A New Approach for Human Forearm Motion Assist by Actuated Artificial Joint – An Inner Skeleton Robot*

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Abstract

In order to help the physical activities of the elderly or physically disabled persons, we propose a new concept of a power-assist inner skeleton robot (i.e., actuated artificial joint) that is supposed to assist the human daily life motion from inside of the human body. This paper presents an implantable 2 degree of freedom (DOF) inner skeleton robot that is designed to assist human elbow flexion-extension motion and forearm supination-pronation motion for daily life activities. We have developed a prototype of the inner skeleton robot that is supposed to assist the motion from inside of the body and act as an actuated artificial joint. The proposed system is controlled based on the activation patterns of the electromyogram (EMG) signals of the user's muscles by applying fuzzy-neuro control method. A joint actuator with angular position sensor is designed for the inner skeleton robot and a T-Mechanism is proposed to keep the bone arrangement similar to the normal human articulation after the elbow arthroplasty. The effectiveness of the proposed system has been evaluated by experiment.

Key words: Power Assist, Inner Skeleton Robot, Artificial Joint, Human Motion, EMG

1. Introduction

With each passing year, a decrease in birth rate and increase of aging society lead the robotics researchers towards the development of new technology for the elderly persons to help their activities in daily life. In the field of welfare, much research has been carried out for the elderly and physically disabled people who lost their original body function in order to support their motion, or to make up their lost function ⁽¹⁾⁻⁽⁹⁾. We have been developing power assist exoskeleton robots to assist the motion of the physically weak persons for the purpose of rehabilitation and daily use ⁽³⁾⁻⁽⁵⁾. Electromyogram (EMG) signals of human muscles which directly reflect the motion intention of human subject have been used as the main input information for the control of the exoskeleton robot, prosthetic devices, and robotic rehabilitation devices ^{(1)-(5),(8)-(9)}. Moreover, the force caused by the motion difference between the user limb and worn robotic exoskeleton or some form of mechanical control (switches, cables, etc.) are also used in lieu of, or in addition with EMG signals to control the motion assist robotic system ^{(3),(5),(7)}. Despite the numerous advantages offered by the exoskeleton robot, it is inconvenient in certain daily life activities like during taking shower or bath. Usually, EMG signals on the surface of the skin are measured by surface electrodes to control the exoskeleton robot. Surface EMG signals are easier to measure than intramuscular EMG signals as it does not require any skin puncture. However, the

estimation of human motion intention using the surface EMG signals is more difficult than that using the intramuscular EMG signals ⁽¹⁰⁾. Moreover, it is sometimes difficult to pick up the EMG signals from some deep muscles using the surface electrode as several muscles are overlapped in a limited space inside of the human limb ⁽¹⁾.

To alleviate the inconveniency possessed by the exoskeleton robot and the surface EMG signals as a controller input information for the exoskeleton robot, we propose a new concept of a power-assist inner skeleton robot. In this paper, we describe a first generation prototype of an implantable 2 DOF inner skeleton robot that is designed to assist the elbow flexion-extension motion and forearm supination-pronation motion. The proposed inner skeleton robot is supposed to assist the human forearm motion from inside of the human arm and acts like an actuated artificial elbow joint. The artificial elbow joint (i.e., elbow prosthesis) is used in elbow joint replacement surgery or elbow arthroplasty to get relief the patients from arthritis pain in addition with restoring joint function and stability ^{(11),(12)}. The ultimate goal of this research work is to incorporate actuator with the elbow prosthesis, so that robotized actuator can serve as elbow prosthesis and assists the motion from inside of the body.

