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Efficiency of Using Parallel Mechanisms in Prosthetic Joints

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Abstract

The problem of designing effective prosthetic joints is a very common issue that remains unsolved so far. In this research, we will be studying the efficiency of using Parallel Mechanisms (PMs) and especially the Spherical Parallel Manipulator (SPM) mechanism in designing prosthetic joints as it theoretically offers a solution to many problems faced by Serial-designed prosthetic joints. As we have seen from previous serial and parallel prosthetic designs, serial designs had a problem with providing the whole 3 Degrees of Freedom (DOFs) to the prosthetic due to the limb being overweight, which caused discomfort to the patients. On the other hand, there were not enough parallel designed prosthetics for sufficient analysis. But, when studying the SPM on its own, there were some promising results regarding the transmitted torque and the accuracy and agility of the moving prosthetic leading us to think that SPMs might be convenient to use in several 3 DOFs prosthetic joints such as the waist, shoulder and wrist.

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Chapter 1

Introduction

1.1 What are Parallel Mechanisms (PMs)?

Unlike Serial manipulators which are mechanisms consisting of a single open-loop kinematic chain [19], Parallel manipulators (or mechanisms) are the kinds of manipulators where the mechanism is made out of a closed-loop kinematic chain architecture in which the end-effector is connected to a fixed base using two or more chains.

1.2 Applications of PMs

Typically, PMs are used in pick-and-place robotized systems, stabilization platforms, tracking devices, medical robots, humanoid robots and prosthetic joints.

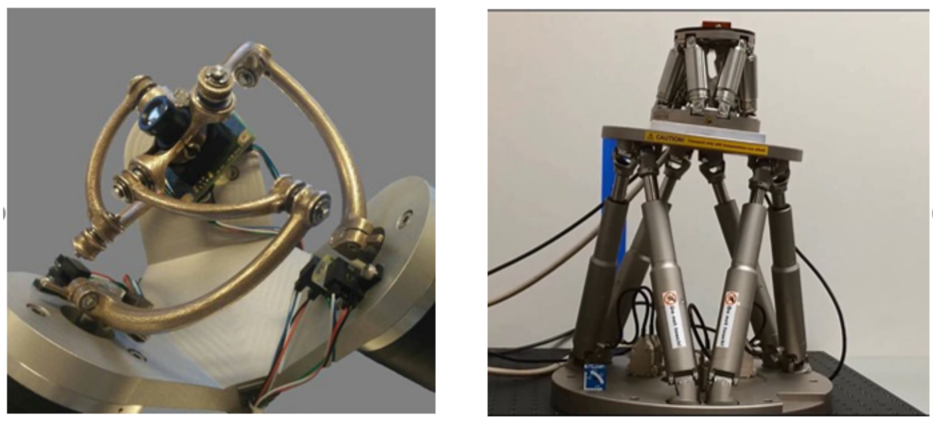

Figure 1.1: Applications of PMs

1.3 PMs in Prosthetic Joints

One of the biggest problems faced in designing and manufacturing prosthetics is mimicking the human body's motion which makes the design far too complicated and sometimes unusable by the patients due to its complexity, which forces the designers to somewhat reduce the Degrees of Freedom (DOFs) to simplify the design. On the other hand, parallel mechanisms can offer the same level of simplicity providing more DOFs to the prosthetic joint [6].

1.4 Advantages of PMs

Rigidity:

In most robot applications, rigidity is a very important factor because any sloppiness in the joints can cause serious problems in the arm itself due to the accumulation of mistakes from the base to the end-effector. This sloppiness is reduced noticeably in parallel mechanisms as the serial ones require large masses to eliminate this amplification of errors in order to get the accuracy needed in the end-effector while PMs can provide the same level of rigidity in much less mass than that of their serial counterparts.

Speed:

Usually, one of the important criteria in designing any mechanism is the speed of accomplishing the required tasks. Serial mechanisms may need more time since each joint in a serial mechanisms is generally driven by an actuator using multistage speed reducer through several drive shafts [14].

Accuracy:

Due to the rigidity of PMs, the end-effector can reach the target point in a more accurate way than the serial mechanisms which may need to slow down a lot in order to reach the same level of accuracy [4].

Agility:

Since, as mentioned before, PMs need less mass than serial mechanisms to reach the same rigidity, PMs have less weight, generally. Adding that to the speed of the PMs, it is found that, compared to serial mechanisms, PMs move in a swifter, more agile way than their serial counterparts.

1.5 Disadvantages of PMs

Non-Linearity:

Usually in PMs, the needed linear or circular motion in the end-effector does not have a direct linear relation to the motion of the motors.

Complexity in Kinematic and Dynamic Analyses:

One of the main drawbacks of using parallel mechanisms is the complexity of its kinematics which makes them hard to analyze since it is necessary to conduct the kinematic analysis, and especially the forward kinematics, in fine detail [19].

Difficulty of Control:

The complexity of kinematics and non-linearity of motion makes the mechanism hard to control without self-collisions in the mechanism resulting in physical interference between the links [19].

Difficulty and Cost of Manufacturing:

Due to the complexity of the design and the accuracy needed in manufacturing the links of a parallel mechanism, the cost of materials needed to make a PM is somewhat high when compared to serial mechanisms.

