Design of a Low Cost Degree of Freedom Hand Exoskeleton

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JULY, 2014

Declaration

I certify that this research work titled "*Design of a Low Cost Degree of Freedom Hand exoskeleton"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Talha Shahid

2011-NUST-MSPhD-Mts-32

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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2011-NUST-MS PhD-Mts-32

Signature of Supervisor

Copyright Statement

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Abstract

The primary objective of designing the hand exoskeleton is to include a controllable degree of freedom (Degree of Freedom) of the finger joints with minimum number of actuation modes. This paper describes the design and development of a multi Degree of Freedom hand-exoskeleton based on the rehabilitation criteria of an amputee to achieve different hand gestures on the passive amputee hand. The problems regarding designing the hand exoskeleton are the interlinked constraints which primarily includes the cost, weight and complexity parameters. There are many designs in this particular field which were focused on these parameters.

This design contains 3 Degree of Freedom, 5 fingered links with the inclusion of thumb and a separate flexion and extension of the wrist joint. The rotation between each of the joint is carried through rigid connecting rods with only 1 degree of freedom which converts the translation motion into rotary motion. The force applied to the end effectors is through lead screw mechanism which is attached to the MCP joint and the connecting rods transmit the power to the end effectors. The direction of motion of these independent finger links is controlled by the rotation of motor and a current feedback sensor which helps in perfect gripping of the object.

This hand exoskeleton can work for the assistive humanoid robotics for the physiotherapy sessions and also to provide different hand gestures including the pinch and power gripping. After several sessions with the physiotherapist, a chart will be formulated with the data collected from the amount of disability travelled to the hand and all the necessary physiotherapy gestures required for the exercise and improving the hand and by adding different classes the therapy sessions can be carried out in the home providing the patient to take the “doctor” with home.

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CHAPTER-1: INTRODUCTION

1.1 Background and scope:

The hand is one of the most effective organs of the human anatomy providing major role in the daily activities. A statistics carried out in 2008; show that there has been an increase in the number of accidents resulting in partial or complete injuries of the human hand [1]. This has increased the need of artificial limbs to assist the functionality of the human hand. As the world exceeded in the field of technology, artificial limbs have also been improvised with better efficiency and functionality [2]. Many of the hand paralyses are caused by the long standing paralysis and the ulnar nerve paralysis [3]. The human hand consists of many muscles to control the movement of the finger. Each finger consists of 6 major muscles that control the curling motion. Three of these muscles are the intrinsic muscles (dorsal, palmar interosseous and lumbrical muscles) [4], [5].

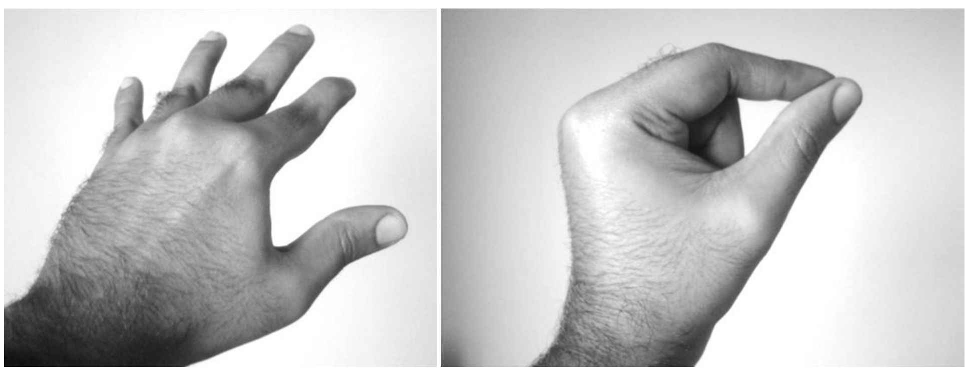

Fig.1. Different paralyses of the intrinsic muscles, (i) Thomas sign, (ii) Mannerfelt and Froment sign

Fig.1 (i) known as Thomas sign, [6] explains the paralysis caused by the weakness of the interosseous muscles. This type of paralysis provides weak gripping and grasping along with less flexion and extension in the finger links [7]. Fig.1 (ii) is the Mannerfelt and Froment sign [8], which occurs due to the ulnar nerve paralysis. This weakens the stability/extension of the Metacarpaophalangeal, during pinch gripping [9].

Currently, most hand gestures and assistive movements are carried out by a physiotherapist. The equipment used in this procedure is costly and the methods involved are time consuming [10]. Furthermore, the patients have to buy expensive components and equipment to carry out the therapy sessions at home.

Fig.2. The figure shows the structure of a human finger, the three joints and the links joining these joints and blood vessels serving as actuators

The bone structure of a human finger consists of three main joints, the Meta-carpaophalangeal (MCP) joint, proximal interphalangeal PIP joint and the distal interphalangeal DIP joint [11]. The links joining these joints are Proximal Phalange, Middle phalange and the distal phalange respectively [12]. In order to move these joints, blood is pumped in the blood vessels to tighten the muscles and fats surrounding the bone structure and to move the finger link to a particular point in space. A similar technique is used for gripping objects as well [13]. Simply put, a single finger consists of 3 revolute joints and a single actuator that drives these joints respectively.

The implementation of this mechanism, however, is not that simple. Many methods and techniques have been implemented on the exo-skeleton to achieve similar kinematics of a human finger. HANDEXOS has developed a single actuation driven 4 D.O.F finger link using a 6 pulley system to drive the finger link [14]. HEXOSYS-II has developed a 2 D.O.F finger link with a single actuator (motor) using different rotary kinematics and mechanics [15]. However each design lacked in some applications required to serve the major functionality of a hand-exoskeleton. HANDEXOS can endure greater load on different phalange, however the cable systems used were under tremendous structural stresses, proving it to be fatal in the long run. HEXOSYS-II had the advantage of a simpler design and much simpler kinematics but could not attain a specific position in the workspace.

