotation axis due to the change of the CGH. This misalignment causes discomfort to the patients during rehabilitation and leads to reduced workspace for rehabilitation. If the robot moves excessively despite the misalignment, patients might get hurt with a joint glide. Hence the implementation of the shoulder girdle mechanism in the exoskeleton robot will provide the patients more workspace for and comfort during rehabilitation.

Stroke patients cannot perform shoulder girdle movement by themselves due to neurological disorder, ankylosis or some other aftereffects of stroke. So it is essential that the robot assists the patient's shoulder girdle movement with an actuator. During the rehabilitation process, patients tend to compensate the difficulty to move the shoulder girdle with movement of the trunk which reduces the effectiveness of rehabilitation. Hence it is essential to strap the patient's body to limit compensatory movement and induce increased use of the shoulder girdle. This is the reason why joint axes misalignments in shoulder between robot and patients cannot be compensated by the trunk movement. To align joint axes between the robot and the patients, the robot must follow the change of the CGH caused by shoulder girdle movement.

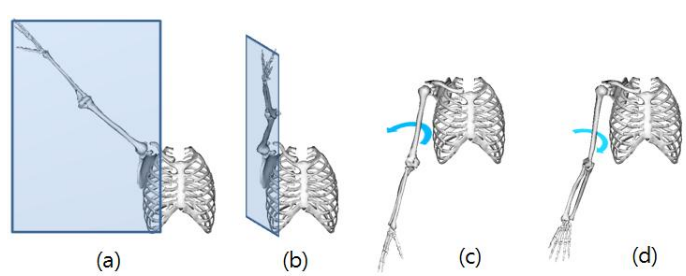


Figure 3. (a) Shoulder abduction (b) Shoulder flexion (c) Shoulder internal rotation (d) Shoulder external rotation

III. PREVIOUS RESEARCH

At the early stages of research about exoskeleton robot for arm rehabilitation, same shoulder mechanism by three serially connected revolute joint was commonly utilized. Recent research proposes different shoulder mechanisms which accounts for shoulder girdle movements. This section introduces the mechanism of each robot's shoulder actuation mechanism. The symbols and abbreviations used in this section are as shown in the following figure (fig. 4). Ball and socket joint is equivalent to serially connected three revolute joints.

A. MGA Exoskeleton

The MGA (Maryland-Georgetown-Army) exoskeleton [7] is one of the first approaches to take shoulder girdle movement into consideration. This robot only considers a movement of the shoulder girdle elevation and depression by using one revolute joint that is connected to the ball and socket joint for shoulder movement (fig. 5). Use of only 1 DOF for shoulder girdle causes misalignment between the robot and the patient rotation axis.

B. ARMin III

The ARMin III [9] also proposed a shoulder mechanism that considered only the movement of shoulder girdle elevation or depression. This mechanism uses misalignment between the robot and patient’s shoulder elevation axis to allow the CGH to make circular path similar to the real CGH motion (fig. 6). The advantage of this mechanism is that it does not require extra actuators for aligning; However, it has its weaknesses as it cannot allow independent shoulder girdle movement in order to reduce synergy pattern due to the absence of extra actuators.

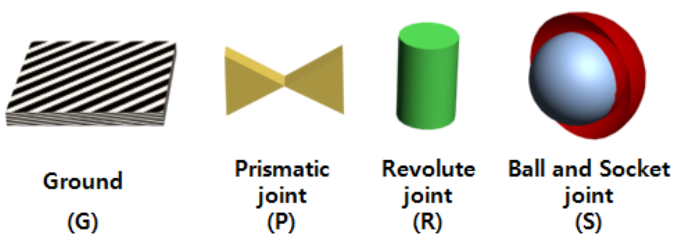


Figure 4. Symbol description

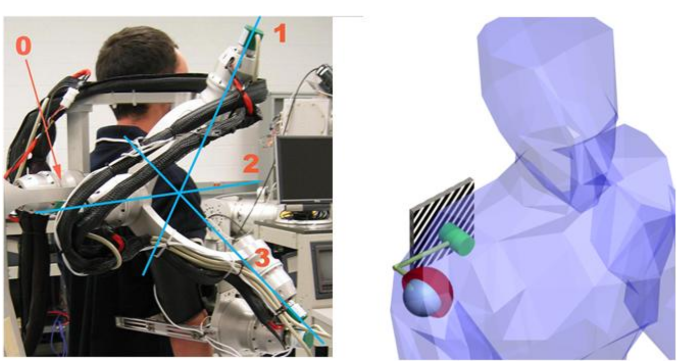


Figure 5. Shoulder mechanism of the MGA exoskeleton (RRRR) left figure is shown in [8]