In order to realize the natural motion assist from inside of the body, our approach is to design the inner skeleton robot that can imitate the functions provided by the normal human articulation. Human elbow complex provides two DOF with specific range of motion and the specific shape of the bony surfaces which form the articulations, keep the movement within the normal range. The inner skeleton motion assist can be realized by replacing the bony surfaces of an articulation with the stator and rotor of an implantable joint actuator that is designed based on the shape and range of motion of that articulation. Although there are many available actuation technologies used in HRI (Human Robot Interaction) robot design ⁽¹³⁾, inner skeleton motion assist is difficult to accomplish by using a conventional actuator. Numerous actuation technologies especially traditional rotary electric motor is used in upper limb power assist exoskeleton robot, prosthetic arm and biologically inspired humanoid robot arm to generate human-like specific range of arm motions. In recent years, a number of actuators capable of generating multi DOF motion have also been proposed for robot manipulators ⁽¹⁴⁾⁻⁽¹⁶⁾. However, the implantable joint actuator has not existed yet. In this study, a prototype of implantable joint actuator, an angular position sensor, and a T-mechanism have been developed to make the proposed inner skeleton robot. The principle mechanism of the joint actuator is similar to that of the switched reluctance actuator. The range of motion and, the stator and rotor of the actuator have been designed according to the human joint motion. Traditional DC motor consists of complex mechanical structure and includes permanent magnet or windings on the rotor. The designed joint actuator provides simple structure and complete absence of permanent magnet or windings on the rotor makes it inexpensive and suitable to implant inside of the body. The piezoelectric ultrasonic actuators are also claimed to be lighter, more compact and larger generating torque than the conventional electromagnetic actuators, but they could not gain wide acceptance due to their high cost and the necessity of high amount of voltage at ultrasound frequencies. Furthermore, the movable part of the ultrasound actuator becomes locked when the power is turned off. Since the joint actuator does not provide complete rotary motion and, its stator and rotor are supposed to attach with the bony surface of the articulation, it is inconvenient to use a conventional position sensor to determine the rotor position for angular feedback to control the actuator. As a result, a contact type potentiometric angular position sensor has been designed for the semicircular joint actuator. In normal human elbow complex, the radius and ulna bone of the human forearm are parallel to each other during supination motion and the radius bone rotates and crosses over the ulna bone during pronation motion ⁽¹⁷⁾. To keep the similar bone arrangement after the elbow arthroplasty, we introduce a T-mechanism for the proposed inner skeleton robot. The intramuscular EMG signals can be

used as the control input signals for the inner skeleton robot to realize the natural motion assist. Since the estimation of motion intention using the intramuscular EMG signals is easier than that using the surface EMG signals, better control performance can be expected by the inner skeleton robot than the exoskeleton robot. A fuzzy-neuro control method has been used to control the inner skeleton robot which enables the cooperative motion of the human elbow and forearm motion ⁽⁵⁾. The proposed 2 DOF inner skeleton robot can be expected to be an artificial elbow joint for future generation.

2. Inner Skeleton Robot

Human elbow complex is formed by three bones, the humerus of the upper arm and the radius and ulna of the forearm, and includes the elbow joint and radioulnar joint. The elbow joint is a complex hinge joint that permits elbow flexion-extension motion and involving the humeroradial joint, between the humerus and radius, and the humeroulnar joint, between the humerus and ulna. The radioulnar joint is formed between radius and ulna, and permits forearm supination-pronation motion. The elbow complex is shown in Fig. 1, and when considered as an entirety, it provides two DOF, elbow flexion-extension and forearm supination-pronation motion ⁽¹⁷⁾.

Fig. 1 Human Elbow Complex.

The schematic diagram of the proposed 2 DOF inner skeleton robot to assist the elbow complex motions from inside of the human arm is shown in Fig. 2. This robot consists of an elbow actuator to assist flexion-extension motion, a forearm actuator to assist supination-pronation motion, and a T-mechanism. It is essential in prosthesis design to keep the limb motion similar to the normal human limb after the arthroplasty. In normal human elbow complex, the radius bone of the human forearm rotates and crosses over the ulna bone during pronation motion whereas during supination motion they lie just about parallel in position. A schematic diagram of the radius and ulna bone during supination-pronation motion is shown in Fig. 3. In order to keep the similar bone arrangement in inner skeleton robot, the T-mechanism is proposed in this study. The T-mechanism, which consists of the elbow actuator rotor, two ball joints, radius and ulna stem, radius and ulna bone, T-link and the rotor of the forearm actuator, is designed to directly transmit the assist power from the forearm actuator to the radius and ulna bone and also to cross the radius bone over the ulna bone like normal human elbow complex. In the proposed system, the stator of the elbow actuator is implanted on the distal part of the humerus bone and its rotor is attached with the proximal part of the forearm by means of radius and ulna stem as shown in Fig. 2. The radius and ulna stem, which are implanted inside of the radius and ulna bone, are attached on the convex face of the elbow rotor by means of two ball joints. The human bones have a comparatively soft, porous bone tissue in the centre which is commonly termed as "canal". In elbow arthroplasty, special instruments are used to remove part of canal from the humerus and ulna bone, and two stems of the elbow prosthesis are inserted into each of the two prepared canals ⁽¹⁸⁾. Bone cement can be used to hold the stems firmly inside of the canals. In the proposed system, the radius and ulna stems are expected to

