Mechanical Design and Development of a 2 Degrees of Freedom Prosthetic Arm

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ABSTRACT

To improve the availability of affordable prostheses in developing regions, there is a need to introduce and produce a readily available and efficient device using locally sourced materials and accessible electronics. This paper presents the mechanical design of a prosthetic human arm with 2 DOFs at the elbow and 1 DOF at the wrist. The objective of this design is to have an anthropomorphic, functional, and low-cost prosthesis. A set of dynamic simulations were performed using SOLID WORKS and MATLAB SIMULINK to determine the feasibility of the mechanism as well as the torque required to perform the activities. The proposed fabricated model was subjected to real-time tests to determine its performance. The results obtained from this study are compared to results from other prosthetic arms including the Utah Arm by motion control Inc, Boston Elbow, and the CINVESTAV-IPN. The prototype weighing 800g is capable of active elbow flexion and extension and wrist Prono-supination this confirmed and supported the fact that the proposed fabricated model is a useful step to achieving affordable prostheses with this approach. These results are in line with the World Health Organization's standard for prosthetics and orthotics and they showed that the design could be a good solution due to the physical characteristics and the kinematic of the system.

Keywords: Prosthetic Arm, Low-Cost Prosthetic, Upper Limb Prosthetic, Biomedical Engineering

INTRODUCTION

Prosthetic arms are required for those who suffer either loss of an upper extremity due to accidents or are born with a physical disability (congenital disorders). Limb loss often has profound economic, social and psychological effects, especially in developing countries where prosthetics are poor. A Prosthetic arm can play an important role in rehabilitation. For many people, an artificial limb can improve mobility and the ability to manage daily activities, as well as provide the means to stay independent.

In a pilot study conducted over a period of 2.5 decades in the Kingdom of Saudi Arabia, 86.9% of upper limb amputations were performed on car accident victims [1]. Dysvascular diseases and cancer are two other factors that contribute to upper extremity amputees globally, and the United States alone is expected to experience 2.2 million upper limb amputations by the year 2020 [2]. Scientists have been working to replace amputated limbs over time. The early instances of prostheses are thought to have been passive devices with more of an aesthetic than a functional purpose. They did not give a variety of options for control or movement. Modern prosthetics have grown more functional from the prosthetic hooks originally developed in the early 1900s, they have proven to be an effective and reliable tool for amputees to use in their daily lives.

Wildly expensive smarter robotic prosthetic arms, which operate by picking up signals from a user's muscles can be exceedingly costly and, in many cases, ineffective and unaffordable to those who require them in developing regions. The primary purpose of this project is the design and fabrication of a cost-effective and functional arm using off-the-shelf parts and materials. The performance of the prototype is compared to available prostheses to serve as a foundation for a future product and also be used as mechanical research into what might be feasible with this design approach.

RELATED WOKS

Simulations Based on MATLAB

Simulation has become an essential part of modern design, research by Prof. Al-Faiz presents a simulation approach used on a human arm, dynamics, direct and inverse kinematics obtained by using the standard D-H modelling approach. This technique was used in a Simulink/Matlab project that included virtual reality to test the human arm's control. The simulation demonstrates the suggested methodology's successful application. It is clear from the results that virtual reality is useful for testing designs' viability before they are implemented in a virtual reality prototype and for performing GA-based PID tuning for prosthetic arms [3].

Rosca (2020) [4] proposed a 3D modelled solution developed with the support of computer-aided design software that is able to mimic the human arm anatomy being therefore easy to produce and suitable to combine the existent and future technology from the market, in order to replace the solutions that are either expensive, uncomfortable or have reduced functionality. In order to validate the model proposed they developed a mathematical model of the human armand simulate the entire functionality of the model. The 3D model proposed to reproduce a wide range of movements regarding the shoulder joint including the abduction movement at an angle between 0° to 90°. Regarding the joint of the wrist, it can also reproduce movements on two axes of rotation in a cylindrical workspace, offering, in addition the possibility of performing the flexion/extension on movement at the same angle as in the case of the anatomical joint of the wrist (0° to 60°).

These methodologies presented examined above are adapted in the design process for our prototype using the Robotics tool kit to model and confirm expected trajectories for the prototype.

The Bebionic 3

The Bebionic 3 is a world-leading commercial myoelectric arm. Like others of its kind, the Bebionic 3 uses a predefined grip system. A user can select from 14 different grip patterns using muscle activity around their upper forearm [5]. The user does not essentially have control of individual finger movements, rather they can select a grip pattern and then use muscle activity to activate the movements of that specific grip. The problem with a predefined grip system is that the user cannot finely control finger positions in order to grip a specific object or complete a task. Rather, a user must choose a grip pattern that best suits the job at hand and then cycle to that grip pattern.

Furthermore, the user must cycle through a number of grip patterns before they get to their desired choice. For example, unzipping a bag, picking up a heavy object, placing it in that bag and then zipping the bag up could require a number of grip changes. As a result, certain simple tasks like this could actually take quite some time to complete and can become tedious and frustrating. Our prototype aims currently aims at complete and direct control over the prosthesis.

