Design of a Robot Arm Based on Human Structure for Humanoid Robots

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Abstract. In this study, we examined a frame model of a robot arm from upper arm to forearm based on human anatomy to develop a tendon-driven humanoid robot that incorporates human anatomical structures. We designed a 3D CAD model of a robot arm incorporating human anatomical features, and evaluated its expected range of motion. The evaluation results demonstrated that incorporating human anatomical features achieved an expanded range of motion compared to a structure without these features. In particular, the offset of the elbow joint affects the range of motion in flexion and extension of the elbow, decreases the range of motion for extension but increases it for flexion. Similarly, the curvature of the ulna and radius affects the range of motion in forearm pronation and supination, decreases the range of motion for supination while increasing it for pronation. Based on the above findings, it can be said that incorporating human anatomical structures is sufficiently effective for enhancing the functionality of robot arms.

Keywords: Humanoid Robot · Robot Arm · Biomechanics

1 Introduction

In many workplaces such as construction sites and nursing facilities, humans perform many of the necessary tasks. However, in modern times in Japan, there is a growing concern over labor shortages[1], which may adversely affect these workplaces.

Up to now, researches aimed at supplementing labor shortages with humanoid robots have been actively conducted. Among these studies, researches on the upper limbs are considered as important as bipedal walking, a major feature of humanoid robots. In particular, those that adopt tendon-driven mechanisms using wires are effective because the passive joints make it easier to ensure flexibility[2], and reduce the risk of injury due to human-robot collision.

Hansol et al.[3] developed a dual-arm robotic system, "LIMS2-AMBIDEX," designed for high-speed manipulation tasks, with the goal of competing in the

IROS2018 Robotic Challenge. This system employs a tendon-driven mechanism, aiming to achieve high precision and speed while ensuring safety. By placing all heavy actuators around the shoulder area, the mass beyond the shoulder is significantly reduced, thereby enabling both high-speed operations and enhanced safety. Although the unique wrist mechanism sufficiently meets the required performance and can be considered highly effective, the load on tendons and wiring when incorporating additional fingers has not been considered. As one potential approach to this challenge, we propose that the structure of the human body serves as an exemplary model.

Kawaharazuka et al. [4] studied on the design and development of a forearm structure with a radius and ulna configuration that accurately mimics human proportions, weight, muscle arrangement, and structure, as well as on the movements using this structure. They succeeded in achieving dexterous movements that leverage the advantages of the radius and ulna structure, but did not meticulously replicate the bone shapes and joint characteristics included in the actual human structure. As these factors are suggested to influence the range of motion, mimicking them is considered to have significant benefits.

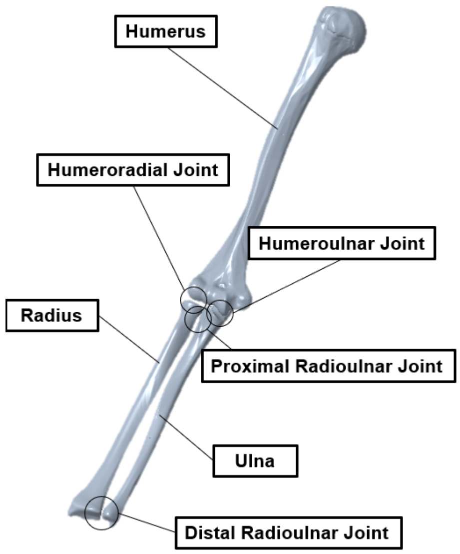
Among the researches on tendon-driven humanoid robots, there are few studies that focus on the skeletal structure from an anatomical perspective, and even fewer that closely analyze and mimic the human structure. Therefore, this paper aims to develop a tendon-driven humanoid robot that incorporates human structures. A skeleton model for the development of a robot arm from the upper arm to the forearm will be examined.