Limited Workspace:

Parallel Manipulators in general have a limited or small workspace when compared to Serial Manipulators, meaning that the volume of space the end-effector can reach is limited in PMs.

1.6 Comparison Results

Requirements for Prosthetic Joints

In prosthetic joints, it is required to make a joint similar to the human body's motion which needs rigidity, speed, high accuracy and agility in a design that is easily controllable and can be manufactured with the minimum efforts and costs possible. Another requirement of prosthetic joints is the limitation of movement as most human joints do not require full 360 degrees motions which can be easily provided with parallel mechanisms, unlike the serial ones which need additional mechanical boundaries to provide this limitation in motion.

What Requirements Each Type Meets

Requirement	*Rigidity*	*Accuracy*	*Agility*	*Motion limiting*	*Control difficulty*	*Manufacturing cost & effort*
Type that meets it better	P	P	P	P	S	S

Table 1.1: Comparison between parallel and serial mechanisms
P = parallel, S = serial

Chapter 2

Prosthetic Wrist Motion and Requirements

2.1 Human Wrist Degrees of Freedom (DOFs)

A human wrist has three Degrees of Freedom, which are: pronation/supination, flexion/extension and abduction/adduction, as shown in Figure 2.1, where each of the pairs resembles the positive and negative motions of the same DOF around one of the axes [2].

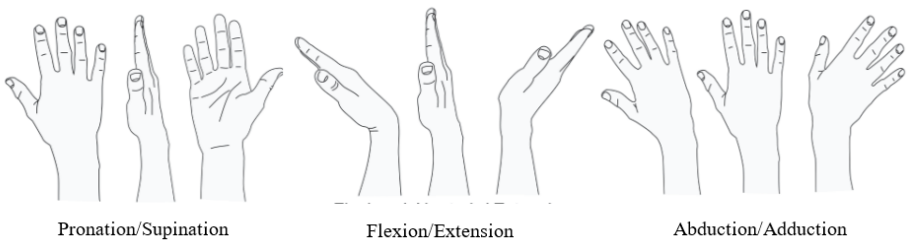

Figure 2.1: Human wrist DOFs

2.2 Ranges of Each DOF

The maximal ranges for each of the previous DOFs are given as follows according to Bajaj et al. [2]:

- Pronation/Supination: 76°/85°
- Flexion/Extension: 75°/75°
- Abduction/Adduction: 20°/45°

2.3 Maximal Torque in Each Position

As Yoshii et al. [20] show in their study about wrist torques in different positions, the maximum wrist extension torques 4.6 ± 1.0 Nm in the neutral, 6.5 ± 1.4 Nm in the pronation, and 5.5 ± 1.2 Nm in the supination positions. And as moticed, the maximum torque was in the pronation position.

2.4 Joint Types Used in Prosthetic Wrists

In most designs, joints of the prosthetic wrist mechanisms were made by combinations of revolute, spherical joints and/or universal joints and sometimes prismatic joints [2] which are all shown in Figure 2.2.

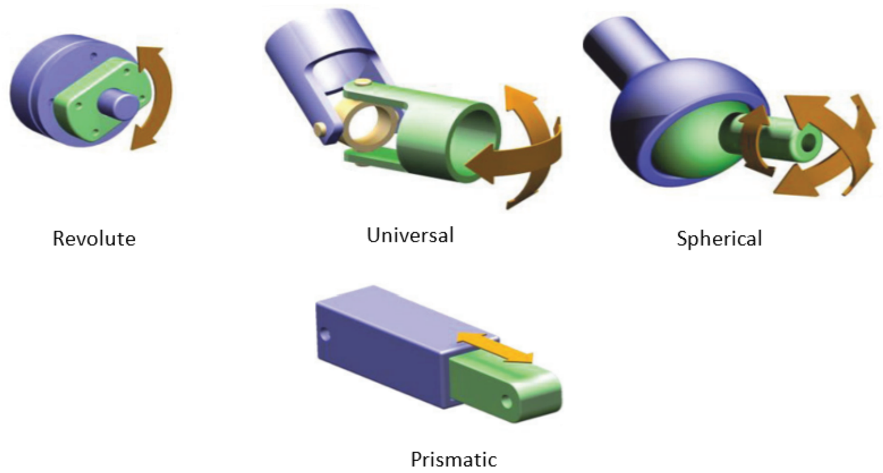

Figure 2.2: Mechanical joints' types

Chapter 3

Designs of Wrist Prosthetics

Note: in this section, only be active wrist prostheses are being studied.

3.1 Serial

- Razak et al. [16] designed and controlled a prosthetic wrist consisting of two DOFs of type 2R joints (two revolute joints). This 2R series was mounted at 90° offset which resulted in additional length to the limb and that excessive length can result in variance between the limbs which can affect the coordination of the manipulator [2].

Figure 3.1: Design of the Razak et al. prosthetic wrist

- Roose [17] designed another prosthetic wrist which is also a 2R prosthetic wrist design that provides the following two DOFs: (Pronation/Supination, Flexion/Extension) but in a more compact way reducing the space required and the problems accompanied by the excessive length in the limb and making it more suitable for practical use. However, according to the conclusion written by Roose, there have been misalignments in the rack and pinion gear combination. Also, because the serial design required a locking mechanism, there has also been issues in consistency between the flexion/extension mechanism and the rotary cylinder.