implant inside of the radius and ulna bone, respectively, like conventional elbow arthroplasty. In order to assist the supination-pronation motion, the forearm actuator is fitted on the convex side of the elbow rotor (between the two stem) that generates motion in a perpendicular plane relative to the elbow actuator. The T-link contains two holes at its two ends as shown in Fig. 2. The rotor (shaft) of the forearm actuator is fixed on the base of the T-link, and the radius and ulna bones pass through the two holes of the T-link. Therefore, the T-link is able to rotate freely on the surface of each bone. Since the base of the T-link is fixed with the shaft of the forearm actuator and its ends are attached to the two bones, rotation of the forearm actuator makes one end of the T-link move upward and the other end move downward as shown in Fig. 2, so that the movement of pronation or supination is generated. The diameters of the T-link end holes are made to be a little larger than the bones sizes, as the bones move inside of the holes during the forearm motion. Moreover, both of the bone surfaces and the holes are supposed to be covered with a protective layer (i.e., artificial cartilage) to reduce the risk of wear and pain. The direction of rotation of the T-link ends during forearm supination-pronation motion is shown in Fig. 2, by dotted and solid line, respectively. Practically, the forearm actuator and the T-link should be small enough to safely place between the muscles of the bones. The thickness and the width of the T-link between the end holes should be designed to be minimal sizes and a highly finished surface with smooth edge is expected to avoid damaging of surrounding muscles as it rotates inside of the arm during the forearm motion. Moreover, it is expected to connect the T-link with the radius and ulna bone in such position where the movement of the T-link does not interact with the surrounding biological tissues such as muscles.

Fig. 2 Schematic Diagram of the Proposed System.

Fig. 3 Position of Radius and Ulna Bone during Supination-Pronation Motion.

Fig. 4 Prototype 2 DOF Inner Skeleton Robot.

A prototype 2 DOF inner skeleton robot shown in Fig. 4 has been developed in this study to realize the proposed motion assist system. Usually, the limitation of the movable range of the elbow flexion-extension motion is 145 degrees in flexion and -5 degrees in extension and that of the forearm supination-pronation motion is 80-90 degrees in supination and 50-80 degrees in pronation. Considering the safety in the proposed system, the limit of the elbow motion is designed to provide 115 degrees in flexion and 0 degree in extension and that of the forearm motion is 55 degrees in both supination and pronation motion. A small size cylinder (26 mm diameter with 50 mm height) made up with nonmagnetic material is used in the prototype robot as a jig to hold the stator of the elbow actuator firmly. A shaft is placed in the centre of the cylinder by means of two ball bearings. The elbow rotor is held up in front of the stator (the convex stator pole faces the concave side of the rotor, i.e., movable plate) with an aluminum bar and the end of the bar is fixed with the center shaft. This makes the elbow actuator to provide hinge motion as like the elbow joint. Although the ends of the T-link are attached with the radius and ulna bone in the proposed system, comparatively lengthy stems are used and the ends of the T-link are connected with the stems to verify the effectiveness of the T-mechanism in the prototype robot. Moreover, the stems are placed in a horizontal plane for the ease of demonstration, although they are supposed to be placed in a vertical plane.

Fig. 5 Schematic Diagram of the Joint Actuator.