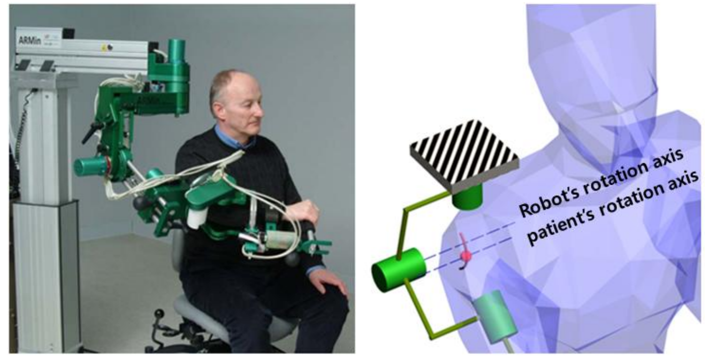


Figure 6. Shoulder mechanism of the ARMin III (RRR) left figure is shown in [10]

C. IntelliArm

The IntelliArm [11] uses 3 DOF for aligning changes of the CGH (fig 7.). Two DOF are passive joints while the remaining DOF is motorized actively. The two passive joints are implemented as linear guide to align horizontal displacement of the CGH with respect to the ground plane. On the other hand the active joint is used to align vertical displacement of the CGH through the linear actuator. Therefore it can assist patients’ shoulder girdle elevation/depression. The IntelliArm can align the CGH exactly because it possesses 3 DOF for adjusting the CGH position. This makes it possible to align the rotation axes between the robot and the patients’ shoulder wherever the CGH might be positioned. Nonetheless since there is only one active joint, the robot cannot provide assistance for patients to practice shoulder girdle protraction /retraction.

D. MEDARM

The MEDARM (Motorized Exoskeleton Device for Advanced Rehabilitation of Motor function) [12] uses 2 DOF for shoulder girdle elevation/depression, and protraction /retraction. The 2 DOF are both actively motorized to assist patient’s shoulder girdle movement which is implemented by two revolute joints intersecting at the sternoclavicular joint (fig. 8). However, misalignment occurs because this mechanism assumes the path of CGH to be a circular motion at the sternoclaviular joint.

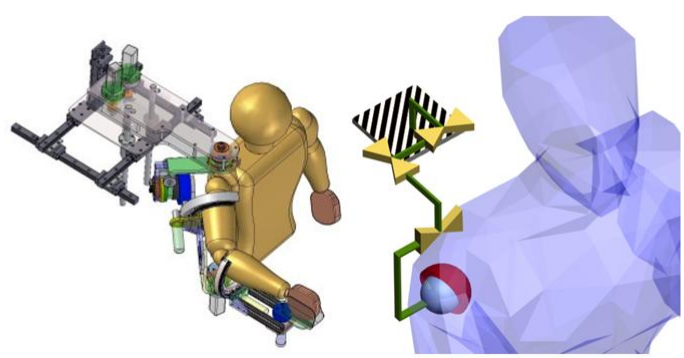


Figure 7. Shoulder mechanism of the IntelliArm (PPPRRR) left figure is shown in [11]

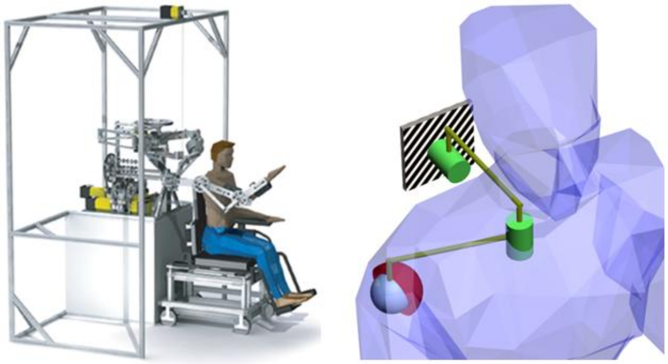


Figure 8. Shoulder mechanism of MEDARM (RRRRR) left figure is shown in [12]

Figure 10. The component which causes humerus elevation constraint

IV. Proposed Shoulder Mechanism

A. *Kinematics of proposed shoulder mechanism*

Proposed shoulder mechanism uses 6 DOF like the IntelliArm. 3 DOF for the shoulder girdle movement, and another 3 DOF for the shoulder movement that are conventionally implemented through the ball and socket joint. Use of 6 DOF allows the alignment of CGH position and the orientation of humerus.

Fig. 9-a is one of the examples that uses 6 DOF for its shoulder mechanism. This mechanism kinematics can be expressed by RPPS (Revolute-Prismatic-Prismatic-Spherical). It can also be expressed by RPPRRR because the spherical joint can be decomposed as three revolute joints that are serially connected.

