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A multi-DoF Anthropomorphic Transradial Prosthetic Arm

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Abstract — **An anthropomorphic transradial prosthetic arm is proposed in this paper. In order to generate the wrist flexion/extension and ulna/radial deviation, a novel wrist mechanism is proposed based on the parallel prismatic manipulators. It is expected to realize high speed operation, higher positional accuracy and anthropomorphic features using the proposed mechanism. The prosthetic arm consists of an under-actuated hand as the terminal device. The hand mechanism is capable of providing the grasping adaptation. With the intention of verifying the effectiveness of the mechanisms in motion generation, motion simulation and kinematic analysis are carried out.**

Key words: Upper Limb Prosthesis, Transradial Prosthesis, Wrist Mechanism, Under-actuated Hand

I. Introduction

Robotic prosthetic limb is a substitution for the lost limb of an amputee. In the present society, the limb amputation is carried out due to war casualties, accidents, cardiovascular disease, tumors or congenital anomalies. It is expected to restore the lost functions and the physical appearance of the amputated limb using the robotic prosthesis.

Among the various levels of amputation, the loss of one arm or both the arms is a major disability that overwhelmingly limits the daily functions of an individual [1]. Therefore, development of the upper-limb prosthetic devices is an interesting research topic among researches. So far number of upper limb prosthetic devices have been developed [2]–[8]. Available upper limb prosthetic devices are capable of providing the amputees with an adequate functional capability to assist their Activities of Daily Living (ADL). However, they are not popular among the amputees due to their cost, poor anthropomorphic (size and weight) and dexterous (accuracy, loading capabilities, human alike simultaneous and smooth motion, fine motor skills) features. Hence, still it is an open research topic to develop prosthetic devices which would meet the anthropometric and dexterous requirements of the users in performing ADL. Amongst some of the robotic prosthetic devices i-limb [4], bebionic hand [6], smart hand [8] are some of the state of the art transradial prosthetic device. These devices are capable of providing the dexterous hand functions required for ADL. However, none of them provide the two wrist motions for the user. Therefore wrist flexion/extension and ulna/ radial deviation should also be included in a transradial prosthetic device.

The use of the Parallel Manipulators (PM) has shown significant results in achieving the higher dexterity in different applications [9]–[11]. PMs are high load bearing structures with a lesser range of motion and a higher accuracy. Even though PMs perform well in achieving above requirements, still enough studies have not been carried out in order to match the dexterous and anthropomorphic requirements of the prosthetic arms with the inherent properties of the PMs.

Since 1947, Gouch platform [12] and in 1965, Stewart platform [13], parallel manipulators are being used in the variety of applications such as flight simulators, automobile simulators, earthquake simulators, force and torque sensors, micro-manipulators and manipulator for ophthalmic surgery operation. These wide range of applications of the parallel manipulators are due to their pleasing mechanical properties like high load carrying capacity, good kinematic and dynamic performance and precise positioning [14]. Previously, Fite *et al* [15], Escudero *et al* [16] and Mendoza *et al* have proposed upper limb prosthetic devices with parallel links. Even though they had acquired some of the parallel manipulator properties [16]–[18] in their designs, they lacked the anthropometric features for a prosthetic device in terms of kinematic structure, geometry and weight. Therefore, this paper proposes an anthropomorphic robotic transradial prosthetic device. Proposed prosthetic device is capable of generating the forearm supination/pronation, wrist flexion/extension and wrist ulnar/radial deviation. In addition, a separate terminal device is available to realize the hand functions. The hand follows the under actuation principle and it is capable of providing the fingertip grasping modes with grasping adaptation for the objects with different geometries. Degree of Adaptation is used as a parameter to evaluate the adaptation capability of the terminal device for grasping different geometries. Further, results of the motion simulation and the kinematic analysis are also presented in the paper.

Next section of the paper discusses the motion requirements of the human lower arm. Section III proposes the design and the mechanism of the transradial prosthetic arm. It is followed by the motion simulation for the proposed wrist mechanism. In section V, kinematic analysis of the proposed wrist mechanism is presented. The final section presents the conclusion and proposals for the future developments of this research.