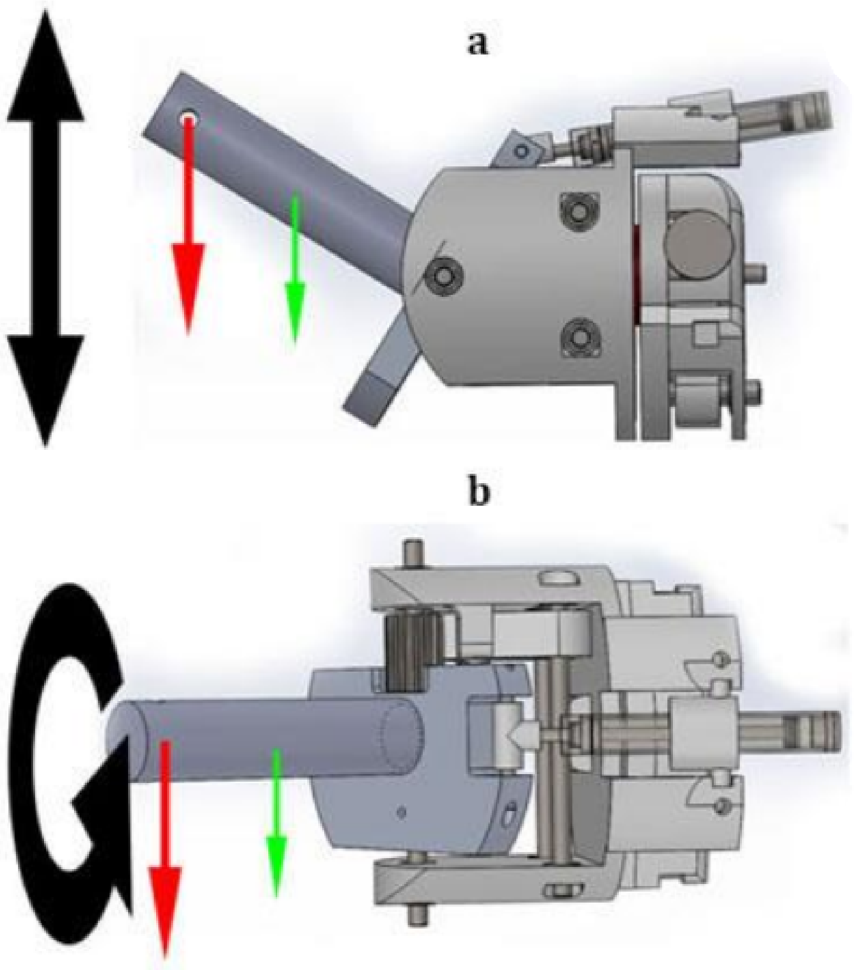

Figure 3.2: Design of the Roose prosthetic wrist

- Moving to a similar 2R prosthetic wrist made by Kyberd et al. [8], their design depended on a differential transmission allowing a tilted installation of the motors putting them outside the socket. This provides more space but results in weight offset and additional weight in the prosthetic which leads to discomfort for the patient and fatigue when wearing the device for long periods of time.