Vanderbilt Hand

Research prosthetic devices are designed to test advanced mechanical designs and sophisticated control methods. Most research hands require an external power system, making them non-suitable as an attachment to an amputee [6]. Many research arms like the Vanderbilt and Bologna Universities anthropomorphic arms experiment with artificial tendon designs to drive finger movements [8]. The tendons running through the fingers and thumb are connected to crush DC motors to drive a pulley system that tensions the tendons. This tension results in all finger joints closing simultaneously, in order to open the fingers, springs have been implemented into each joint. When tension is released in the tendons these springs return the finger to its initial open position. A last notable mention is the CINVESTAV-IPN prosthesis which allows persons who have lost an extremity to reclaim their normal lives and live with fewer restrictions. A parallel system of actuators is used to create the prosthesis, allowing for an increase in the number of active degrees of freedom and thus range of motion [7]. Traditional commercial

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elbow prosthetics still have a long way to go in terms of costs and availability in developing regions.

Design and Analysis of the Prosthetic Arm

The fingers on our prosthetic arm do not take on the full complexity of a human finger. Cable-controlled prostheses use a single steel cable attached distally to the TD and proximally to the control attachment strap, hence the fingers are actuated utilizing a cable attached to the top section and are limited to a single degree of freedom. Each finger is actuated utilizing a cable attached to the top section and drawn by a servo motor.

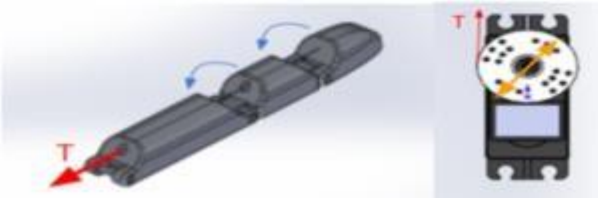

Figure 1: Typical Tendon Mechanism with Servo to Apply Tension (Imran 2020)

Design of Length of the Finger Cables

Two different configurations were tested for this mechanism. In the first configuration, the pulling and return of the finger are achieved by the same motion. This configuration is difficult to execute in practice as it deals with exact string lengths and does not account properly for the motion of the wrist.

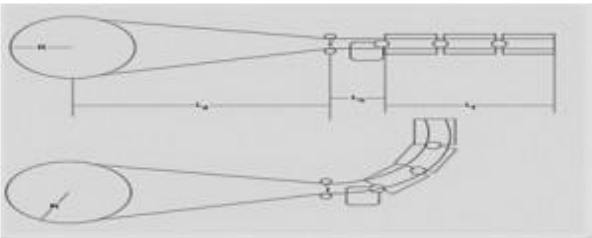

Figure 2: Proposed finger mechanism 1

$$L = 2(\pi R + \sqrt{(R-r)^2 + L_a^2} + L_h + L_f + 5mm) \quad (1)$$

Where L is the length of cable, R is the radius of pulley, R the radius of passage, L_a is the length of forearm, L_h is the length of hand, and L_f is the length of finger.

In the second configuration, the finger is pulled by a motor and a restoring force is used to return the finger to position 1, this restoring force is provided by elastic material placed between the joints of the fingers.

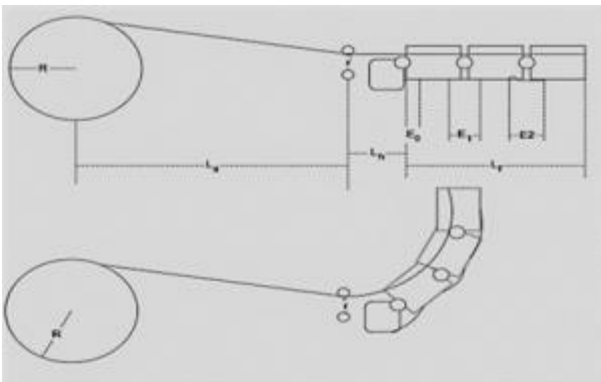

Figure 3: Second configuration of finger mechanism

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The length of the string can be determined from the equation.

$$L = \pi R + \sqrt{(R-r)^2 + L_a{}^2} + L_h + L_f + 3mm \quad (2)$$

And the minimum length of elastic material *E* is expressed as

$E = E_0 + E_1 + E_2$ *(3)*

Where:

E_0*, The length of elastic between hand and finger base*

$= (0.33f_0 + 10)$ (4)

E_1*, The length of elastic between base and mid-section*

$= (0.33(f_1+f_0) + 3)$ (5)

E_2*, The length of elastic between midsection and tip of the finger*

$= (0.33(f_1+f_2) + 10)$ (6)

Kinematic Modelling of Prosthetic arm

Our design removes the motion of wrist abduction and adduction while, motion of fore arm pronation and supination is actuated by q5 and the motion of wrist flexion and extension actuated by q6 while q4 is responsible for wrist flexion and extension