II. Motion Requirement of Lower Arm

Human upper limb consists of the upper arm and the lower arm [19]. In the human upper arm, the distal end of the humerus is connected to the proximal end of the radius and the ulnar at the elbow joint [19] as shown in Fig. 1 (a). The ulnohumeral and radiohumeral joints together generate the

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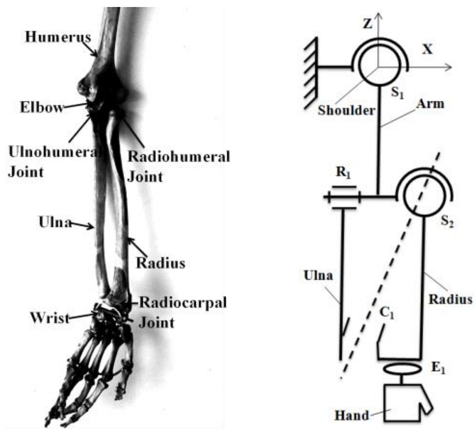
TABLE I. UPPER LIMB RANGE OF MOTION (ROM)[17]

Motion	RoM (deg)	RoM for ADL (deg)
Elbow Flexion/ Extension	150/ 0	140/0
Forearm Pronation/ Supination	80/90	30/40
Wrist Flexion/ Extension	60/70	05/30
Wrist Ulnar/ Radial Deviation	30/20	10/15



(a) (b)

Figure 1. (a) Main anatomical components of human upper limb. (b) Kinematic model porposed by Mansour *et al* [20]

elbow flexion/extension. Furthermore, the radioulnar (elbow) joint generates the supination and pronation. The distal ends of the radial and the ulna bones, make the wrist, which consists of the two joints: radiocarpal and midcarpal. Two wrist motions: flexion/extension and radial/ulnar deviation occur at the radiocarpal joint which allows the motion in two planes [19]. Table I, shows the Range of Motion (RoM) for the human upper-limb motions of a healthy adult male in degrees [17].

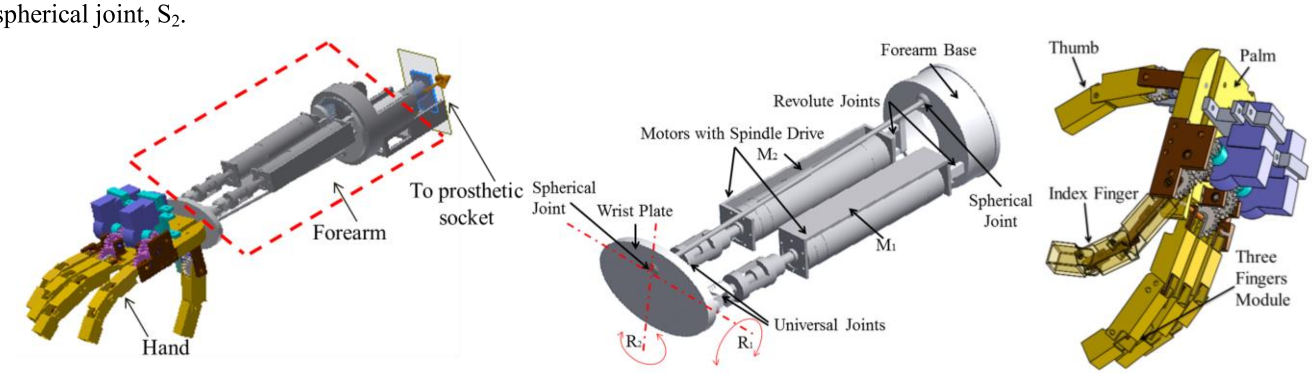
Figure 1 (b), shows the kinematic model of the human upper limb proposed by Mansour *et al* [20] considering the human upper-limb anatomy. It is being modeled as a spatial mechanism and based on the commonly used rigid body assumptions. The shoulder is considered as the frame while arm, radius, ulna and hand are considered as the mobile links. Centers of rotation of the all joints are considered to be fixed. The ball and socket joint of the shoulder is modeled as a spherical joint, S_1 [20]. The elbow joint is modeled as a revolute joint, R_1. Axis of rotation of elbow joint is aligned with the center of the radiohumeral joint and is modeled as a spherical joint, S_2.