2 Significance of Mimicking Human Structure and Analysis of Human Upper Limb

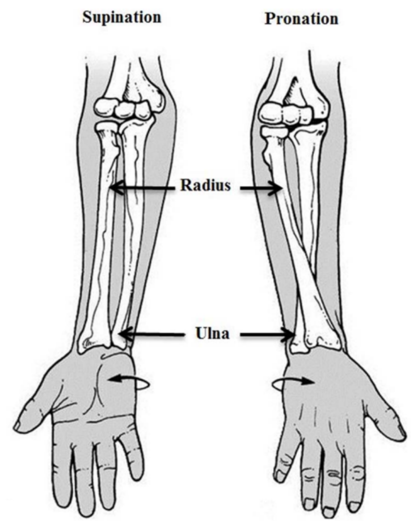
Based on the aforementioned background, this section explains the significance of mimicking human structures for the development of a tendon-driven robot arm that incorporates human anatomy. Furthermore, it describes the structures and movements of the human upper limbs.

2.1 Significance of Mimicking Human Structure

The significance of incorporating human structures into humanoid robots, a key element of this research, lies in the advantages gained from this approach. For instance, in the field of quadrupedal robots, Boston Dynamics' "Spot" and "BigDog[5]" are well-known examples. These robots have skeletons similar to those of quadrupedal animals and excel in navigating rough terrains, a specialty of such animals. Thus, mimicking the skeletons of quadrupedal animals in quadrupedal robots is a logical design philosophy and effective, provided that it suits the required functions. Based on this reasoning, The paper argue that incorporating human structures into humanoid robots is highly effective.



(a) The upper limb bones and joints



(b) Pronation and supination of forearm[7]

Fig. 1. The structure and movement of the upper limb

2.2 Structures and Movements of Human Upper Limb

This section explains the structure and function of bones and joints based on "Functional Anatomy[6]", towards the development of a tendon-driven robot arm that incorporates human structure.

The human upper arm and forearm are composed of three bones: the humerus, ulna, and radius, as shown in Figure1(a). Flexion/extension of elbow involve the bending and straightening of the elbow joint, which operates through two joints: the humeroulnar joint and the humeroradial joint. The fully extended position of the elbow is called the neutral position, serving as the reference angle for joint movements.

Pronation/supination of forearm, depicted in Figure 1(b), involve the rotational movement of the forearm. This movement is facilitated by two joints: the proximal radioulnar joint and the distal radioulnar joint. The pronation and supination of the forearm are enabled by the crossing of the ulna and radius bones, as illustrated on the right side of Figure 1(b).

Where the thumb points outward as shown on the left side of Figure 1(b), is termed pronation. Where the forearm rotates and the thumb points inward as shown on the right side of Figure 1(b), is termed supination. The intermediate position where the thumb is upright is termed the neutral position of the forearm.

The range of motion for elbow flexion and extension, with flexion considered positive, is approximately 150°in total. Starting from the neutral position at 0°, maximum flexion reaches 145°and maximum extension reaches $-5°$. For pronation and supination of forearm, with supination considered positive, the range of motion is approximately 175°in total. Starting from the neutral position at 0°, maximum pronation reaches -85°and maximum supination reaches 90°. These ranges of motion are constrained by the bones, muscles amd ligaments to prevent exceeding the limits.

In the next section explains the characteristics and functions of bones, joints, ligaments, and other related structures.

The Two Bones of the Forearm The forearm is composed of two bones, and as previously mentioned, pronation/supination are achieved by the radius crossing over the ulna. This structure is present not only in humans but also in quadrupedal animals. This configuration contributes to the centralization of mass by allowing the placement of larger muscles closer to the body. According to Kawaharazuka et al., they present three features of the two bones, and here we will describe two of them. The first is the ability to achieve pronation and supination using only the radius while keeping the ulna fixed to an object, such as during soldering or writing. The second is the ability to reduce the load on blood vessels, nerves, tendons, and skin. Assuming that tendon-driven mechanisms are used to drive the fingers in order to ensure human-equivalent functionality, the two bones of the forearm can prevent tendon twisting. Additionally, considering the incorporation of skin as an outer layer to prevent external physical interference, which is a weakness of tendon-driven mechanisms, the ability to disperse skin twisting is a significant advantage. From these points,it can be said that the two-bone method is an example that is superior to the direct drive method using a rotary motor, and the two-bone structure of the forearm is well-suited for tendon-driven mechanisms.