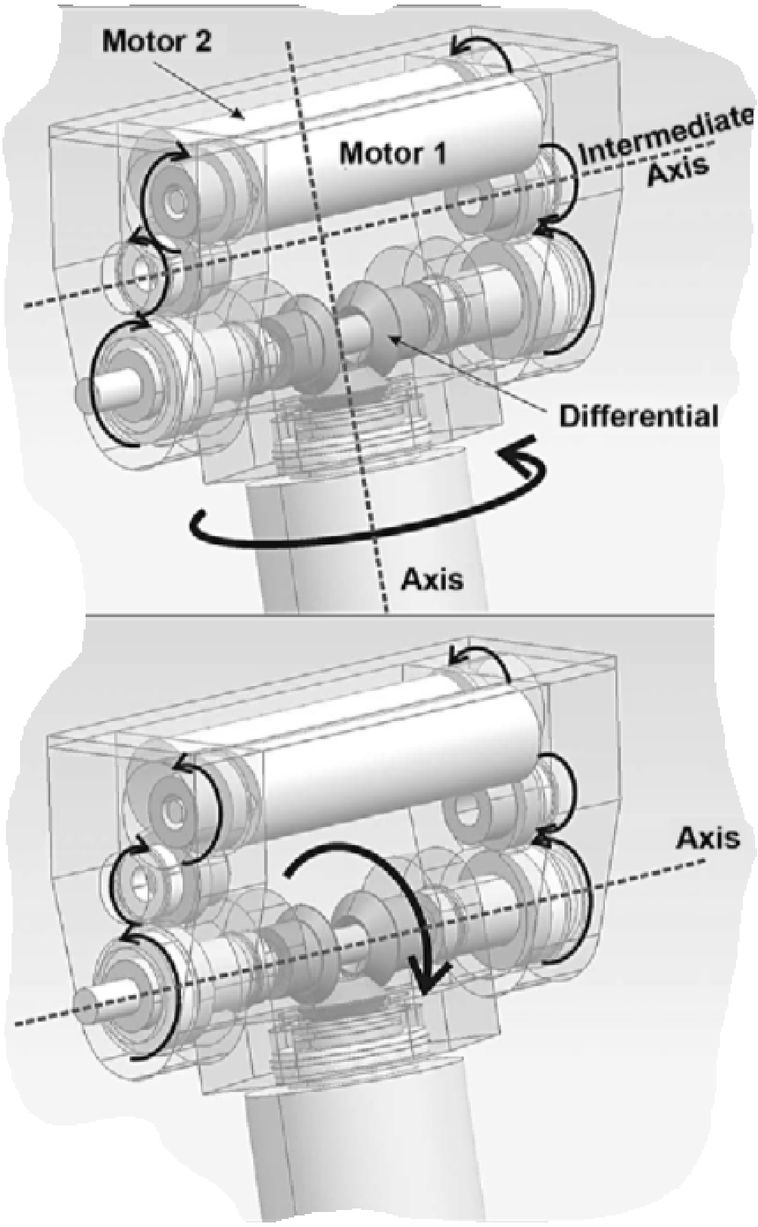

Figure 3.3: Design of the Kyberd et al. prosthetic wrist

- Now, another type of serial designs is discussed. This type provides three degrees of freedom and was designed by Johannes et al.[7] by using 3R joints which provide the Pronation/Supination DOF through using a rotator in the proximal forearm followed by a series of two motors with orthogonal axes.

Figure 3.4: Design of the Johannes et al. prosthetic wrist

- Another example of a 3R joints 3 DOFs wrist design is a design made by Mahmoud et al. [10]. This design differs from the previous one in the way the three motors are connected by being put together at right angles with one another.

Figure 3.5: Design of the Mahmoud et al. prosthetic wrist

- The next design in the study is an S joint (spherical joint) design which, according to Bajaj, Spiers and Dollar [2], is the only active wrist using a spherical joint. This, in spite having a spherical joint, does not provide 3 degrees of freedom as the Abduction/Adduction DOF is prevented because of using pins in the sphere of the spherical joint. This Bebionic Wrist design was made by the RSL Steeper in the United Kingdom.

Figure 3.6: Design of the RSL Steeper Bebionic Wrist

- The last serial design discussed in this study was made by Pinson [15] and provides the 3 degrees of freedom of the human wrist using an RS joint. Theoretically, RS joints give 4 DOFs. But, in this design, one of the three DOFs of the spherical joint is not permitted. However, the Pronation/Supination is achieved through the revolute joint which made the design more complicated and gave more length and weight to the prosthetic leading to problems referred to in previous designs.