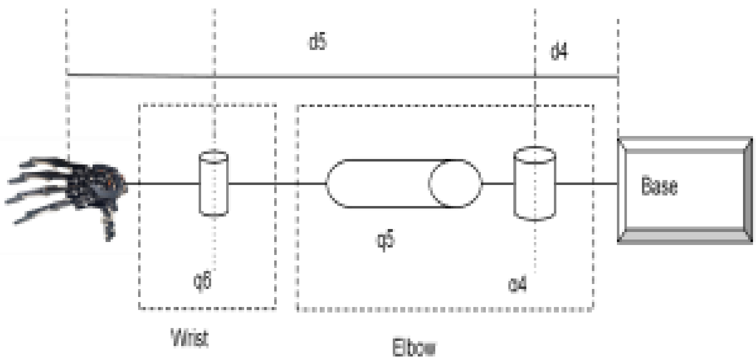

Figure 4: Kinetic diagram of prosthetic arm

By adjusting the frame of the end effector (the hand) and aligning it with *q6*, the resulting D-H parameters for the manipulator as shown in Table 1. This allows us to compute various poses.

Table 1

Link	α(rad)	di(m)	ai	*i*
q4	- π/2	0	0	*1*
q5	π/2	d5	d5	*2*
q6	π/2	0	0	*3*

The D-H parameters yield the transformation matrices

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$$ {}^{3}_{4}T = \begin{bmatrix} cos\theta_1 & sin\theta_1 & 0 & -\pi/2 \\ 0 & 0 & -1 & 0 \\ -sin\theta_1 & -cos\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{4}_{5}T = \begin{bmatrix} cos\theta_2 & sin\theta_2 & 0 & \pi/2 \\ 0 & 0 & 1 & d5 \\ sin\theta_2 & cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{5}_{6}T = \begin{bmatrix} cos\theta_3 & sin\theta_3 & 0 & -\pi/2 \\ 0 & 0 & 1 & 0 \\ sin\theta_3 & cos\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ \mathbf{{}^{4}_{6}T = {}^{3}_{4}T * {}^{4}_{5}T * {}^{5}_{6}T} $$

$$ \begin{bmatrix} \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_3 & \cos\theta_1\cos\theta_2\sin\theta_3 + \sin\theta_1\cos\theta_3 & \cos\theta_1\sin\theta_2 & A^2\cos + A(D\sin\theta_1 - A) \\ \sin\theta_1\cos\theta_2 & \sin\theta_1\sin\theta_3 & \cos\theta_2 & A\sin\theta_2 \\ -(\sin\theta_1\cos\theta_2\cos\theta_3 + \cos\theta_1\sin\theta_3) & \sin\theta_1\sin\theta_3 - \cos\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_2 & -(A\sin\theta_1\cos\theta_2 + A\sin\theta_1 + D\cos\theta_1) \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The DH parameters are fed to MATLAB to simulate the prototype. This made the testing of joint angle values required for various poses an easy process, and the relevant mathematical operations were encoded into MATLAB to generate the transfer function, as represented below.

$$ TF = \begin{bmatrix} A & B & C & D \\ E & F & G & H \\ I & J & K & L \end{bmatrix} \qquad (7) $$

A = (cos(θ1)*(666*sin(θ2) + 1226*y*sin(θ3) + 1226*z*sin(θ2) - 361*sin(θ2)*sin(θ3)*sin(θ4) + 361*y*z*sin(θ4)))/(50*s).

B = -(cos(θ2)*(666*sin(θ1) + 1226*x*sin(θ3) + 1226*z*sin(θ1) - 361*sin(theta1)*sin(theta3)*sin(theta4) + 361*x*z*sin(theta4)))/(50*s).

C = -((613*cos(θ3)*(x*sin(θ2) + y*sin(θ1)))/25 - (361*cos(θ3)*sin(θ4)*(sin(θ1)*sin(θ2) - x*y))/50)/s

D = (361*cos(θ4)*(sin(θ3)*(sin(θ1)*sin(θ2) - x*y) - z*(x*sin(θ2) + y*sin(θ1))))/(50*s)

E = -(cos(θ1)*(1226*sin(θ2)*sin(θ3) - 666*y - 1226*y*z + 361*y*sin(θ3)*sin(θ4) + 361*z*sin(θ2)*sin(θ4)))/(50*s)

F = -(cos(θ2)*(1226*sin(θ1)*sin(θ3) - 666*x - 1226*x*z + 361*x*sin(θ3)*sin(θ4) + 361*z*sin(θ1)*sin(θ4)))/(50*s)

G = -((613*cos(θ3)*(sin(θ1)*sin(θ2) - x*y))/25 + (361*cos(θ3)*sin(θ4)*(x*sin(θ2) + y*sin(θ1)))/50)/s

H = -(361*cos(θ4)*(sin(θ3)*(x*sin(θ2) + y*sin(θ1)) + z*(sin(θ1)*sin(θ2) - x*y)))/(50*s)

I = 0

J = 0

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K = 0

L = 0

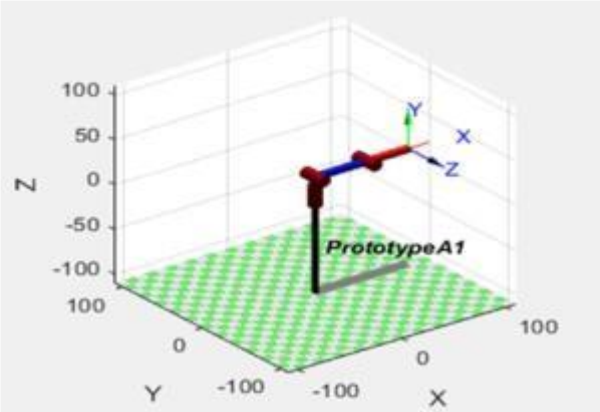

Figure 5: MATLAB GUI for Prototype.