The Offset of Elbow Joints The part of the humerus that is farther from the body is called the distal humerus, while the part of the ulna that is closer to the body is called the proximal ulna. These form the humeroulnar joint, which is responsible for elbow flexion and extension. The distal humerus is inclined forward at an angle of 30 to 45 °, and similarly, the proximal ulna is inclined forward at the same angle. This characteristic offsets the center of rotation for flexion and extension from the long axes of the humerus and ulna, allowing for a greater range of motion. As shown in Figure 2, this allows the arm to bend back 180°, contributing to an extended range of motion and improved stowability. Therefore, this design is adopted in many industrial robots and manipulators[8]. Additionally, according to Kapandji, there is the advantage of providing space for the muscles located around the elbow[6].

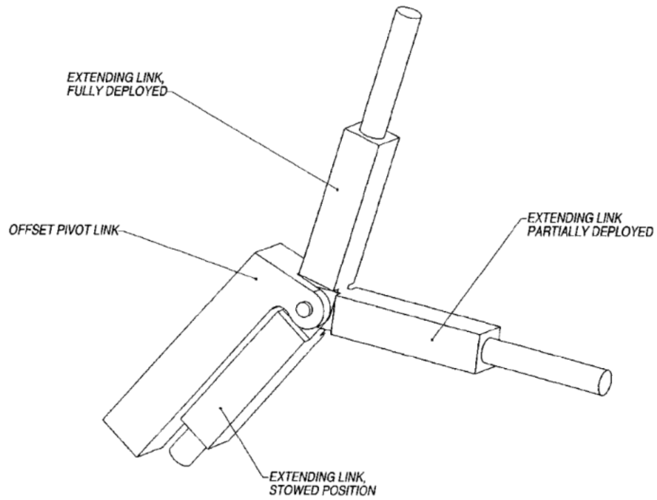


Fig. 2. An example of offset joints[8]

The Curvature of Ulna and Radius The two bones that make up the forearm, the radius and the ulna, are curved as shown in Figures 3 and 4. They exhibit a curvature that bends posteriorly in the pronated position[9]. This curvature allows the concave curves of the two bones to face each other during supination, enabling the distal end of the radius to move further posteriorly relative to the distal end of the ulna. This configuration achieves a wider range of motion in pronation/supination.

Annular Ligament The annular ligament, which restricts the position of the proximal end of the radius, acts like a bearing to facilitate smooth pronation/supination assisting in the rotation of the radius. The annular ligament is attached to the ulna and moves while holding the radial head in place during flexion/extension of elbow.

The Rotation Axis of Pronation and Supination The axis of rotation for pronation and supination of the forearm occurs around two distinct joints, as illustrated in Figure 1(a), namely the proximal radioulnar joint and the distal radioulnar joint. This axis is inclined towards the ulna as it approaches the distal end of the forearm, depicted in Figure 5 [10]. Figure 5 shows the angle a formed between the line connecting the centers of both ends of the radius and the axis of forearm rotation. This angle averages 6.7°, ranging from 4.5 to 8.5°, enabling pronation and supination of forearm.