At the first step toward the development of the proposed inner skeleton robot system, it is necessary to develop an actuator that is able to act like a human articulation and assist the motion from inside of the body. The joint actuator has to be designed according to the joint shape and range of motion of the joint. In this study, we have developed an example of

implantable joint actuator for the elbow joint to assist the elbow flexion-extension motion and a DC servo motor (RH-5A-5502-E03640, Harmonic Drive) has been used for forearm supination-pronation motion. However, the proposed actuator can be designed for both of the elbow and forearm motion. The schematic diagram of the actuator is shown in Fig. 5. Unlike the conventional actuator, the designed actuator does not provide complete rotary motion as the movable range available at the elbow joint is limited by the bony geometry as well as by the resistance provided by the soft tissues. Thus the range of motion of the actuator (i.e., the movable range of the proposed system for the elbow motion) is limited according to the elbow joint motion. The stator (fixed part) and the rotor (movable part) is designed so that they can be safely attached with distal part of humerus bone and proximal part of forearm respectively, like elbow arthroplasty and generate human like motion. Since the design of the actuator is different from the traditional rotary actuator, the absence of permanent magnet in the actuator reduces the possibility to interact with the surrounding environment, so that it is suitable to implant inside of the body. The stator and rotor of the actuator have been machined from 0.5 mm sandwiched silicon laminated steel plate. The stator part of the actuator consists of 20 poles in two rows; 10 poles in upper row and 10 poles in the lower row and the combination of the upper and lower row poles makes 10 exciting phases. The coils are wound around the poles in a way that 1 upper stator pole and its consecutive 1 lower pole generate two opposite magnetic poles to form one exciting phase as shown in Fig. 5. The radius of the stator pole face is 25 mm and the radius of the concave face of the rotor (the movable plate) is kept to be 26 mm and thus maintains 1 mm intermediate space (i.e., air gap length) between the stator and the rotor of the actuator.

Fig. 6 Excitation Sequence of the Stator Phases for CW and CCW Rotation.

The design of the actuator assures a simple excitation sequence of the stator phases and the direction of the actuator as well as the direction of the movable plate can be reversed by simply changing the excitation sequence of the stator phases. The excitation sequence of the stator phases for clockwise (CW) and counterclockwise (CCW) rotation of the rotor is shown in Fig. 6. Since the forearm is supposed to attach with the rotor of the actuator, fully extended and flexed position of the forearm can be realized with the stator-rotor combination as shown in Fig. 6(a) and 6(d), respectively. For example, at the extended position exciting sequence 5-6-7-8-9-10 will result the CW (flexion) motion of the movable plate whereas exciting sequence 6-5-4-3-2-1 will result the CCW (extension) motion of the movable plate from its flexed position. At the extended position, consecutive excitation of the stator phase 5 and 6 will generate the CW rotation of the rotor as shown in Fig. 6(a)-6(c). On the other hand, consecutive excitation of the stator phase 6 and 5 will rotate the rotor towards the CCW direction from the flexed position as shown in Fig. 6(d)-6(f). When the stator poles are at unaligned position, the poles will be excited by supplying current and the

current supply have to be terminated after reaching the aligned position. The stator poles and the movable plate have been designed to provide about 19 degree step increments when current applied to the proper sequence on the stator phase. Since the direction of current is immaterial for the direction of rotation, relatively inexpensive and small size semiconductor is used to control the actuator. Considering a linear magnetic characteristics of the actuator, the torque produced by the movable plate can be calculated by the Eq. (1).

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (1)$$

where L , θ , and i are inductance, rotor position and current, respectively. Equation (1) can be written as:

$$T = \frac{1}{8} k_1 \frac{N_p^2}{l_g} i^2 \quad (2)$$

where k_1 is a constant and, N_p and l_g are the number of turns of stator coil and air gap length between stator and rotor, respectively. It can be observed from Eq. (2) that the torque is proportional to the square of current and square of number of turns of stator coil, and inversely proportional to the air gap length. As the torque of the designed actuator is controlled based on the EMG signals, the controlled amount of input current has to be applied on the respective stator phases according to the rotor position to obtain clockwise and counterclockwise direction and this arises the necessity of an angular position sensor to control the actuator. The conductive plastic element (CPE) is used here to design the angular position sensor to control the actuator. The CPE is used as the resistive material and attached with the upper row stator poles and a wiper is attached with the movable plate as shown in Fig. 5. The shape of the conductive plastic element is designed according to the shape of the stator part of the actuator. Applying a small amount of constant voltage to the ends of the CPE generates variable voltage at its conductive layer face and the amount of generated voltage is proportional to the angular distance of the conductive layer face. The wiper is attached with the movable plate in a way that during the movement of the movable plate the wiper travels across the conductive layer face to pick up the voltage. The position of the movable plate is determined by measuring the voltage value picked up by the wiper.