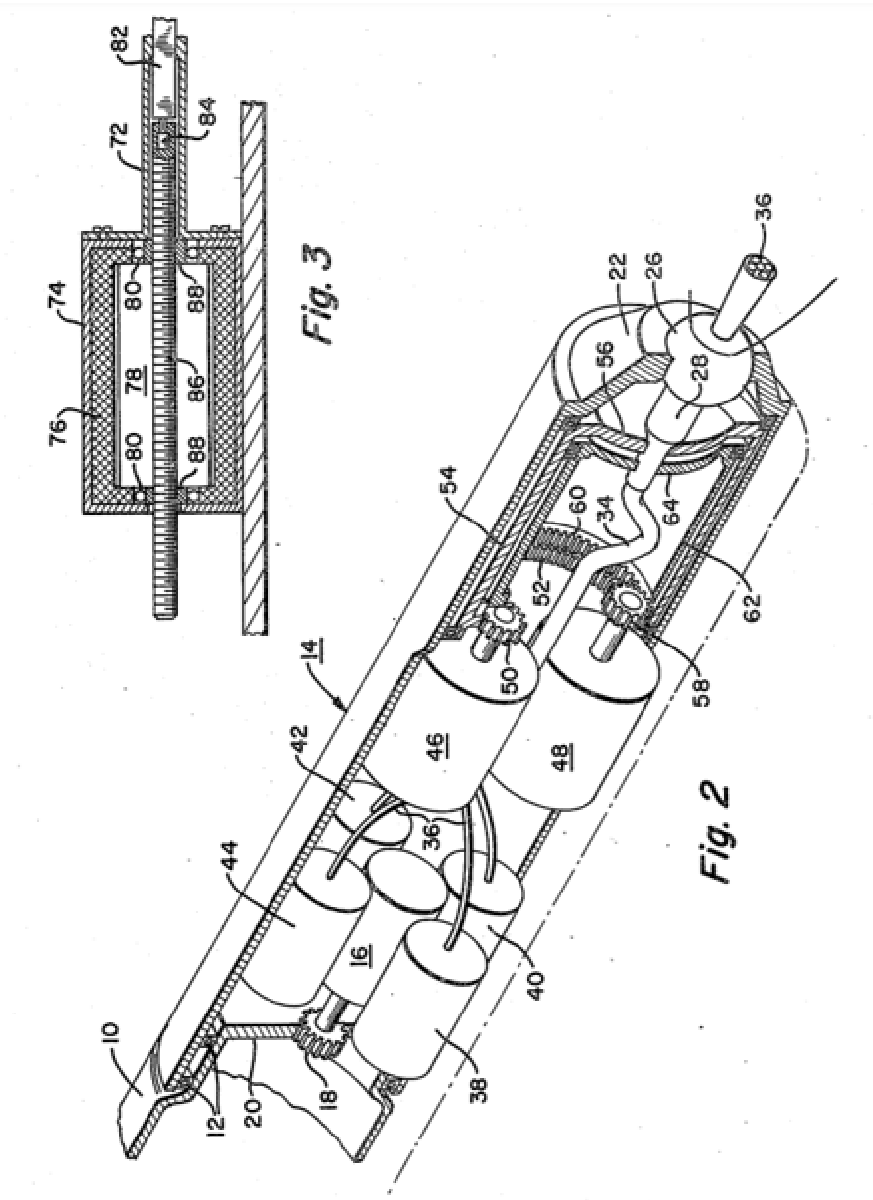

Figure 3.7: Design of the Pinson prosthetic wrist

3.2 Parallel

- According to Bajaj, Spiers and Dollar 2015 [2], there has only been one wrist prosthesis using a parallel mechanism. This prosthesis was made by Mustafa et al. [11]. It is a 3 DOFs wrist prosthesis similar to the biological human arm in the structure as it uses a 5 SPS (spherical and prismatic) structure of joints to provide the 3 degrees of freedom to an S joint in the end of the prosthetic wrist. This structure made it possible to drive the wrist using cables (like tendons in the human wrist), making the prosthesis lighter and more rigid than any previous serial design. A prototype has been made, but no tests have been made yet.

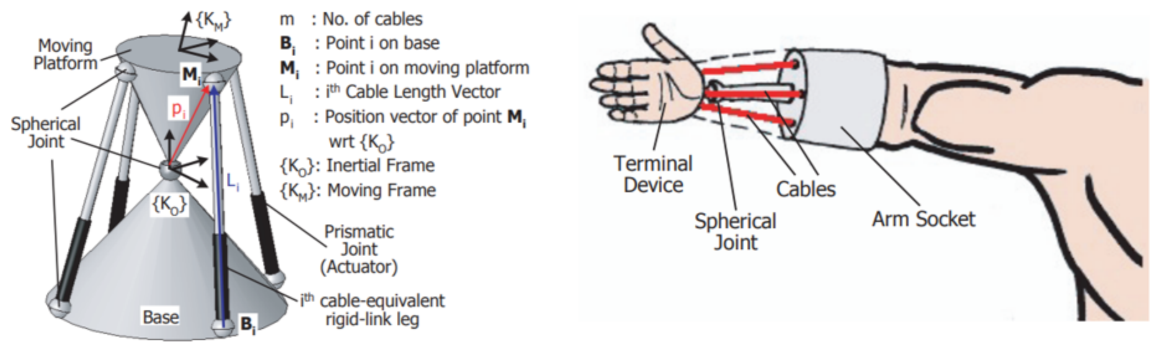

Figure 3.8: Design of the Mustafa et al. prosthetic wrist

- Another design was made as a graduation project at the HIAST by Saba and Samaan [18] where a Coaxial Spherical Parallel Manipulator mechanism was used to provide the 3 DOFs of the wrist. This mechanism will be discussed thoroughly later on. However, this design faced a problem in the manufacturing process due to the high accuracy needed to make the Coaxial SPM mechanism in order to limit the friction between the axes.

Figure 3.9: Design of the Coaxial SPM mechanism

3.3 Hybrid

There are some designs using hybrid mechanisms where the Pronation/Supination is achieved by an S joint in serial with a parallel 2 DOFs mechanism providing the Flexion/Extension and Abduction/Adduction degrees of freedom.

- One of these designs is a design made by Bandara [3]. This prosthetic wrist had the ability to work in high speeds with accurate positioning. However, the proposed mechanism did not achieve the full motion range of the wrist for the Flexion/Extension DOF which was said to be a result of using a parallel mechanism that limited the workspace of the wrist mechanism.

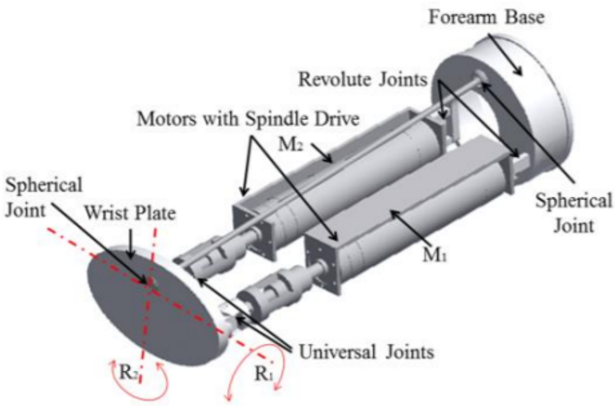

Figure 3.10: Design of the Bandara prosthetic wrist

3.4 General Comparison between the Designs

As we finished viewing and studying previous designs and prototypes of prosthetics that have been made so far in the world, we can now note that serial designs mostly omitted one degree of freedom or had a large, overweight prosthetic that caused fatigue and discomfort for the patients. On the other hand, parallel designs made so far are not sufficient and did not have final test results. But, theoretically, these designs solved most of the major serial designs' problems creating other issues such as the non-linearity of controls in addition to the complexity of the mechanisms' kinematics.