CAD Modelling and Fabrication

The dimensions for the arm were obtained from anthropometric measurements taken from 500 people between the ages of 16 to 51. We chose to use SolidWorks modelling software to build the file for the hand we wanted to use. Utilizing the data provided from earlier parts of the study a skeletal form was designed using SolidWorks. A skeletal-like frame structure complete with joints and other load-carrying elements, designed to enable easy access to all components during the test phase. After the material selection process the major joints were 3D printed in PLA.

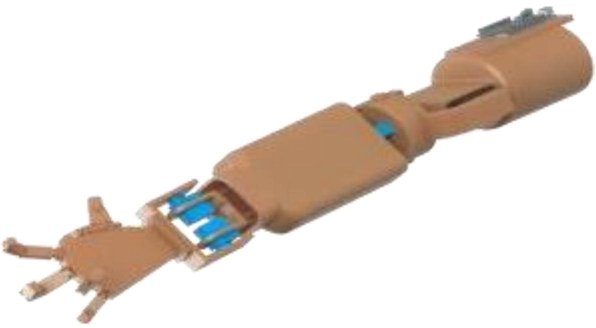

Figure 6: Prototype CAD Model.

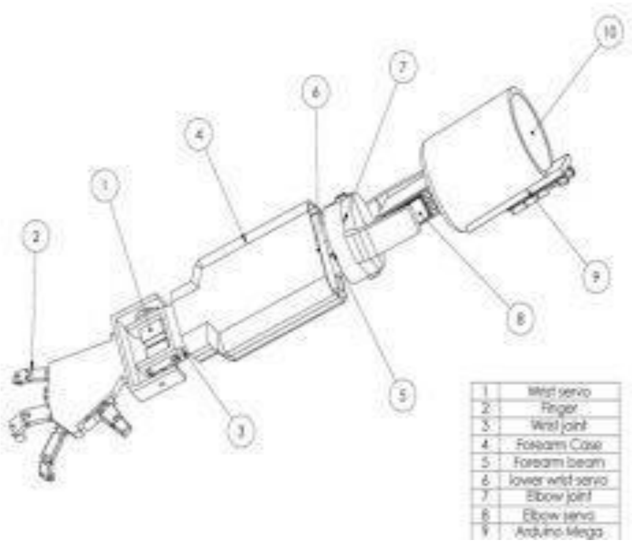

Figure 7: Component of prototype arm.

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Inputs and Control

The control of the arm is built around input received by the microprocessor from the EMG sensors. The microprocessor then sends PMW signals to the various servo motors in the arm. The control process of the prosthetic arm appears linear and open as they are no direct sensors on the arm to act as built-in feedback loops. In reality a feedback loop exists in a broader bio-mechatronic system where the eyes act as sensors that give feedback in form of visual information to the brain. The brain then processes the signal and sends out muscle signals to the EMG sensors. The prototype is manipulated by a simple Simulink model as it can be seen in Fig.8. The prototype arm is represented by several blocks that account for each joint as a subsystem.

Three surface electrodes at each site is generally used in this type of arm, one acting as reference electrode, another as active electrode and the third as ground electrode. The difference signal between reference and active electrode is processed to reduce noise in the system. The frequency ranges of EMG signal which shows change with opening and closing of hand is 10 to 500 Hz and is dominant in the 50 to 150 Hz range [9]

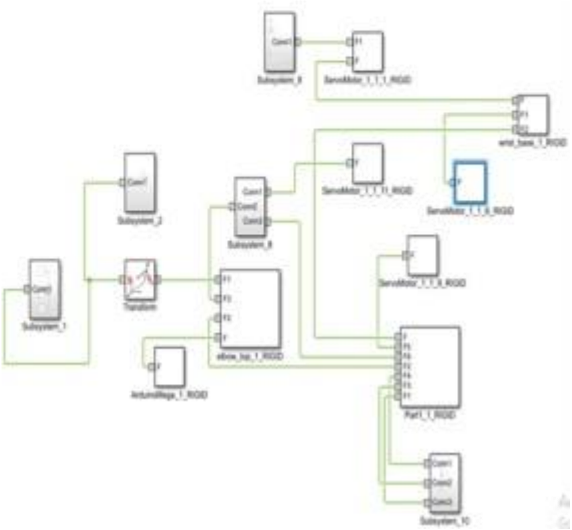

Figure 8.1: Simulink Model.