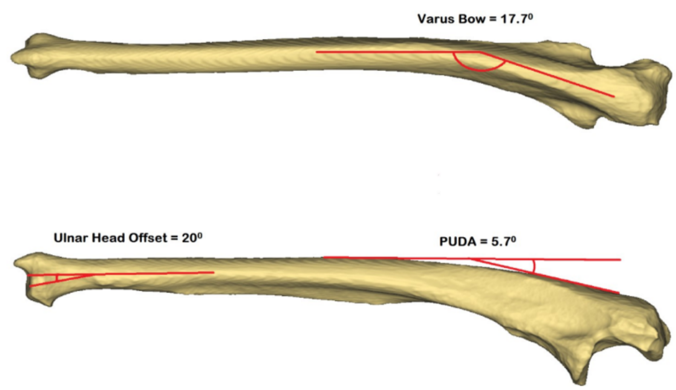


Fig. 3. The curvature of the ulna bone

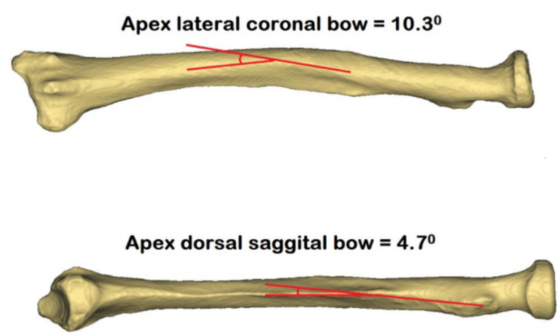


Fig. 4. The curvature of the radius bone

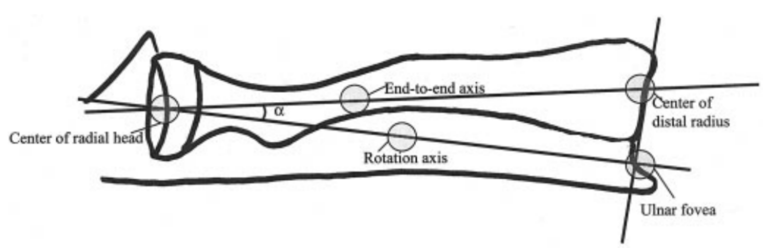


Fig. 5. The rotation axis of pronation and supination[10]

3 Consideration of Robot Arm Incorporating Human Structure and Design of Frame Model

Based on the findings of the previous section, we examined the robot arm from the upper arm to the forearm to incorporate the features of human structure into an actual humanoid robot. Based on the examination, we designed a frame model of the robot arm.

3.1 Overview of Robot Arm Aimed for Development

This section outlines the tendon-driven robot arm that incorporates human structure.

Since the robot arm is intended to be incorporated into a humanoid robot, its applications include labor in construction sites and caregiving facilities. Specifically, these applications involve using tools such as screwdrivers for fastening screws, opening and closing doors, and lifting individuals requiring assistance. Based on these applications, the design requirements for the robot arm are as follows.

- Capable of operating safely in proximity to humans
- Able to use tools
- Strong and with a range of motion comparable to that of humans
- Capable of precise movements

To ensure safe operation in environments where people are nearby, tendon-driven actuation is considered appropriate. As previously mentioned, this reduces potential harm from collisions with nearby individuals or objects. This capability is crucial for ensuring the highest level of safety in labor environments. Regarding tool usage, it is necessary to have a hand composed of five fingers, allowing for controlled force similar to humans. This involves multiple fingers operating accurately and independently, facilitating operations in environments similar to those humans work in. To achieve both strength and a range of motion comparable to humans, strong actuators and structural designs contributing to mobility range are essential. Precise movements to enable efficient operations require advanced feedback control for managing force, position, and posture effectively.

Table 1 summarizes the specifications of the robot arm to be developed in this study based on the above design requirements, and Figure 6 shows an image of the robot arm to be developed. To adapt well to labor environments, the weight and range of motion are set to values comparable to those of humans, and the lengths of the overall arm, humerus, ulna, and radius were determined based on multiple literature sources[9][10][11].

Table 1. The specification of the robot arm

Overall Length(humerus, ulna, radius)[mm]	540(305, 246, 235)
Weight[kg]	4.2
Degree of Freedom	2
Range of Motion of Flexion/Extemsion(Neutral Position=0°)[°]	−5〜145
Range of Motion of Pronation/Supination(Neutral Position=0°)[°]	−85〜90
Joint Restraints	Hinge Joint
Driving Method	Tendon-Driven
Actuater	Motor
Number of Actuater	4
Controlling Method	Feedback Controll
Sensor	Potentiometer