The distal radioulnar joint is considered as a cylindrical joint, C_1 and its axis of rotation passes through the distal end of the ulna and the center of the capitulum of the humerus. According to this configuration the radius slides and rotates on the fixed ulna when the forearm rotates [20]. The wrist is modeled as a universal joint, E_5. Even though the modeling of the wrist as a universal joint suggests that two wrist motions have two different axes, some research work [21] has shown that they occurred in four different axes of rotations. Accordingly, the flexion and the extension axes are different. The radial and the ulna deviation axes are also different to each other [21], [22]. However none of the currently available prosthetic devices have followed the exact kinematic structure of the human upper extremity. It could be an important design strategy to follow, which will make the design furnished with anthropometric features while maintain a higher dexterity.

III. DESIGN AND MECHANISM OF PROSTHETIC ARM

A design of a prosthetic device should be capable of mimicking the exact human motion pattern, power requirement, and anatomical/ cosmetic features. Despite the existing upper-limb prosthetic devices are capable of providing the amputees' motion requirements to a certain extent, still there are some improvements and the design challenges that need to be addressed towards an improved prosthetic device. In this research the prosthetic arm is designed to look more anthropomorphic. Thus, the prosthetic arm is designed to generate the forearm supination/ pronation, not in a separate terminal device like in most of the existing upper limb prosthetic devices [2]. Further, the design tries to mimic the anatomical structure of the human upper limb as much as possible by having two links correspond to the ulna and radial bones. Those two links are introduced to the design in the form of the linear actuators and they together expected to generate the wrist motions.

In this section, the details of the mechanical design and the mechanisms of the proposed prosthetic device are presented. The multi-DoF transradial prosthetic arm can generate forearm supination/pronation, wrist flexion/ extension, wrist ulnar/radial deviation and finger motions. The design of the transradial prosthetic arm is shown in Fig. 2. Separate brace has to be used to attach the prosthetic arm to the right stump arm of the amputee. In order to get the hand functions, the terminal device shown in Fig. 2(c) is attached to the wrist plate.



(a) (b) (c)

Figure 2. (a) Proposed transradial prosthesis (b) Parallel manipulator wrist (c) Hand

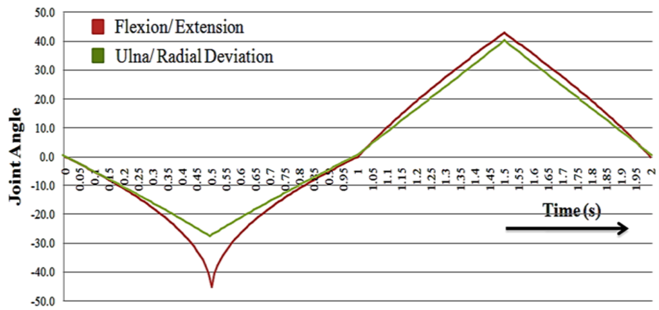


Figure 3. Joint angle for ulna/radial deviation and flexion/extension of wrist (+ Angle for wrist extension and ulna deviation)

The forearm motion is realized separately at the proximal end of the wrist mechanism. Next subsections present the details of each mechanism.

A. Wrist

The proposed wrist is shown in Fig. 2(b). It is almost in line with the upper limb kinematic model and it allows the motion in two planes for the wrist, similar to the radiocarpal joint. The mechanism is developed using two linear actuators and one passive link for rigidity. Two linear actuators are connected to the wrist plate through two universal joints (See Fig. 2). Single linear actuator consists of a motor (EC22, maxon motors) and a spindle drive (GP22-S, maxon motors). They are connected to the forearm wheel through two revolute joints perpendicular to each other. The passive link connects the moving wrist plate to the forearm base using spherical joints at the both ends as shown in Fig. 2 (b) to assure the rigidity of the mechanism. Forearm base acts as the base for the 2-UPR and SS (U-Universal, P-Prismatic, R-Revolute, S-Spherical) parallel link mechanism. The wrist plate is the moving platform. As shown in Fig. 2 (b) the mechanism is operated using the two linear actuators. When the lengths of the actuators M_1 and M_2 get extended, the moving plate rotates clock wise about R_1 axis. When the actuator lengths get retracted the plate rotates anti-clock wise about R_1. These motions generate the wrist flexion and extension respectively. When the length of the actuator M_1 extended and the M_2 retracted, the wrist plate rotates clock wise about the R_2 axis. Extension of the length of the M_2 and the retraction of M_1 resulted in the anti-clock wise rotation of the plate about the R_2. These two motions generate the wrist radial deviation and ulna deviation respectively.