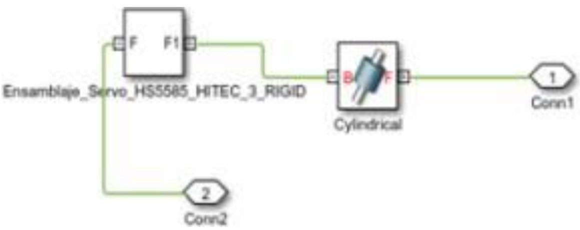

Figure 8.2: Subsystem2 (forearm pronation and supination)

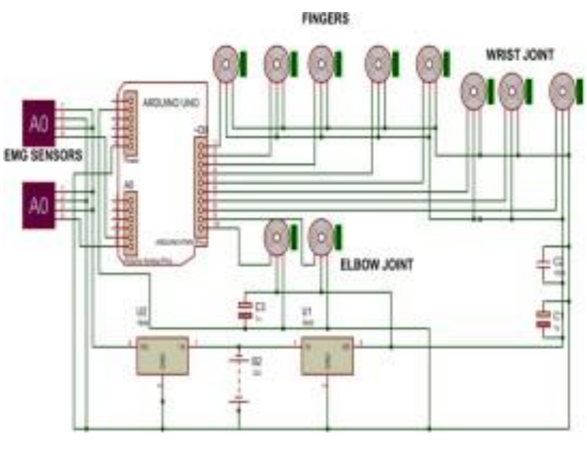

Figure 9: Circuit.

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RESULTS AND DISCUSION

The arm is to be compared to earlier and similar myoelectric prosthesis; Utah Arm by motion control Inc., the Boston Elbow and the CINVESTAV-IPN [10]. These were chosen as these arms are closer to the prototype in terms of performance and complexity. These arms have to be outperformed greatly in the coming iterations before a comparison with million-dollar projects can be established. The performance of the prototype was tested against predicted trajectories and speeds. The performance results are shown in Table 4.4.

Table 4.4: Arm Comparison among myoelectric prosthesis.

Characteristics	**Utah Arm**	**Boston Elbow**	**CINVESTAV-IPN**	**Our Prototype**
Types of movement (P=passive, A=active)	**Flexion extension - A Humeral rotation -P**	**Flexion extension - A**	**Prono-supination-A Flexion extension - A Humeral rotation - A**	**Flexion Extension – A Prono-supination –A Humeral Rotation - P**
Degrees of Freedom at Elbow	**2**	**1**	**3**	**2**
Degrees of Freedom at wrist	**1**	**1**	**0**	**1**
Weight	**913 g**	**1100 g**	**1050 g**	**800 g**
Actuator movement	**Sequential**	**Sequential**	**Parallel**	**Parallel**
Lifting Weight	**1 kg**	**2.3 kg**	**2 kg**	**0.39 k g**
Power supply	**12v**	**12v**	**24v**	**9v**
Cost	**$ 10,000**	**$ 3,500**	**$ 2,000**	**$160**

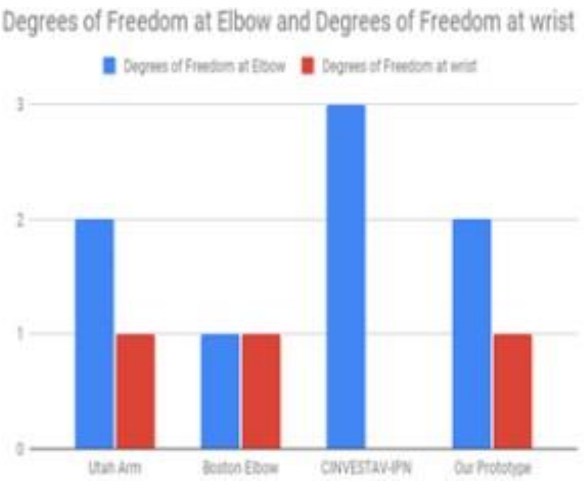

Figure 10: Comparison of degrees of freedom

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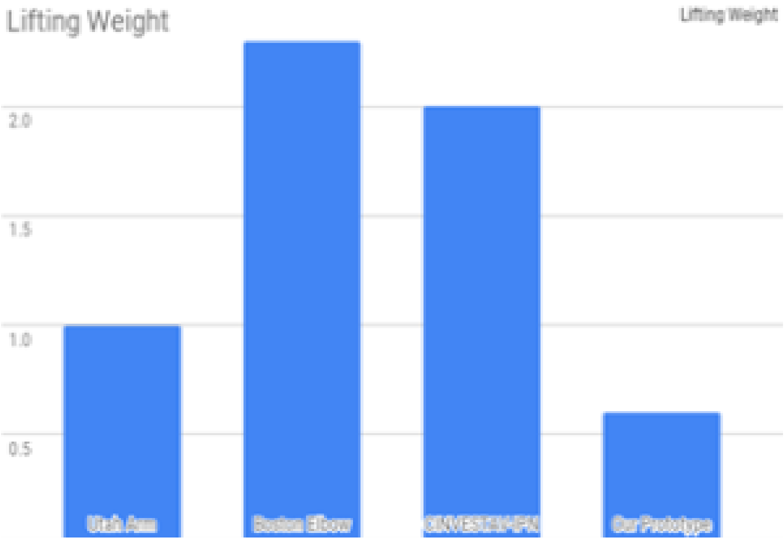