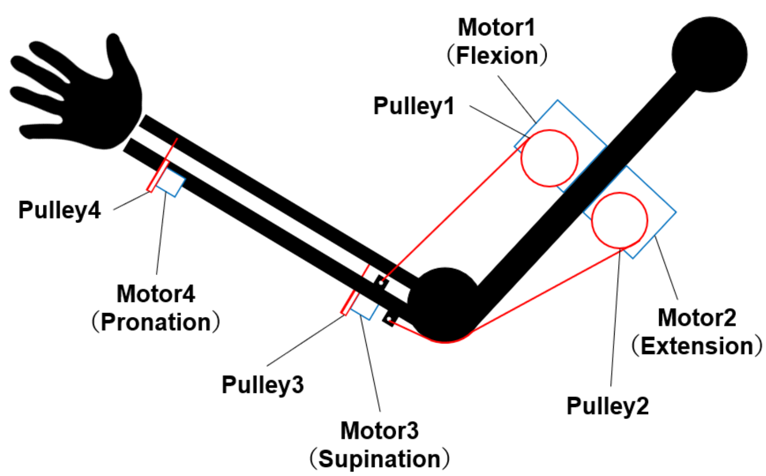


Fig. 6. Conception of the robot arm

Joint constraints are implemented using hinge joints, which are pierced by rods or shafts. This is different from the ligament-based constraints observed in humans and other animals. However, hinge joints aim to maintain a consistent center of rotation, facilitating subsequent design and analysis. For the same reasons, the carrying angle is also not replicated.The carrying angle is the acute angle formed between the long axis of the upper arm and the long axis of the forearm when the elbow and forearm are extended and supinated. Furthermore, considering ease of placement in confined spaces and the need for high output, motors have been chosen as actuators for use.

The driving mechanism is tendon-driven, where motor rotation is transmitted through pulleys to drive via tensioned wires or strings. Therefore, more motors than the assumed degrees of freedom are required, and the robot arm being developed in this study necessitates four motors. The four motors actuate the flexion and extension of the elbow, as well as the pronation and supination of the forearm, through tension applied via wires or strings. Human muscles operate in a more complex and multifaceted manner than this. However, due to the use of hinge joints for joint constraints in this study, muscles that assist in the stabilization of movements, such as the anconeus, are deemed unnecessary. Therefore, a minimum of four motors are utilized. Although the muscles of the fingers are not the focus of this study and thus are not discussed in detail, it is assumed that they would be positioned proximally in the forearm to centralize mass, similar to those in humans.

Control is achieved through feedback control, using potentiometers to measure angles for regulating elbow flexion/extension and forearm pronation/supination.

3.2 Design of Frame Model

Based on the specifications outlined in the previous section and human anatomy, we have designed the frame model of the robot arm being developed in this study. This section explains each part of the designed frame model and discuss how human anatomy has been incorporated into it.

Figure 7 depicts the frame model designed using 3D CAD software. This model primarily consists of the humerus, ulna, and radius bones. In the robot arm's frame model, all joints are constrained using hinge joints.The offset joints, as shown on the right side in Figure 7, are each inclined 45°forward. Moreover, the forward offset distance from the long axis of the humerus to the axis of rotation at the elbow is set at 10.0 mm based on [12]. This offset is expected to expand the range of motion achievable by the joint. The curvature of the radius and ulna was incorporated into the frame model based on multiple references [9][13][14]. The function of the Annular Ligament is replicated using bearings, reducing resistance at the humeroulnar joint, humeroradial joint, proximal radioulnar joint, and distal radioulnar joint. Regarding the axis of rotation for the forearm, it is designed to replicate the line connecting the centers of both ends of the radius and the axis of rotation of the forearm, with an angle α as shown in Figure 5. Designed to maintain a deviation within the range of 4.5 to 8.5°, as illustrated on the right side of Figure 7[10].