B. Forearm Joint

Two linear actuators correspond to the ulna and radial bones of the forearm. They are connected to the forearm base, which directly contributes to the forearm motion, supination/pronation. An internal gear is connected to the forearm base with 1:3 reduction ratio. The driver gear is coupled with the motor (A-max 19, maxon motors) and the gear system (GP22, maxon motors) which results a torque of 1.2 Nm. The moving part is connected to the forearm holder with a needle roller bearing (K64×70×16, NTN). Motor transmits the torque to the forearm base of the wrist mechanism to generate the supination/pronation. This mechanism is capable of allowing the forearm motion to occur in the forearm itself, making a difference from the existing mechanisms which generate the motion at the wrist.

C. Hand

The terminal part of the transradial prosthetic arm is developed as a separate device and it follows the intrinsic and the under-actuation principles. Thus, it consists of an anthropomorphic hand as shown in Fig. 2 (c). The hand consists of separate actuation module each for the thumb, index finger and the remaining three fingers. They together produce 7DoF. Each module is actuated using the motors (RE16, maxon motors) and power is transmitted via gear to the links (See Fig. 2 (c)). Except the thumb, other fingers follow the modified Cross Bar Mechanism (CBM) [23] in their designs. Modified CBM facilitates the finger to be under-actuated and to achieve grasping adaptation during the grasping of different geometries. This grasping adaptation is achieved as a result of the introduced link-spring construction to the CBM linkages. When the finger motions are restricted from a certain geometry, springs allow the fingers to adjust their joint angles accordingly [23]. More details of the hand mechanism can be referred in [23].

IV. Motion Simulation

The prosthetic arm is modeled in the Autodesk Inventor student license package. The proposed wrist mechanism is evaluated to verify that it is free of mechanical constraints that are due to joints collision or links collision. The inbuilt mobility analysis in Autodesk Inventor showed that the expected mobility is equal to 2.

The mechanism is simulated applying predefined, arbitrary actuation lengths provided by the linear motors, with the dynamic motion analysis tool of the package. The output joint angles are obtained and values of the stroke of the actuators and the output are recorded. Analyzing the obtained results with the stroke values, a better input pattern is identified to be fed as the simulation inputs. According to the results, the realized radial deviation of the prosthetic wrist is around 21^{o} and ulna deviation is around 31^{o}, which are in line with the expected range for the ulna/ radial deviation. About 45^{o} for the flexion and around 43^{o} for the extension were obtained (see Fig. 3). Even though the realized motion ranges have minor difference than the human motion ranges, they lie well within the motion ranges required for the ADL. The obtained results show that the proposed wrist mechanism is capable of providing high speed position generation and higher positional accuracy, which are the inherent properties of parallel manipulators.

Consider the ulna deviation as an example. The required stroke length for the maximum motion range is 14 mm. The actuator is capable of achieving a positional accuracy of 0.2 mm. Furthermore, the output angle has a linear relationship with the input, stroke length (see Fig. 3). Therefore, in between the neutral position and the maximum point, there are 70 intermediate points that the actuator can separately reached for. Accordingly, for the wrist ulna deviation it has 70 intermediate angular points and thus angular positional accuracy for the motion would be 0.443 (31/70) degrees. Hence, the motion inherits higher positional accuracy. In addition, the actuator has 6 mm/s speed at its peak power point. If the same motion is considered, it needs a 14 mm stroke length for its peak point, 31 degrees. It results in around 13.3 deg/s angular speed to the wrist motion which is a considerable speed. Thus, the proposed parallel link wrist is capable of providing the expe-