Figure 11: Comparison of weights of various prosthesis

Trajectory Plots of the fingers and the wrist joints

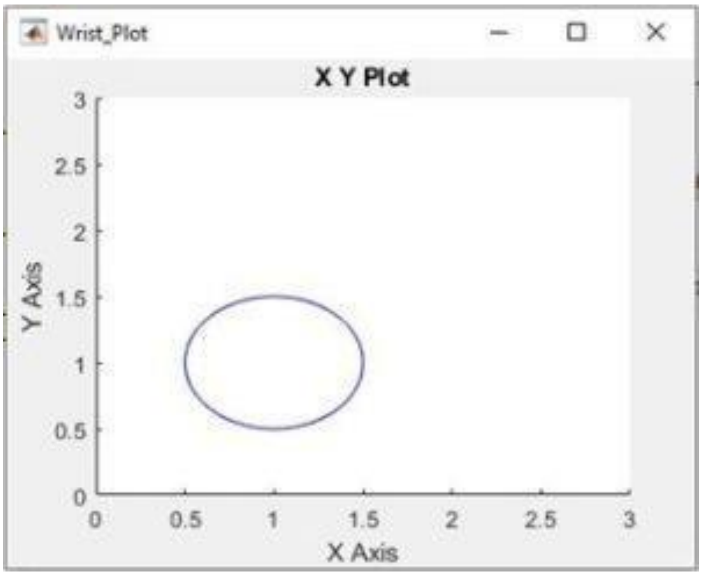

Figure 12: wrist plot without tuning PID

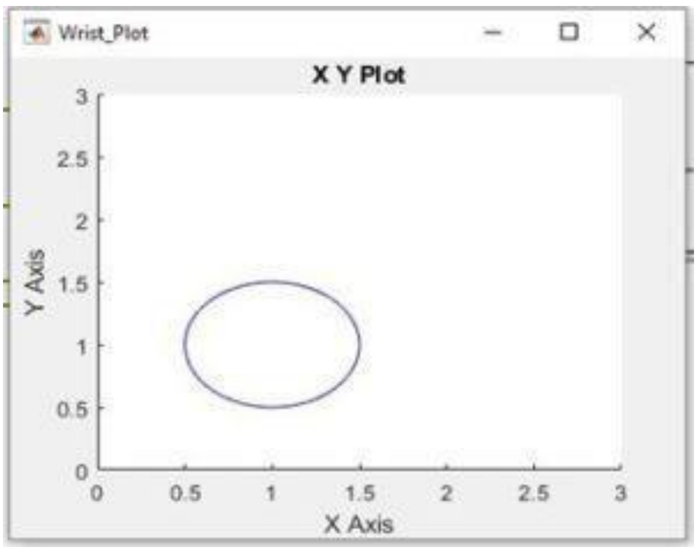

Figure 13: wrist plot after tuning

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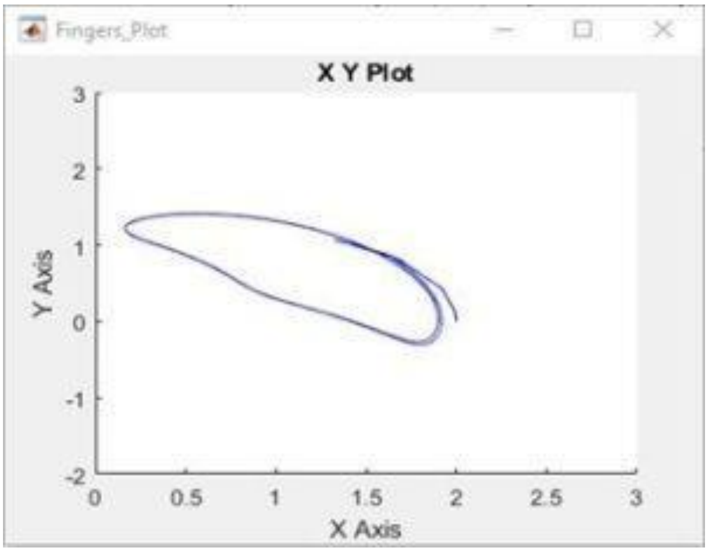

Figure 14: Finger Plot without Tuning.