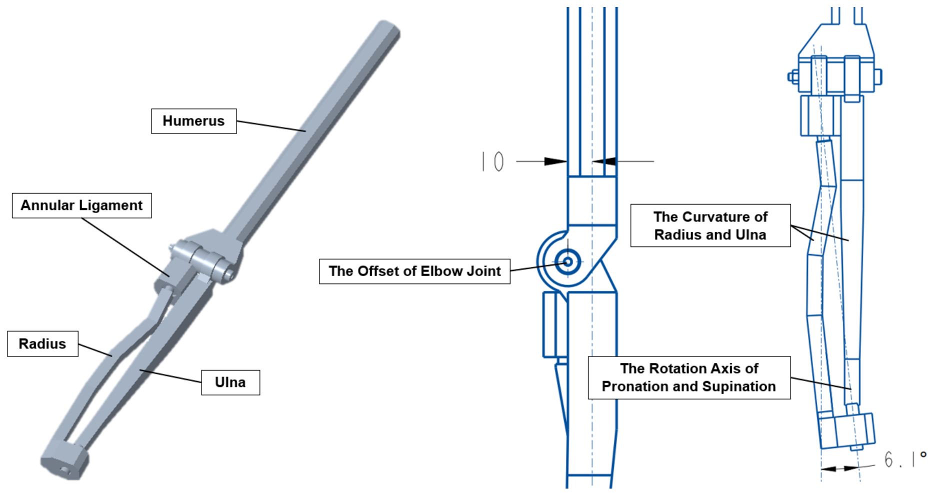


Fig. 7. The frame model of a robot arm designed using 3D CAD

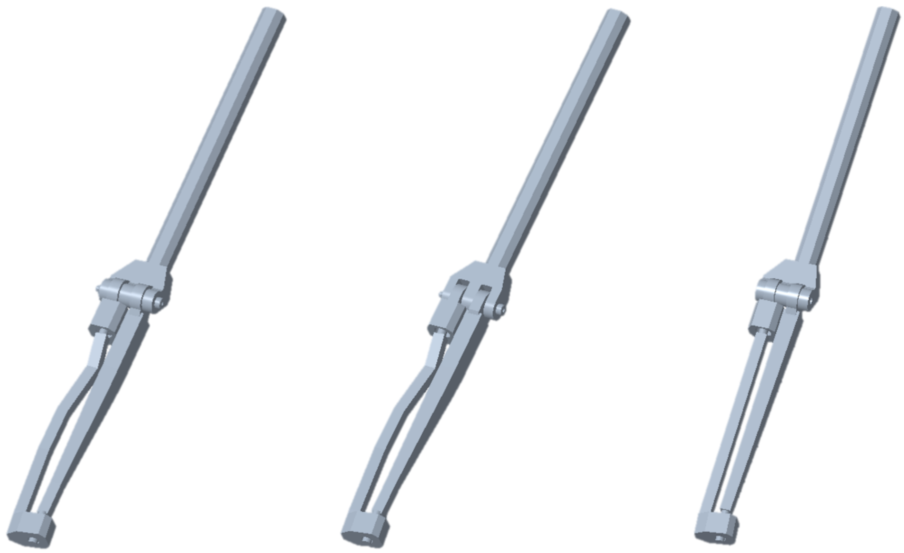
4 Evaluation of Designed Frame Model

Based on the aforementioned section, we conducted an evaluation of the frame model from a functional perspective. The evaluation primarily focuses on the range of motion, given that features such as the offset of the elbow joint and the curvature of the ulna and radius are expected to enhance the range of motion.

4.1 The Method for Evaluating the Frame Model

This section describes the evaluation method for the designed frame model. The evaluation focuses on the range of motion, assessing the affect of bone curvature and joint offsets on the range of motion. To evaluate the range of motion, comparative frame models were created using 3D CAD, and compared their ranges of motion based on the presence or absence of these structural features. Angle measurement functions in 3D CAD were employed for comparing the ranges of motion, using three frame models shown in Figure 8 for comparison. Figure 8(a) represents the frame model shown in Figure 7. Figure 8(b) illustrates a structure where the elbow joint is not offset, meaning that the center of rotation for flexion and extension of the elbow is aligned with the long axis of both the humerus and the ulna. Figure 8(c) shows a structure where the radius and ulna are not curved.

The range of motion for elbow flexion/extension, as well as forearm pronation and supination, is based on the specifications of the robot arm shown in Table 1. With the neutral position set at 0°, and with flexion as positive, the maximum flexion is 145°and the maximum extension is −5°. For forearm pronation/supination, with the neutral position at 0°, the maximum pronation