TABLE II. A COMPARISON OF JOINT ANGLES, POSITIONAL ACCURACY AND JOINT SPEEDS

	Ulnar Deviaiton	Radial Deviation	Flexion	Extension
Normal JA	30	20	75	75
JA for DL[17]	15	10	5	30
Realized JA	31	21	45	43
Stroke Length	14	9	6.6	15
Positional Accuracy	0.443	0.467	1.364	0.573
Joint Speed	13.3	14	40.9	17.2

a. JA is for Joint Angle and are in degrees, Stroke Length is in mms, Joint Speed is in Deg/s

cted motions with a higher positional accuracy and with a higher operation speed. Table II shows a comparison of the human upper-limb joint angle, the joint angles required for the daily life activities and the joint angles realized from the wrist mechanism together with the motor stroke length, the positional accuracy and the angular speed for the wrist motions. The calculated weight of the proposed wrist assembly is about 500 g including the two linear motors. The weight value would lie within human anthropometric range.

V. KINEMATICS ANALYSIS OF THE WRIST MECHANISM

When selecting the joints and bodies to design the wrist mechanism, they should be selected such that, they are capable of providing the required DoFs. Figure 4, shows such selected joints and frames for the mechanism of the proposed wrist joint. The mechanism could be checked for the required number of DoFs theoretically. Accordingly the mobility, F of a parallel manipulator is determined by the Kutzbach Formula:

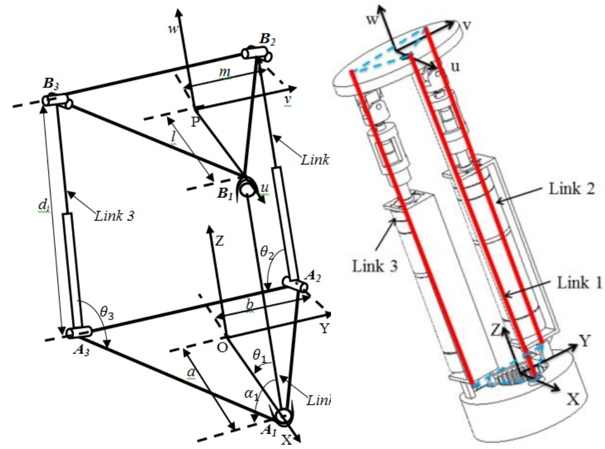
$$F = 6(n - j - 1) + \sum_{i=1}^{j} f_i \tag{1}$$

where n is the number of links, j is the number of kinematic pairs and f_i is the number of DoF of the ith pair. In the proposed wrist mechanism n=7, j=8 and Σf_i is equal to 14. According to (1), the DoF of the mechanism is equal to 2. Therefore the proposed mechanism is capable of generating required 2 DoFs of the wrist.

Figure 4 (a) shows the schematic of the novel parallel wrist mechanism. Corresponding equivalent schematic diagram on actual design is shown in Fig. 4 (b). The base Cartesian coordinate system is fixed to the centroid of the $A_1A_2A_3$ triangle. X axis is pointing towards the spherical joint, A_1. Z axis is normal to the plane $A_1A_2A_3$. Y axis is defined using the right hand rule. Similarly, moving Cartesian coordinate system is fixed to the centroid of $B_1B_2B_3$ triangle. Axis u is pointing towards the spherical joint, B_1. Axis w is normal to the plane of $B_1B_2B_3$. Axis v makes the right hand coordinate system uvw. A_1B_1, passive link connects the two spherical joints of the base and its length is d_1. Link 2 and 3 represent the linear actuators and have varying lengths d_i (i=2,3). Accordingly, the coordinates of the revolute joints and the spherical joint of the base are given in (2). The coordinates of the two universal joints and the spherical joint of the moving plate are given in (3).

$$\left.\begin{aligned} A_1 &= [a \quad 0 \quad 0]^T \\ A_2 &= \left[-\tfrac{a}{2} \quad b \quad 0\right]^T \\ A_3 &= \left[-\tfrac{a}{2} \quad -b \quad 0\right]^T \end{aligned}\right\} \tag{2}$$

$$\left.\begin{aligned} B_1 &= [l \quad 0 \quad 0]^T \\ B_2 &= \left[-\tfrac{l}{2} \quad m \quad 0\right]^T \\ B_3 &= \left[-\tfrac{l}{2} \quad -m \quad 0\right]^T \end{aligned}\right\} \tag{3}$$