Most existing robot's ROM and workspace are insufficient for rehabilitation due to collision of their components with each other (fig. 10). To solve these problems, the proposed mechanism changes the sequence of the joints from RPPRRR to RPRPRR (fig. 9-b and fig. 11). Changes of the sequence do not affect the ability of the original mechanism because the axis of the second prismatic joint from the ground coincides with the axis of the second revolute joint. Consequently it preserves the ball and socket joint with the last three revolute joints. Due to the stroke length of second prismatic joint, the collision components are farther apart from each other.

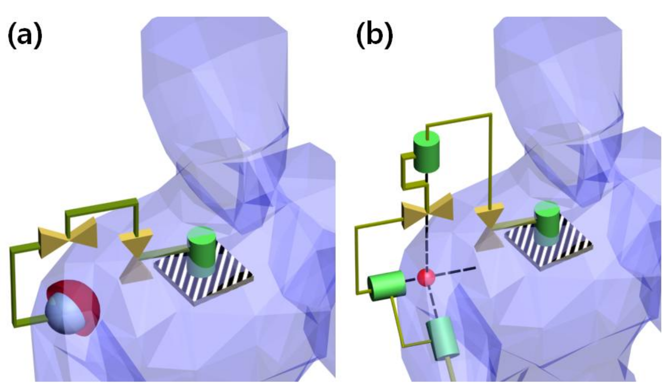


Figure 9. Proposed shoulder mechanism

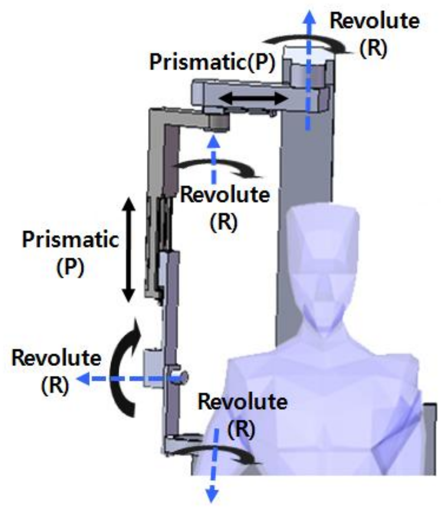


Figure 11. Proposed RPRPRR shoulder mechanism

B. *The advantages of the proposed shoulder mechanism*

The proposed mechanism can provide advantages as follows.

1) Provide accurate alignment between the robot and the patient's rotation axes.

It is impossible to predict the CGH movement as introduced in section II. Therefore the robot must align the CGH in real time. The proposed mechanism can provide accurate alignment in real time in the following manner.

Consider a situation where a patient moves his humerus which changes the CGH position from point 1 to point 2 (fig. 12-a). This means that there is force acting from point 1 to point 2. This force can be decomposed into three orthogonal forces F1, F2, and F3 (fig. 12-b). F1 and F3 are both sensed by 6 axis F/T sensor at the robot's shoulder. This mechanism does not require any additional sensors because it is using a redundant 2 force axes of conventionally used sensor at the shoulder (fig. 12-c). If F1 force is sensed, the linear actuator compensates for vertical displacement of the CGH position until no longer sensed. Also when F3 is sensed, protraction/retraction actuator operates until it is no longer sensed. Differing from other forces, F2 freely slides via the linear guide (fig. 12-c). This mechanism also holds for any CGH position changes by shoulder girdle movement or shoulder movement caused by scapulohumeral rhythm.

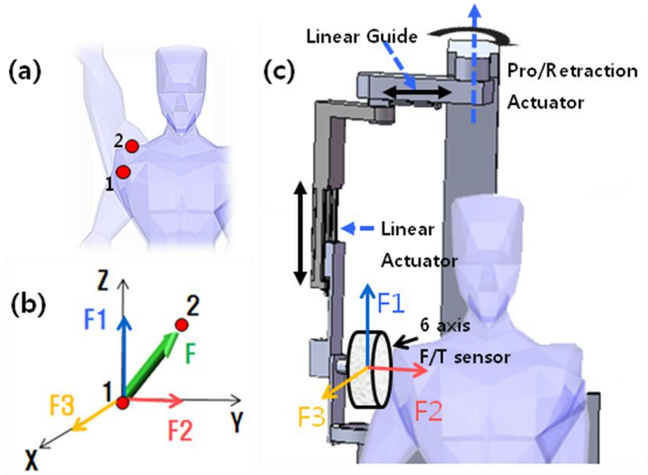


Figure 12. Procedure of aligning the CGH

2) Assist for shoulder girdle protraction/retraction.

Patients with stroke cannot perform shoulder girdle movements by themselves. Therefore the rehabilitation robot needs to actively assist the shoulder girdle movement by employing actuators. The proposed mechanism uses two actuators for shoulder girdle elevation/depression and protraction/retraction to assist patients. Since the two actuators can operate regardless of the scapulohumeral rhythm, simple shoulder girdle movements such as shrugging shoulders can be carried out to enhance recovery synergy after stroke attacks.