(a) The frame model

(b) The frame model without offset of elbow joint

(c) The frame model without curvature of ulna and radius

Fig. 8. The 3 models used for evaluation

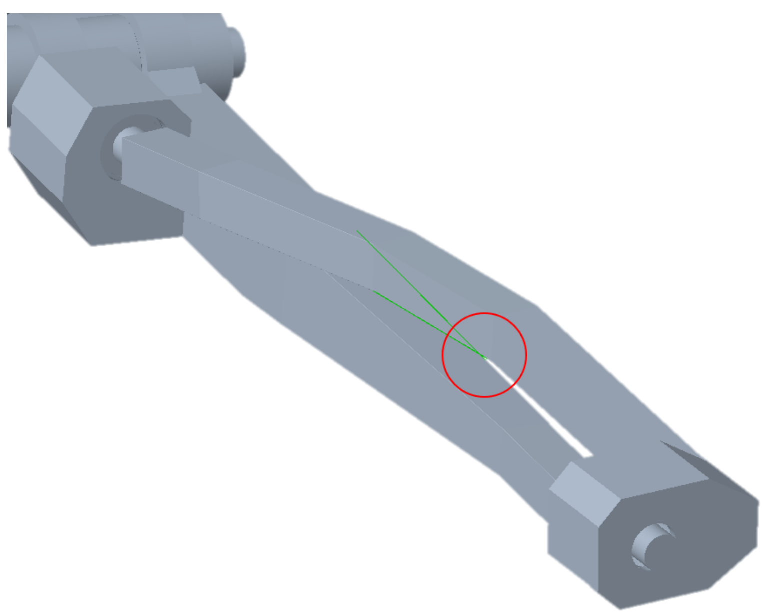


Fig. 9. Evaluation of the range of motion

is $-85°$and the maximum supination is $90°$, with supination as positive. As previously mentioned, the range of motion is restricted by bones, muscles and ligaments to prevent exceeding the functional range. In this evaluation, the absence of muscle constraints means that exceeding the range of motion is not an issue. The specific measurement method involved simulations of the model in 3D CAD. The limits of the range of motion for each movement were determined by the positions where skeletal components came into contact with each other shown in Figure 9, and the range was measured by extracting these angles.

4.2 Result

The results of the range of motion comparison based on the three frame models presented in the previous section are shown in Table 2. It displays angles for four limb positions—maximum flexion, maximum extension, maximum pronation, and maximum supination—when the neutral position is set at 0°. For the elbow, the direction of flexion is considered positive, and for the forearm, the direction of supination is considered positive.

In model (a), it is evident that the range of motion for maximum flexion, maximum extension, maximum pronation, and maximum supination meets the design requirements.

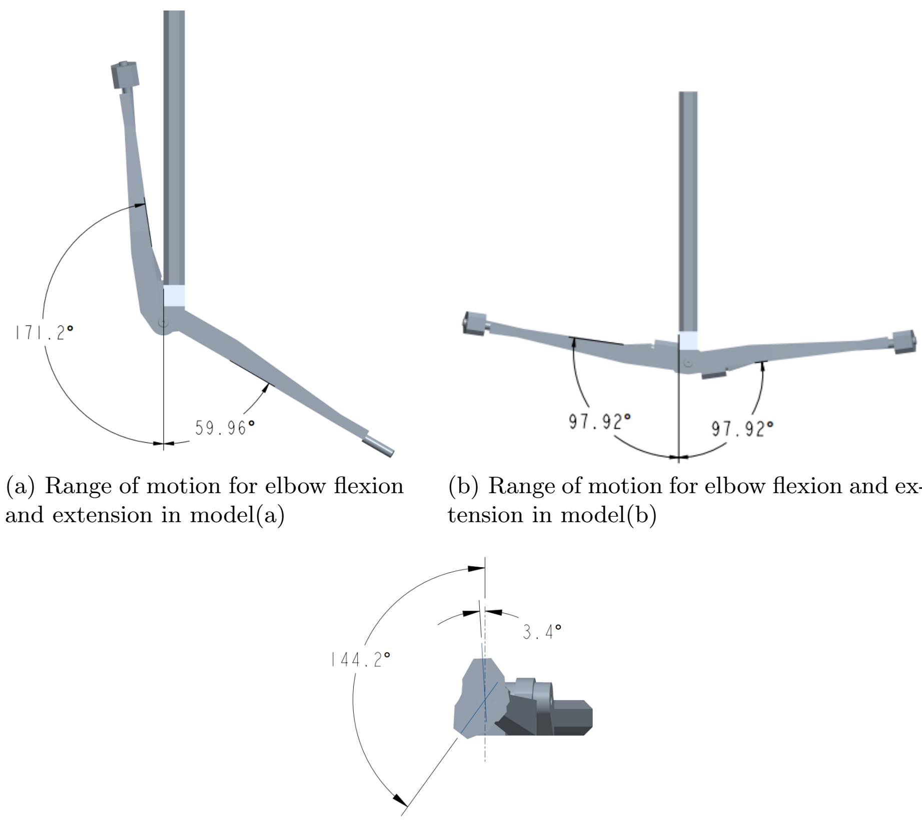
Model (b) satisfies the design requirements for two positions: maximum pronation and maximum supination, similar to model (a). However, for maximum flexion, it falls short by approximately 47°, achieving only 97.92°.