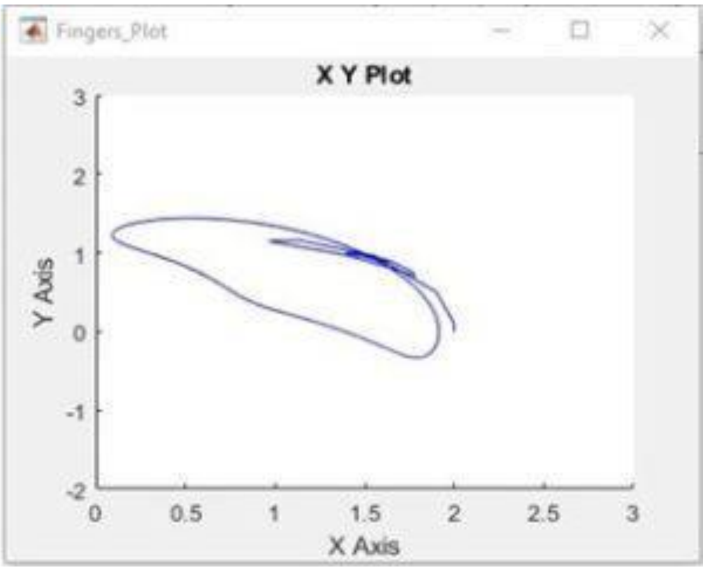

Figure 15: Finger Plot after Tuning the PID Controller

Plots of Various properties of the system

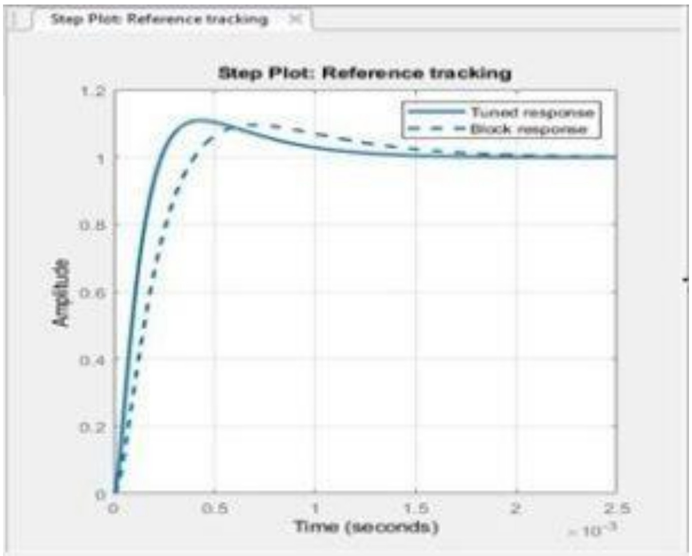

Figure 16: Finger Reference tracking.

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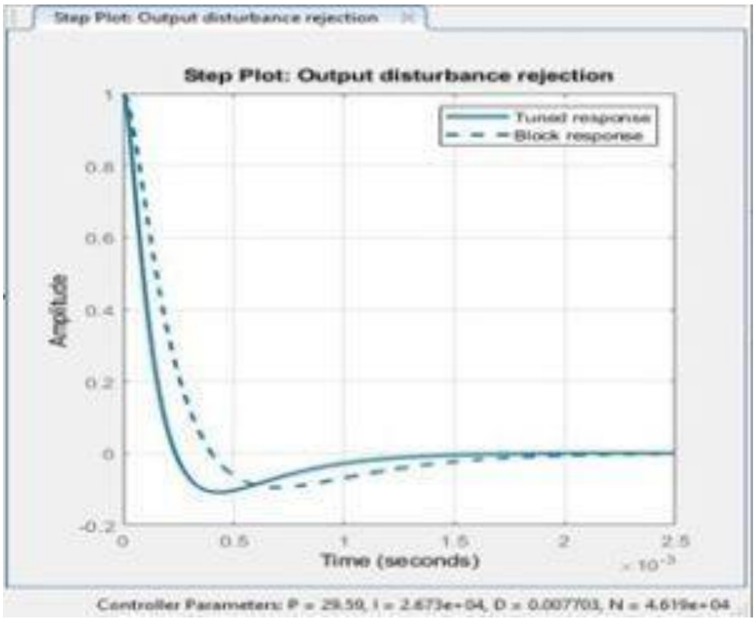