(a) (b)

Figure 4. (a) Schematic diagram of novel wrist mechanism (b) Equivalent schematic diagram on actual design

The coordinate frame uvw with respect to the base coordinate frame can be described by the rotation matrix of direction cosines and is given in (4).

$${}^{A}R_{b} = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} \tag{4}$$

The matrix consists of direction cosines of u, v and w. Elements in (4) satisfies the orthogonal conditions and they are given in (5).

$$\left.\begin{aligned} u_x^2 + u_y^2 + u_z^2 &= 1 \\ v_x^2 + v_y^2 + v_z^2 &= 1 \\ w_x^2 + w_y^2 + w_z^2 &= 1 \\ u_x v_x + u_y v_y + u_z v_z &= 0 \\ u_x w_x + u_y w_y + u_z w_z &= 0 \\ v_x w_x + v_y w_y + v_z w_z &= 0 \end{aligned}\right\} \tag{5}$$

Position vectors of the joints in the wrist plate with respect to the base coordinate frame can be obtained by (6).

$$B_i = P + {}^{A}R_b.{}^{B}b_i \tag{6}$$

By substituting (2), (3) and (4) into (6);

$$B_1 = \begin{bmatrix} P_x + lu_x \\ P_y + lu_y \\ P_z + lu_z \end{bmatrix} \tag{7}$$

$$B_2 = \begin{bmatrix} P_x - \frac{l}{2}u_x + mv_x \\ P_y - \frac{l}{2}u_y + mv_y \\ P_z - \frac{l}{2}u_z + mv_z \end{bmatrix} \tag{8}$$

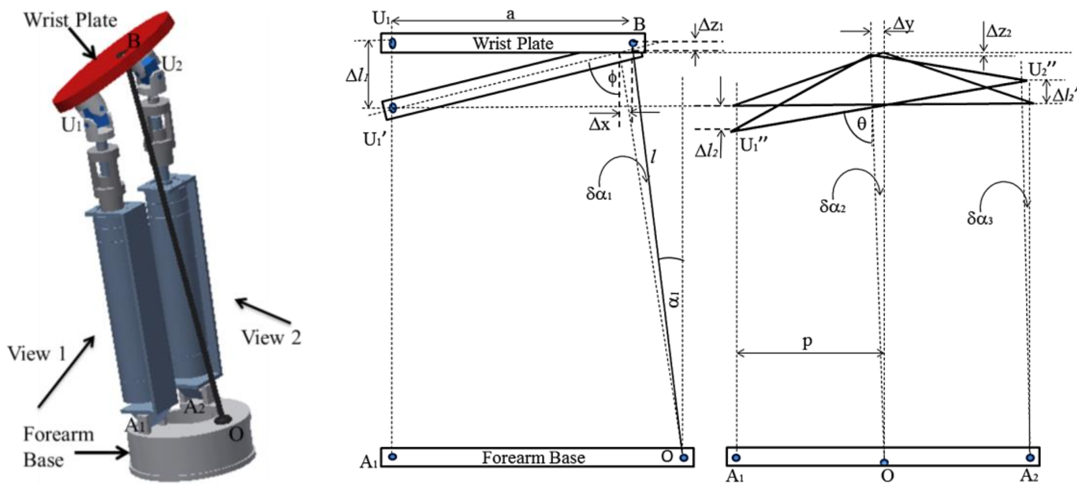
$$B_3 = \begin{bmatrix} P_x - \frac{l}{2}u_x - mv_x \\ P_y - \frac{l}{2}u_y - mv_y \\ P_z - \frac{l}{2}u_z - mv_z \end{bmatrix} \tag{9}$$

Length of a link d_i, can be derived using the relationship in (10).