Model (c) meets the design requirements for maximum flexion and maximum extension, similar to model (a), but for maximum pronation, it deviates by 3.400°towards supination from the neutral position. In other words, there is a deficiency in the range of motion for pronation.

As a supplement, figure 10 illustrates the visualized range of motion for the three models. Figure 10(a) shows a side view of model (a), illustrating the range of motion for flexion and extension, which meets the design requirements. Figure 10(b) presents a side view of model (b), depicting the range of motion for flexion and extension; however, it does not satisfy the design requirements in terms of the flexion range. Figure 10(c) provides a view of forearm viewed from the longitudinal axis direction, visualizing the range of motion for forearm pronation and supination. It is evident that model (c) fails to meet the design requirements for pronation.

Table 2. Summary of the range of motion in 3 models

	Max Flexion	Max Extension	Max Pronation	Max Supination
Design Requirements	145°	−5°	-85°	90°
Model(a)	171.2°	−59.96°	-88.70°	107.4°
Model(b)	97.92°	−97.92°	−88.70°	107.4°
Model(c)	171.2°	−59.96°	3.400°	144.2°



(a) Range of motion for elbow flexion and extension in model(a)

(b) Range of motion for elbow flexion and extension in model(b)

(c) Range of motion for forearm pronation and supination in model(c)

Fig. 10. The range of motion for flexion and extension in model(a) and (b), and pronation and supination in model(c)

4.3 Discussion

Based on the results discussed in the previous section, this section will examine the characteristics and range of motion of each model. By incorporating joint offsets and bone curvature, which are part of the human structure, an expanded range of motion was achieved compared to models without these features. From the results of maximum pronation and maximum supination for models (a) and (c) in Table 2, The offset of the joint can be said to reduce the range of motion for extension while increasing the range of motion for flexion. Similarly, bone curvature reduces the range of motion for supination while increasing the range of motion for pronation. Even if the radius and ulna are made thinner, their respective ranges of motion can be expanded; however, a model incorporating the human structure would still result in a greater overall range of motion.From the above, incorporating human anatomical structures is sufficiently effective for enhancing the functionality of the robot arm.

5 Conclusion

This study aims to develop a tendon-driven humanoid robot that incorporates human anatomical structures, focusing on the development of a robot arm from the upper arm to the forearm. The skeletal structure was examined to achieve this goal. Human anatomical structures and their functions were explained, providing an overview of the robot arm being developed and describing the actual frame model of the robot arm created. The evaluation of the designed frame model revealed its effectiveness in terms of the range of motion. By incorporating joint offsets and bone curvature as found in human anatomy, an expanded range of motion was achieved compared to a structure without these features. It can be said that these features are advantageous for the range of motion, there is still room for further investigation into other advantages and disadvantages that these structures may present.

In future works, we will improve the skeletal model to accommodate motors, pulleys, sensors, and other components based on the design requirements and specifications of the robot arm. Additionally, we will evaluate the effectiveness of incorporating ligaments, tendon sheaths, interosseous membranes, and the number and arrangement of muscles, which were not considered in this study. In this paper, the effectiveness of several structures was demonstrated through the evaluation of range of motion. However, it is also necessary to evaluate and discuss the impact of these structures on strength, kinematics, and practical applicability.

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