Chapter 4

The Spherical Parallel Manipulator

4.1 Introduction

One of the proposed solutions to design a wrist prosthetic is the Spherical Parallel Manipulator mechanism (SPM mechanism), which is a mechanism consisting of two pyramid shaped platforms. SPMs are widely used because of their high speed and accuracy which, in our case, is very important to have [13]. Another very important advantage of the SPM mechanism is having the ability to share the load between the three actuators which makes it possible to use smaller motors to manipulate the load which, in this case, is the prosthetic hand [12].
The design can either be asymmetrical where the two pyramids are not regular, or symmetrical where it is made of two regular pyramids with the angles β for the mobile platform and γ for the fixed platform which are shown in Figure 3.1-a. In special cases, γ can be equal to zero where the mechanism is called the Coaxial Spherical Parallel Manipulator which is shown in Figure 3.1-b [1].

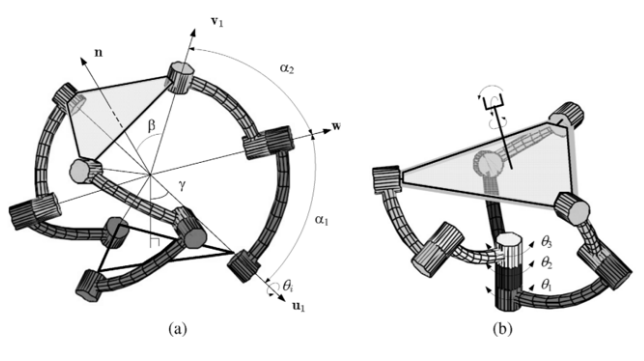

Figure 4.1: The Symmetrical Spherical Parallel Manipulator Design

4.2 Inverse Kinematics

To find the motor angles $\theta_1, \theta_2, \theta_3$ corresponding to a certain orientation of the end-effector, the Inverse Kinematics of the manipulator should be known. Which is done by finding u_i, v_i, w_i and entering them to the equation: $\boxed{w_i.v_i = \cos\alpha_2} \ldots (*)$. This leads to the following equations:

$$A_i t_i^2 + 2B_i t_i + C_i = 0, \qquad i = 1,2,3$$

Where:

$$\theta_i = 2\arctan t_i$$
$$A_i = (\sin\gamma.v_{i2} - \cos\gamma.v_{i3}).\cos\alpha_1 - (\cos\gamma.v_{i2} + sin\gamma.v_{i3}).\sin\alpha_1 - \cos\alpha_2$$
$$B_i = \sin\alpha_1.v_{i1}$$
$$C_i = (\sin\gamma.v_{i2} - \cos\gamma.v_{i3}).\cos\alpha_1 + (\cos\gamma.v_{i2} + \sin\gamma.v_{i3}).\sin\alpha_1 - \cos\alpha_2$$
$$u_i = [-\sin\eta_i.\sin\gamma, \cos\eta_i.\sin\gamma, -\cos\gamma]^T$$
$$v_i = Q.[-\sin\eta_i.\sin\beta, \cos\eta_i.\sin\beta, \cos\beta]^T$$
$$w_i = \begin{bmatrix} (\cos\eta_i.\sin\theta_i - \sin\eta_i.\cos\gamma.\cos\theta_i).\sin\alpha_1 - \sin\eta_i.\sin\gamma.\cos\alpha_1 \\ (\sin\eta_i.\sin\theta_i + \cos\eta_i.\cos\gamma.\cos\theta_i).\sin\alpha_1 + \cos\eta_i.\sin\gamma.\cos\alpha_1 \\ \sin\gamma.\cos\theta_i.\sin\alpha_1 - \cos\gamma.\cos\alpha_1 \end{bmatrix}$$
$$\eta_i = 2(i-1)\frac{\pi}{3}$$
$$Q \text{ is the rotation matrix}$$

A detailed solution for the inverse kinematics can be found in [1]. However, for the purposes of our study, only the final equations are mentioned.

4.3 Forward Kinematics

Here, the goal is to obtain the positions of the end-effector, which is defined by the Jacobian matrix of the manipulator J which can be obtained by differentiating equation $(*)$ and noting that $\dot{v}_i = \omega.v_i$ and $\dot{w}_i = u_i \times w_i.\dot{\theta}_i$ which leads to:

$$J_i = \frac{(w_i \times v_i)^T}{(u_i \times w_i).v_i}, \qquad i = 1,2,3$$

Where: J_i is the i$^{\text{th}}$ row of the Jacobian matrix. Also, the detailed solution to the forward kinematics can be found in [1].