3) Increase workspace for rehabilitation

The robots introduced in section III cannot provide sufficient workspace for rehabilitation due to collision of some components with each other. The proposed mechanism can provide humerus elevation of about 170 degrees while that introduced in section III can provide less than 147 degrees (fig. 13). Also the proposed mechanism can mimic natural motion of human shoulders through accurate alignment of the CGH, allowing patients to perform a full range of motions with comfort. In addition, it can enhance the recovery process by performing stretching and many ADL (Activities of daily livings) training.

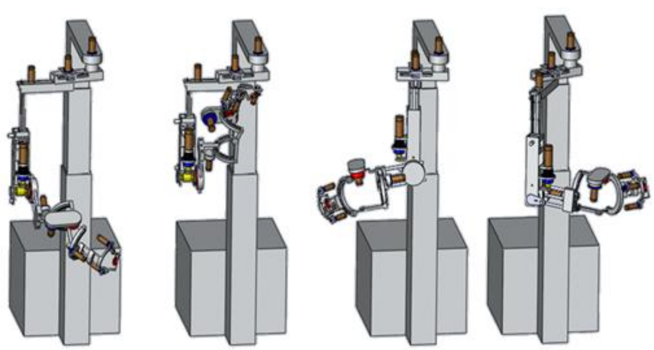


Figure 13. Rehabilitation workspace of proposed shoulder mechanism

4) Ease using both arms.

The robot that employs the proposed mechanism can be used for both arms just by rotating the protraction/retraction actuator by 180 degrees, because it has a symmetric structure with respect to the sagittal plane (fig. 14). In order to be used for both arms, the robot requires that each component is symmetric.

5) Does not require additional adjusment.

The exoskeleton type rehabilitation robot must have the ability to adjust to various patients who have different arm lengths and joint characteristics. The adjustment process is very cumbersome and time-consuming work for therapists. While the mechanisms introduced in section III need additional adjustment for different shoulder girdle characteristics (fig. 15), the proposed mechanism does not require additional adjustment because it uses linear guide to slide freely when patients wear the robot.

V. Conclusion

This paper introduces an existing shoulder mechanism that takes shoulder girdle movement into consideration. The proposed mechanism combines the advantages of the IntelliArm and the MEDARM, which are their abilities to align and assist for shoulder girdle movement. Also it creates the benefit of increased workspace for rehabilitation. The comparison results are in table II. Although the manufacture of the proposed mechanism is difficult due to its structural high complexity and the need of more actuator than others, we expect that it would give more effective rehabilitation with many advantages.

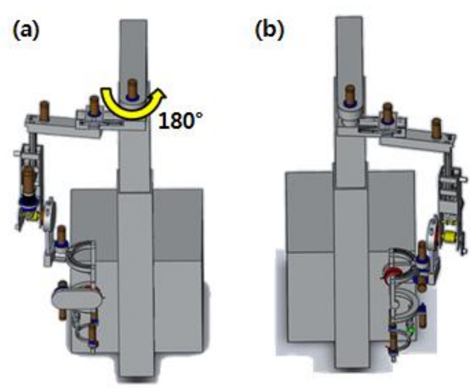


Figure 14. Two postures for arm rehabilitation

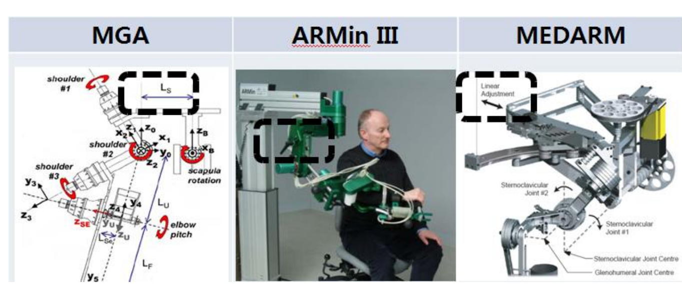


Figure 15. Adjustment part of existing robots

TABLE II. SHOULDER MECHANISM COMPARISON OF PROPOSED WITH EXISTING ROBOTS

	MGA	*ARMinIII*	*IntelliArm*	*MEDARM*	*Proposed*
Actuators	4	3	4	5	5
Mechanism	RRRR	RRR	PPPRRR	RRRRR	RPRPRR
Align CGH	Inaccurate	Inaccurate	Accurate	Inaccurate	Accurate
Maximum humerus elevation	147°	125°	110°	-	170°
Shoulder girdle assist	E	E	E	E, P	E, P
Availability for both arms	X	O	O	X	O
Number of adjustment	1	1	0	1	0

E : elevation/depression

P : protraction/retraction

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