$$d_i^2 = [B_i - a_i]^T [B_i - a_i] \tag{10}$$

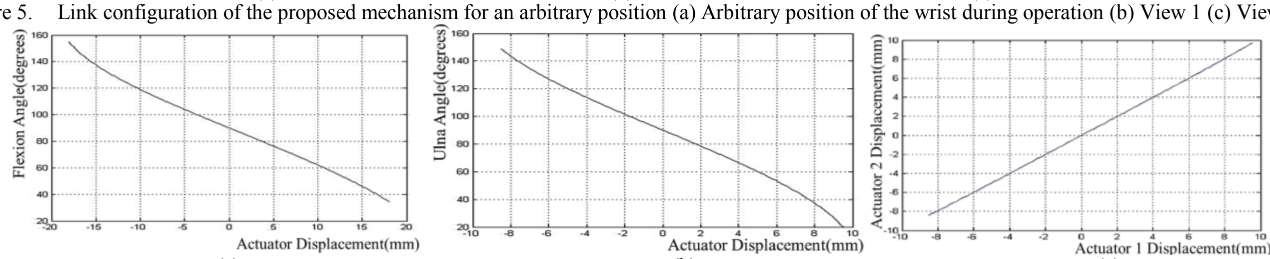
By substituting (7), (8) and (9) into (10);

$$d_1^2 = (P_x + lu_x - a)^2 + (P_y + lu_y)^2 + (P_z + lu_z)^2 \tag{11}$$



(a) (b) (c)

Figure 5. Link configuration of the proposed mechanism for an arbitrary position (a) Arbitrary position of the wrist during operation (b) View 1 (c) View 2



(a) (b) (c)

Figure 6. (a) Varation of Flexion/ Extension angle (b) Variation of Ulna/ Radial Deviation angle (c) Actuator displacement for Ulna/ Radial Deviation

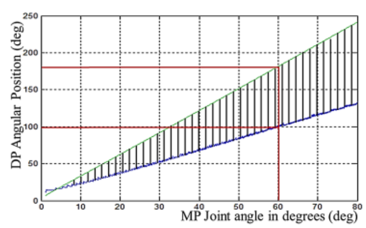


Figure 7. Angular displacement of distal phalanx

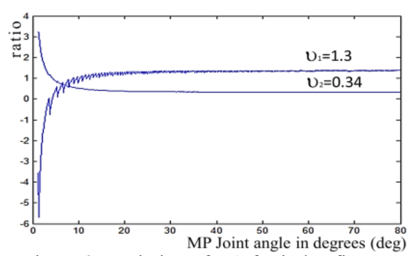


Figure 8. Variation of DA for index finger

$$d_2^2 = \left(P_x - \frac{l}{2}u_x + mv_x + \frac{a}{2}\right)^2 + \left(P_y - \frac{l}{2}u_y + mv_y - b\right)^2 + \left(P_z - \frac{l}{2}u_z + mv_z\right)^2 \quad (12)$$

$$d_3^2 = \left(P_x - \frac{l}{2}u_x - mv_x + \frac{a}{2}\right)^2 + \left(P_y - \frac{l}{2}u_y - mv_y + b\right)^2 + \left(P_z - \frac{l}{2}u_z - mv_z\right)^2 \quad (13)$$

The inverse kinematic solution of the proposed wrist mechanism is presented in (11), (12) and (13).

Figure 5, shows the basic link, actuator configuration of the proposed wrist mechanism. O and B are the two centers of the ball joints on the base and the moving plate respectively. U_1 and U_2 are the centers of the universal joint. A_1U_1 and A_2U_2 are the linear actuators used to actuate the wrist mechanism. In Fig. 5 (b), an actuation of Δl_1 is given to the both actuators and in the Fig. 5 (c), an actuation of Δl_2 is given to the A_1U_1 actuator only. With the other parameters marked in the Fig. 5, following relationships can be obtained.