4.4 Workspace

The workspace of a mechanism is defined as a system of equations, each defining a singularity surface separating the mobility region of the link from the immobility region. Each link workspace in the SPM can be defined by two parallel planes found by solving the equation of the inverse kinematics which gives the following equation:

$$x_i \sin\eta_i.\sin\gamma - y_i.\cos\eta_i.\sin\gamma + z_i.\cos\gamma - \cos(\alpha_1 \pm \alpha_2) = 0, \qquad i = 1,2,3$$

A more detailed solution can be found in [1].
In Figure 3.2, the workspace of a single link of the SPM corresponding to the case where $\alpha_1 = 60^\circ, \alpha_2 = 90^\circ, \gamma = 60^\circ$ is shown. The region between the two planes is the mobility region or the attainable workspace and the two regions outside the planes resemble the immobility region:

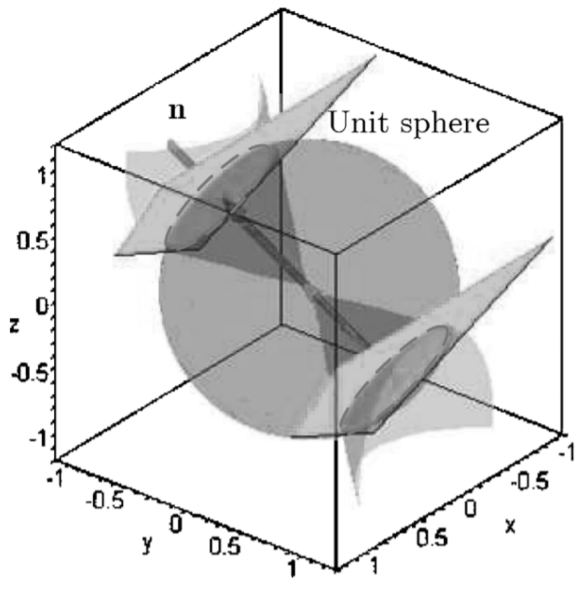

Figure 4.2: Workspace of a Single SPM Link Bounded by Two Planes

4.5 Torque Transmission

Assuming τ the torque vector of the joint drive, M the torque vector supported by the end effector, the relationship between τ and M can be given by [9]:

$$M = G.\tau$$

Where $G = (J^{-1})^T$ is the force Jacobian matrix of the manipulator.

As seen from the relationship between the two torques, the torque transmitted to the end-effector is related to G which is variable with the position of the platform.

4.6 Wrist Design Using SPM

In this section, a design made by Naranjo in 2017 [12] will be studied. This design used a symmetrical SPM with the angles shown in Table (2) for the prosthetic wrist.

Angle Name	*Value*
β	54.73°
γ	54.73°
α_1	60°
α_2	80°

Table 4.1: Angles of the Wrist SPM Mechanism

Where β and γ angles were chosen as suggested in [5] and the angles α_1, α_2 where determined after calculating the torque for different values in the range $[50°, 80°]$ choosing the best suiting values for the two angles.

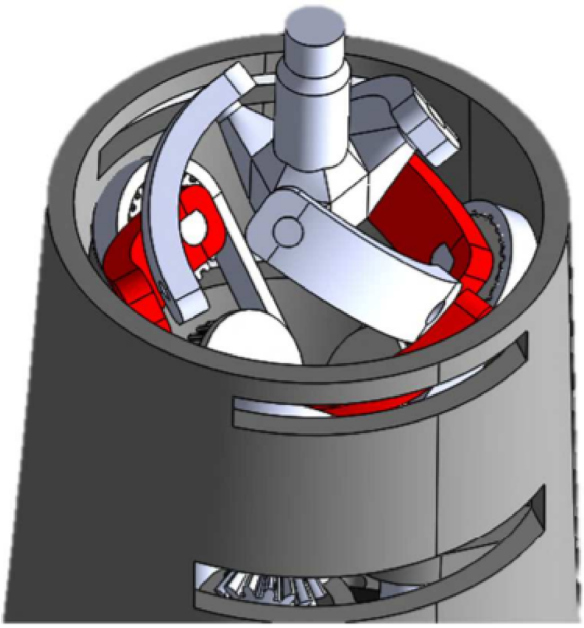

Figure 4.3: Design of the M. e. I. J. A. L. Naranjo Prosthetic Wrist

These parameters for the design fulfilled the required 40° for each of the flexion/extension and 40° of combined radial/ulnar deviation (abduction/adduction).
To test the design, 3 tests have been made:

- Flexion/Extension from -40° to 40° shown in Figure 4.4-a.
- Abduction/Adduction from -15° to 15° shown in Figure 4.4-b.
- Pronation/Supination from -20° to 20° shown in Figure 4.4-c.