3. Control of the Inner Skeleton Robot

A fuzzy-neuro control method has been used to control the proposed prototype of inner skeleton robot which enables the cooperative motion of the human elbow and forearm motion. The design of the fuzzy-neuro controller is similar to that as proposed in our previous study ⁽⁵⁾. The proposed inner skeleton robot is supposed to be controlled based on the activation pattern of the intramuscular EMG signals of the user's muscles in order to realize natural motion assist. Although a number of muscles are responsible for the elbow and forearm motion, eight kinds of EMG signals (ch.1: pronator teres, ch.2: flexor carpi radialis, ch.3: anconeus, ch.4: supinator, ch.5: medial part of biceps, ch.6: lateral part of biceps, ch.7: medial part of triceps and ch.8: lateral part of triceps) are measured for control of the forearm supination-pronation motion and elbow flexion-extension motion in this study. Three of them (ch.1: pronator teres, ch.5: medial part of biceps and ch.6: lateral part of biceps) are used for the elbow flexion motion and another two (ch.7: medial part of triceps and ch.8: lateral part of triceps) are used for the elbow extension motion. Furthermore, three of them (ch.1: pronator teres, ch.2: flexor carpi radialis and ch.3:

anconeus) are used to determine the pronation motion and another three (ch.4: supinator, ch.5: medial part of biceps and ch.6: lateral part of biceps) are used to determine the supination motion. Thus, the biceps is used for both the forearm supination motion and elbow flexion motion, and pronator teres is used for both forearm pronation motion and elbow flexion motion. The position of the designated muscles to monitor the EMG signals is shown in Fig. 7.

Fig. 7 Position of the Electrodes.

The EMG signals are amplified and then sampled at a rate of 2 KHz. Since it is difficult to use raw EMG signals for input information of the system, feature has to be extracted from the raw EMG signals. There are many kinds of feature extraction methods, for example, mean absolute value, mean absolute value slope, zero crossings, waveform length or root mean square⁽¹⁹⁾. In this study, Root Mean Square (RMS) value is calculated to extract the feature of the EMG signals. The RMS is determined using the Eq. (3)

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N v_i^2} \quad (3)$$

where, v_i is the voltage value at i^{th} sampling, and N is the number of samples in a segment. The number of samples is set to be 100 in this study.

Fig. 8 Architecture of the Fuzzy-Neuro Controller.

The initial fuzzy IF-THEN control rules are designed based on the analyzed human forearm and elbow motion patterns in a pre-experiment and then transferred to the neural network form to be a fuzzy-neuro controller. The architecture of the fuzzy-neuro controller is depicted in Fig. 8. The input variables of the fuzzy-neuro controller are the eight RMS values of the EMG signals and the outputs are the torque command for the forearm supination-pronation motion (τ), the desired impedance parameters (B_e is the damping coefficient and K_e is the spring constant) and the desired angle (q_d) for the elbow

flexion-extension motion of the proposed actuator. Since the role of each muscle is changed according to the arm posture, the magnitude of the EMG signals is also affected by the arm posture. In order to cope with this problem, multiple fuzzy-neuro controllers have been designed and applied under certain arm posture region ⁽²⁰⁾. The RMS of the pronator teres (ch.1) is used as an input variable as shown inside the dotted rectangle in Fig. 8 to adjust the weight in the consequent part of the fuzzy control rules for the supination motion assist ⁽⁵⁾.