Considering the displacement of the center of spherical joint, at the moving plate in Fig. 5 (b);

$$\Delta z_1 = \Delta l_1 - a\cos\phi = l\cos\alpha_1 - l cos(\alpha_1 + \delta\alpha_1) \quad (14)$$

$$\Delta x = a - a\sin\phi = l\sin(\alpha_1 + \delta\alpha_1) - l\sin\alpha_1 \quad (15)$$

$$l' = l\cos(\alpha_1 + \delta\,\alpha_1) \quad (16)$$

$$\Delta y = p - p\sin\theta = l'\sin\delta\alpha_2 \quad (17)$$

$$\Delta z_2 = \Delta l_2 - p\cos\theta = l' - l'\cos\delta\alpha_2 \quad (18)$$

Using (14)-(18) relationships between the input and the output can be obtained. Figure 6 (a) shows the relationship between the input to the two actuators and the output flexion angle of the wrist. Figure 6 (b) shows the relationship between the input from the actuator one (M_1) and the output ulna deviation angle of the wrist. In Fig. 6 (c) the corresponding actuation of the second actuator (M2) is shown with respect to the actuation of M_1.

In addition to this, a kinematic analysis based motion simulation is carried out to verify the hand design for the expected motion generation. Figure 7 shows the functioning range of angle of flexion of distal phalanx with rotation angle of the input shaft (MP Joint angle) of the finger mechanism. Here at MP joint angle of 60 deg, the finger mechanism is capable of varying the position of the distal phalanx from 100 deg to 180 deg. Thus the finger has the capability of handling any geometry within this range of angular position for the distal phalanx. Further, degree of adaptation (DA) was introduced in [23], as a parameter to evaluate the performance of under-actuated finger designs. It measures the ratio between range of angle of a phalanx can vary at a given metacarpophalangeal (MP) joint angle, δθ and MP joint angle, θ. DA is denoted by ν,

$$\nu = \frac{\delta\theta}{\theta} \quad (19)$$

DA is used to give an idea about the effectiveness of the adaptation mechanism. It shows the ability of a finger joint to adopt according to the different geometries. Higher the value of the parameter, higher the adoptability of the finger joint will be. DA analysis results are shown in Fig. 8 for the index finger. It rapidly converges to a fixed value within first 10 degree of the MP joint angle. DA for distal phalanx is υ_1=1.3 and for middle phalanx is υ_2=0.34

VI. Conclusion

This paper proposed a multi-DoF transradial prosthetic arm to generate the forearm, wrist and hand motions. A novel 3-DoF mechanism is proposed to realize the wrist motions. The design mimicked the human anatomical configuration with the introduction of the two links corresponded to the bones of the forearm. A kinematic analysis and a motion simulation were carried out in order to verify the effectiveness of the proposed mechanism in motion generation. The results of the geometrical analysis show that the wrist mechanism is capable of achieving required joint angles. The motion simulation results showed that the mechanism is capable of achieving high speed operation and higher positional accuracy, while providing the anthropometric features. Further, forearm design is also capable of achieving the human motion ranges according the simulation results. Thus the proposed prosthetic arm is successful in achieving both dexterous and anthropomorphic features in a single design.

Proposed new mechanism provides the expected full motion range for the wrist ulnar/radial deviation. Even though it is not capable of providing the full motion range for the wrist flexion/extension, it is capable of providing the motion range required for ADL. This is due to the parallel link mechanism, where the workspace of PMs is limited. In order to enhance the range of motion of the wrist mechanism, design parameters are to be optimized during the next phase of the research.

In addition a 7DoF hand mechanism with three actuation modules is also proposed. The hand design is under-actuated and furnished with the capability of grasping adaptation for different geometries. The simulation results based on the kinematic analysis for the hand design are also summarized. The hand is capable of generating the dexterous fingertip motions with grasping adaptation for different geometries. Further, the new parameter, DA was used to evaluate the self-adapting finger designs. Thus for the proposed finger design, the adaptability of the finger mechanism increases with the MP joint angle.

The prosthetic arm is expected to control according the motion intention of the amputee. Accordingly, Electromyography (EMG) signals from the amputee's stump muscles can be used as main input to the controller. In addition, to compensate the lack of EMG signals due to the lost muscles, other sensor types such as inertial measurement units, vision based sensors and/ior foot pressure sensors can be used. Further, with built in controllers, the prosthetic arm can be converted to a modular type prosthetic device, so that the each joint requirement can be used separately according to the requirement of the user.

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