All tests were done with a load of $5N$ plus the weight of the hand which is $0.23kg$ at a distance d of approximately $0.1m$ resulting in a torque M of about:

$$5 \times 0.1 + 0.23 \times 10 \times 0.1 = 0.73Nm.$$

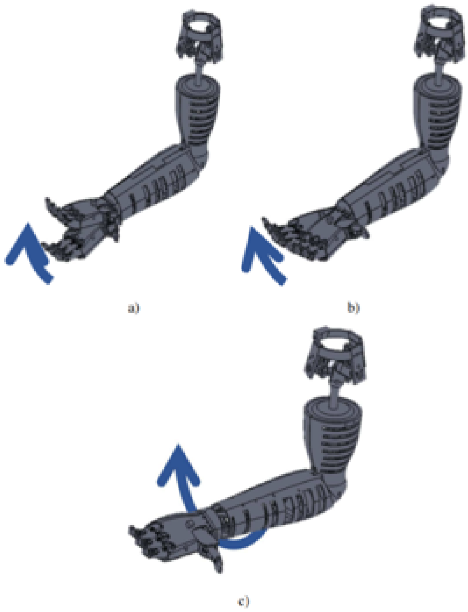

Figure 4.4: Tests made for the M. e. I. J. A. L. Naranjo Prosthetic Wrist Design

1. In the first test, the angular displacements of the motors were as shown in Figure 4.5-a, the maximum torque was $0.45+0.35+0.1=0.9Nm$ at the mid-point as shown in Figure 4.5-b which is close to the $0.73Nm$ loaded on the end-effector giving a transmission ratio of $0.73/0.9=81\%$ and the motors angular velocity behaved smoothly reaching a maximum of approximately $60deg/s$ as shown in Figure 4.5-c.

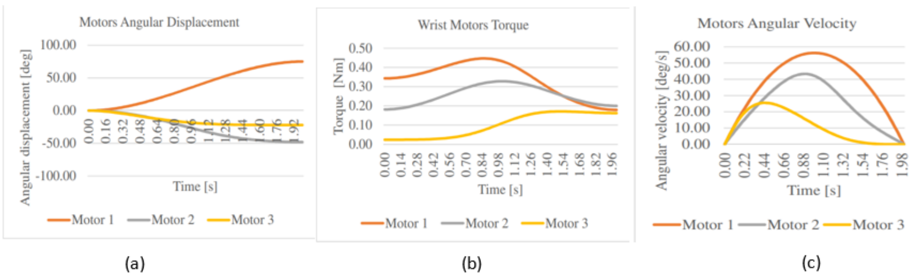

Figure 4.5: Results of test: (1)

2. In the second test, the angular displacements of the motors were as shown in Figure 4.6-a, the motor torques were almost constant with a maximum value of $0.45+0.3+0.1=0.85Nm$ as shown in Figure 4.6-b giving a transmission ratio of $0.73/0.85=86\%$ and the motors' angular velocities were slow but also behaved smoothly reaching a maximum of approximately $20deg/s$ as shown in Figure 4.6-c.

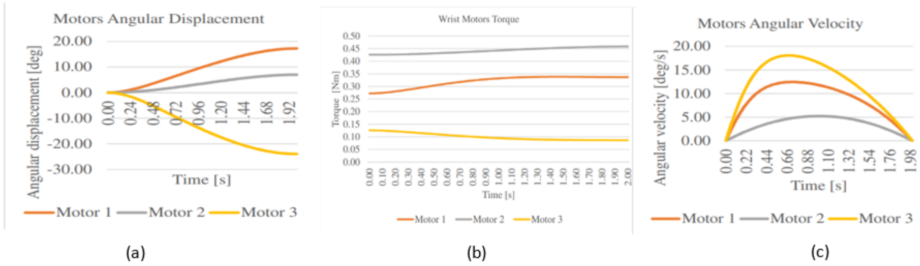

Figure 4.6: Results of test: (2)

3. In the third test, the angular displacements of the motors were identical as shown in Figure 4.7-a, the motor torques showed little variations with maximum value of $0.51 + 0.4 + 0.1 = 1.1Nm$ as shown in Figure 4.7-b giving a transmission ratio of $0.73/1.1 = 66\%$ and the motors' angular velocities were also identical due to the symmetry of the design reaching a maximum of approximately $25deg/s$ as shown in Figure 4.7-c.

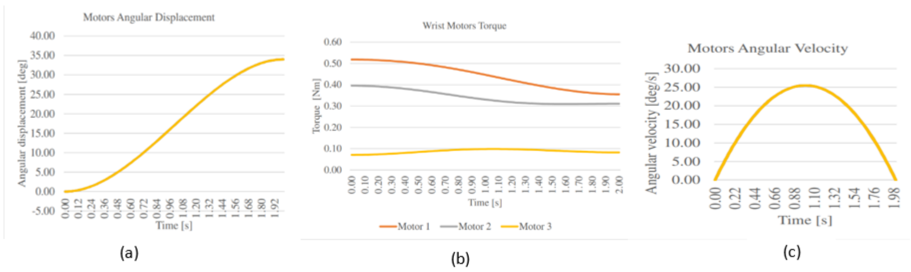

Figure 4.7: Results of test: (3)

Chapter 5

Conclusion

Parallel or Serial Mechanisms?

According to our study on the Spherical Parallel Manipulator mechanism, we can say that SPMs are more efficient to use than their serial counterparts which have been made so far in most 3 DOFs joints. SPMs' ability to share the load made it possible to use lighter and smaller actuators than the ones needed in a regular serial mechanism. The workspace available to an SPM is enough to fulfill the requirements of the human joints. And finally, the torque transmitted through the SPM is enough to bear normal human activities.

Figure 5.1: Parallel Mechanisms Vs Serial Mechanisms

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