The controller output torque command for the forearm actuator is then transferred to the DC motor through the motor driver (PC-0121-2, Titech Driver), which is then finally transferred to the radius and ulna bone through the T-Link. Impedance control is performed with the derived impedance parameters and the derived desired angle for the elbow joint control of the inner skeleton robot ⁽³⁾. The torque of the proposed actuator (τ_e) for elbow flexion-extension motion is calculated using the following equation:

$$\tau_e = M_e \ddot{q}_d + B_e (\dot{q}_d - \dot{q}) + K_e (q_d - q) + \tau_x \quad (4)$$

where, M_e is the moment of inertia of the forearm, τ_x is the external torque, and q is the angle of the actuator measured by the designed position sensor. The elbow torque command is then converted into the voltage value and applied to the base of the semiconductor that are used to control the current in the stator phase. In this study, 10 TIP-102 NPN transistors are used to control the current in 10 stator phases. The torque command as well as the voltage command is applied to the base of the transistor as the base current controls the current flow between the collector and the emitter of the transistor. It can be noted that the excitation of the appropriate stator phase (i.e., selection of the transistor) will be depend upon the position of the rotor (movable plate). The structure of the controller for the designed actuator is shown in Fig. 9.

Fig. 9 Structure of the Controller.

4. Experiment

Experiment has been carried out to evaluate the measurement accuracy of the designed angular position sensor and the effectiveness of the inner skeleton robot by using EMG signal. The schematic diagram of the experimental setup is shown in Fig. 10. In the experimental setup, for the ease of experiment, the CPE is fitted on the top of the cylinder that holds the stator and the wiper is connected with the Al bar that holds the rotor in such a way that during the movement of the rotor the wiper travels across the conductive layer face of the CPE. A second order low pass filter (cut off frequency 8 Hz) is used to reduce the noise from the voltage signal picked up by the wiper. The sampling time was set to be 500 microsecond for every experiment. The measurement accuracy of the designed angular position sensor is compared with an incremental rotary encoder (NOM-S600-2MC, Nemicon). The encoder is attached with the center shaft of the cylinder. As the rotor is attached with the center shaft by means of the Al bar, the amount of shaft rotation indicates the rotor position. In order to verify the measurement accuracy of the designed sensor for any velocities of the actuator in this experiment, the evaluation is performed under two different angular velocities. At the same time, the angular position of the rotor is measured by the encoder for comparison. The experimental results for a low and high velocity of the

actuator are shown in Fig. 11(a) and 11(b), respectively. The experimental results indicate that the proposed angular position sensor can measure the rotor position properly in both cases.

Fig. 10 Experimental Setup.

Fig. 11 Comparison of Measurement Accuracy of the Designed Sensor with a Rotary Encoder.

In order to verify the performance of the proposed system by using EMG signal, experiment has been carried out with a healthy human male subject (28 years old). Since the intramuscular EMG signals require skin puncture, for the ease of experiment in this study, we carried out the experiment by using surface EMG signals. The effectiveness of the designed elbow joint actuator has examined based on the human elbow flexion-extension motion. Although the ultimate goal is to implant the actuator inside of the arm, the effectiveness of the actuator is verified outside of the human body. In the experiment, similar condition is maintained for both of the subject's arm and for the actuator. Here, the subject carried out elbow flexion-extension motion without carrying any external load in his hand and the actuator is activated without any external load applied on the rotor also. If the subject carries an external load in his hand, the activity level of the muscles increases in accordance with the amount of the load and that results in increase of generating torque of the actuator. Therefore, the similar results would be obtained if the subject carries an external load in his hand. As the EMG signals vary for different arm motions, the experiment is performed for slow and fast elbow motions in order to verify the

controllability of the actuator for different levels of EMG signals. The experimental results for a slow and fast arm motions are shown in Fig. 12(a) and 12(b), respectively. Since the medial part of biceps and lateral part of triceps are the most active muscles for elbow flexion and extension motion respectively, only the EMG signals of channel 5 and channel 8 are depicted in Fig. 12. The experimental results show that the flexion motion is generated when the biceps muscles are activated and consequently extension motion is generated when the triceps muscles are activated. Moreover, the actuator can follow the desired joint angle (trajectory) generated by the fuzzy-neuro controller (i.e., one of the output of the fuzzy -neuro controller: q_d).