Figure 17: Finger output disturbance rejection

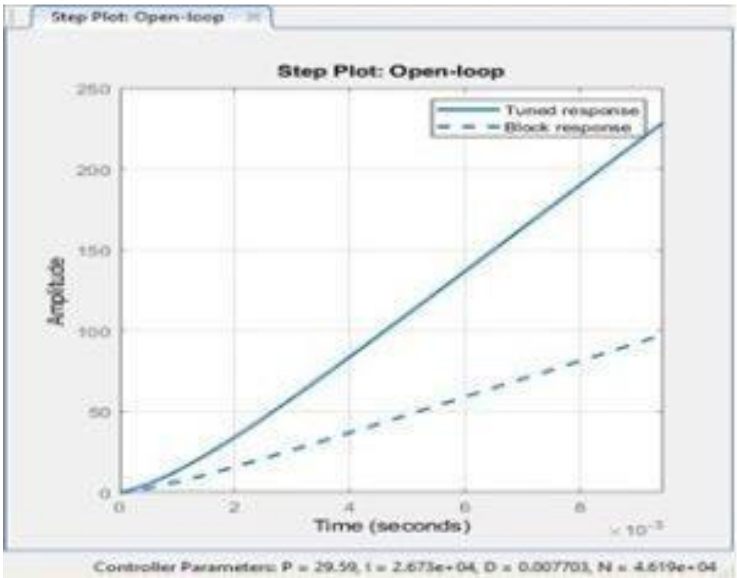

Figure 18: Finger Open Loop Plot

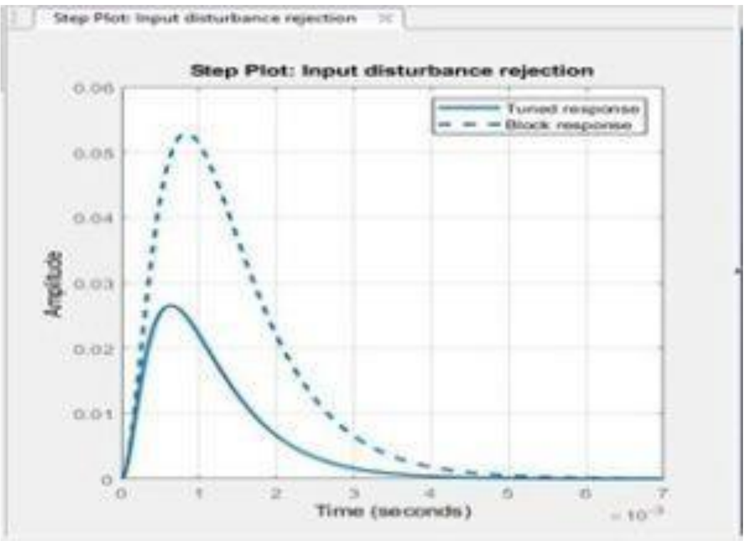

Figure 19: Finger Input disturbance rejection

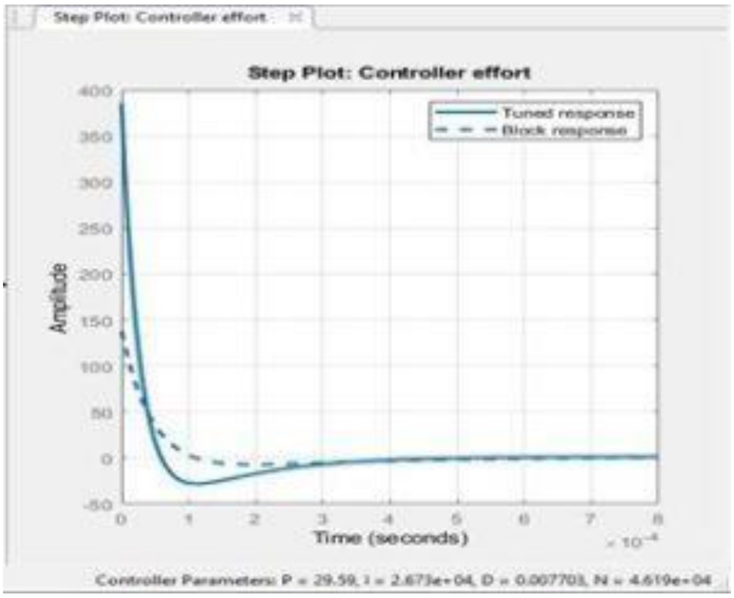

Figure 20: Finger Controller Effect

The wrist plot (fig. 12.) shows the desired trajectory of the wrist joint as defined by the forward kinematics of the robot arm without tuning the PID controller. The movement of the wrist is accurately defined as there are no steady-state errors, while fig 13. explains the wrist plot after tuning the PID controller. The PID controller was tuned to eliminate lag and steady-state errors that appeared in the fingers' end effectors trajectory plots. The results did not disturb the wrist joint trajectory. The result of the finger plot without tuning the PID controller (fig.14) shows the desired trajectory of the fingers joints' net movement as defined by the forward kinematics of the robot arm. The plot shows a steady state error, indicating a lag in the response of one or more finger(s). The finger plot (fig. 15) after tuning the PID controller to eliminate lag and steady-state errors that appeared in the finger's end effectors trajectory plots shows amplification in the steady-state error, which is likely due to the need for slight flexibility in the joints as defined. The reference tracking plot (fig. 16) shows the reference tracking of the amplitude of the controller, the tuned response as well as the initial Simulink block response. The overshoot in the amplitude from point 0 to point 1.1 shows the steady-state error in the fingers joints plot. Fig 17 shows the output disturbance rejection in the controller with an undershoot in both the block response and the tuned response at point -0.1. The finger open loop plot (fig. 18) clearly defined the behavior of the open loop controller, as the motions of the finger joints do not send any response back to the wrist. The tuned response spans over a higher amplitude range showing the variation in response stability between the block response and the tuned response.

The finger Input disturbance rejection plot (fig. 19) shows the system's rejection of input disturbance, the block response has a higher amplitude, indicating critically unstable input signals, in contrast to the tuned response, which has a lower amplitude, indicating a relatively stable input signal, while the finger controller effect plot (fig. 20) shows the behavior of the system's controller, the undershoot of the tuned response indicates that the system takes less time to produce error signals of a larger range of input signals (-30 to 380) into the system for performance. Thus, the tuned response increases the controller efficiency of the system.

CONCLUSION

The Prototype developed stands as a proof of concept and a basis for future low-cost prosthetic arms. This study also paints a better picture of reality of costs in the development of technology in the region. The prototype weighing 850g is capable of active wrist and elbow, flexion and extension, and forearm pronation and supination this confirmed and supported the fact that the proposed fabricated model is a useful step to achieving affordable prostheses with this approach.

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