Fig. 12 Experimental Results for the Actuator.

Fig. 13 Experimental Results for the Proposed 2 DOF Inner Skeleton Robot.

The effectiveness of the proposed prototype of 2 DOF inner skeleton robot for a combined motion of the elbow flexion-extension and forearm supination-pronation motions has also been evaluated. In this experiment, the subject is performed the cooperative motion of the elbow and forearm (i.e., a combination of elbow flexion-extension motion and forearm supination -pronation motion) without any external load in his hand and the inner skeleton robot is allowed to generate motions without any external load applied on the rotor of the actuators also. The similar results would be obtained if the subject carries an external load in his hand, since the activity level of the muscles is increased in accordance with the amount of the external load. The experimental results for a slow and fast arm motion are

shown in Fig. 13(a) and 13(b), respectively. The biceps muscles are activated during both the elbow flexion motion and forearm supination motion. The pronator teres muscle is responsible for the forearm pronation motion as well as for the elbow flexion motion. And the activation of the triceps muscles results the elbow extension motion. Therefore, the same muscle is sometimes used for both of the flexion-extension and supination-pronation motion. The fuzzy-neuro controller is designed to recognize the effect of the muscles which are common to both of the flexion-extension and supination-pronation motion. Although eight EMG signals are used to control the inner skeleton robot, for the ease of demonstration only three EMG signals (lateral part of biceps, lateral part of triceps and pronator teres) are depicted in Fig. 13. The experimental results show that the robot generates the elbow flexion motion when the lateral part of biceps is activated more than the lateral part of triceps. On the other hand, activation of the lateral part of triceps over the lateral part of biceps results the elbow extension motion. Moreover, it is also evident from the experimental results that the supination and pronation motion of the proposed inner skeleton robot can be controlled according to the EMG activation patterns of the lateral part of biceps and pronator teres, respectively. Figure 13 shows that the proposed system generates the flexion-extension and supination-pronation motion according to the EMG signals of the muscles. Consequently, it is evident that the proposed 2 DOF inner skeleton robot can be controlled according to the human muscles EMG signals and can assist a combination of elbow flexion-extension motion and forearm supination-pronation motion. Moreover, it is verified that the proposed T-mechanism keeps the similar configuration of the radius and ulna stem during forearm supination-pronation motion like the radius and ulna bone during normal human forearm motion.

5. Conclusion

In this paper, a new concept of a power-assist inner skeleton robot has been proposed and a prototype 2 DOF inner skeleton robot has been introduced to assist the elbow flexion-extension and forearm supination-pronation motion from inside of the body for physically weak persons. The controllability of the designed joint actuator has been verified according to the motion intention of the user with applying a maximum of 3.0 ampere current that generates about 0.1 Nm torque. The amount of generated torque can be increased by reducing the distance between the stator and rotor plate, and by increasing the number of turns of stator coil. The proposed system is supposed to be implanted inside of the human arm like elbow arthroplasty and controlled by intramuscular EMG signals. Implantable Titanium coated flexible wire with needle tip can be expected to measure the intramuscular EMG signals for the proposed system. The inner skeleton robot is an active implantable device which requires power source to function from inside of the body. Although the power source for the implantable actuator is still undefined, Transcutaneous Energy Transfer (TET) system^{(21), (22)} or implantable battery with high power density can be considered as the power source for the proposed system. Moreover, from the standpoint of safety, the material for the proposed system and the insulation of the actuator stator and rotor parts lead the necessity of much research on it. To keep the bone arrangement similar to the normal human elbow complex after the elbow arthroplasty and to transmit the assist power to the radius and ulna bone, a T-mechanism has been introduced for the inner skeleton robot. As the ulna bone does not cross over the radius bone during the supination motion, it is not necessary to keep the length of the two ends of the T-link to be the same. The ratio of length of the ends of T-link can be changed according to the users bone geometry. The proposed inner skeleton robot can be expected to be actuated artificial elbow joint for the future generation and supposed to act as a complete functional substitution of the normal human elbow complex.

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