The Anthropomorphic Hand Exoskeleton [16], was used for assisting the astronauts during extravehicular activities against fatigue. The design consists of 3 fingered 4 bar mechanism, hand-exoskeleton coupled together by modes of rigid brackets driven by varying the PWM of a dc motor. The sensors running through the finger links identifies the force requires for different grasping methods. The hand-exoskeleton performs the power grasping and the pinch gripping but the constraints involves the weight of the entire hand-exoskeleton and restrictions in more D.O.F of the finger links. The improvements requires in more fuzzy logic for the coupling of the finger links resulting in the increase in complexity and weight of the entire hand-exoskeleton

1.2 Terminologies and abbreviations:

The terminologies and abbreviations used in this thesis are as follows:

- HANDEXOS- Hand exoskeleton
- HEXOSYS- Hexo system exoskeleton
- PWM- Pulse Width Modulation
- D.O.F- Degree of Freedom
- DIP- Distal interphalangeal
- MCP- Meta-carpaophalangeal
- PIP- Proximal interphalangeal
- IP- Intermediate Phalange
- CMC- Centre Meta-carpaophalangeal
- CAD-Computer Aided Design
- CNC- Computer Numeric Controller
- COG-Centre of Gravity

1.3 Thesis statement:

Hand exoskeleton is the primary prospect in the field of humanoid robotics since the dawn of technology. There are many different areas in which the performance and efficiency has improved a lot but the cost effectiveness has always been sidelined. The public needs to know the "need" of exo-skeleton and its prosperous results, and considering the need of the most important and complex anatomy of the human being, which is the hand, we must make sure to design a perfect design which caters off the above stated problems.

The idea was to introduce a unique idea which is simple yet effective while keeping in view the cost of the entire system as well. The idea was taken from the crank shaft mechanism which changes the circular motion to linear motion. This helps the reduction of excessive electronics on the hand exoskeleton and very much control over the entire system as well. The current feedback is again a very simple method to keep a check on the gripping power of the exo-skeleton which will eventually help out the system to differentiate between gripping objects with different materials likewise.

1.4 Rationale:

The aim of this research is to design and develop a cost effective hand exoskeleton which has all the advantages (simple design, low weight and low cost) as compared with the previous hand exoskeleton designs. This research will ensure that an amputee can no longer have to face the problem of expenses, weight of the exoskeleton hand, difficulty when using it due to complex electronics. This research will help us develop a manufactured hand exoskeleton with simple design and low weight. This hand will help an amputee to recover his disability and hopefully an amputee won't require any physiotherapist to help him recover his disability.

Majority of the hand disabilities occurs primarily because of Thomas sign and mannerfolt sign. These disabilities happen among the amputees due to dysfunctional nervous system. With proper session with physiotherapist; this exoskeleton will help the patient to recover his disable muscle tendons and recovering a full functional nervous system.
Normally exoskeleton designs are too expensive to commercialize at larger scale. To tackle this obstruction, this design will help the market to commercialize a prototype which is low weight, simple design, easy to be manufactured and most of all it is cost effective.

1.5 Objectives:

The objectives of this thesis includes:

- A complete design of a low cost hand exoskeleton.
- Designing of all individual parts of hand exoskeleton which includes four fingers, thumb, all the finger joints, wrist joint, link joints, connecting rod, and rigid constituent body.
- Assembling all the individual parts into one complete hand exoskeleton.
- Structural analysis (Static and Dynamic) of the hand design will show the sustainability of the hand against applied stress. Also a mechanism analysis on the hand exoskeleton will show the power transmission from one link to another link.
- To design a manufacturable hand exoskeleton which contains all the advanced manufacturing design techniques to ensure an easy to use (simple design) hand exoskeleton.
- To propose a low-cost hand exoskeleton design that will help the prototype to be commercialized in the market.
- Necessary mathematical calculations and equations for all the individual parts and their assemblies which are under stress.
- To develop a control and D-H table for the entire system which will help the researcher to improvise or modify in case of stability and controllability of the hand exoskeleton in future.

1.6 Research type:

The main focus was to carry out a optimum design which is simple, sleek and perform the primary objectives of a hand-exoskeleton. The main constraints were the cost and the weight of the hand-exoskeleton. The primary concern for this research was to design and calculate the best possible exoskeleton which has all the attributes of the available exo-skeleton and is simple to be implemented as well. This includes the CAD design of the exoskeleton and the different structural, material and mechanism analysis to ensure the sustainability of the hand exoskeleton.

The secondary objectives were to control of the finger links by feedback sensor and to increase the speed of the reaction of different hand gestures provided by the controller. Since the primary objective included the simplicity, the electronics involved were simple micro-controllers and motor drive circuits to ensure the closing and opening of the finger links and their independent behavior. The motor used to drive the finger links and the efficiency of the power distributed to the end-effectors also was a secondary objective in this research. The power dissipation of wrist joint and the knuckle rotating mechanism requires high torque because of the Centre of Gravity, falls directly under the rigid wrist joint, the wrist joint could be redesigned but it would greatly affect the material selection and the complexity of entire system

1.7 Methodology:

There are many methodology involved for designing a hand-exoskeleton which involves different parameters including modes of actuation, degrees of freedom of each finger links, number of finger links in a hand-exoskeleton, feedback control of the system. By calculating the designing techniques of many hand-exoskeleton available, the main foci of pre-designing the exoskeleton primarily includes the number of finger links and the degree of freedom of the finger links and the hand-exoskeleton. Lead screw mechanism is used to transfer the power to the finger links. The screw is attached to the motor which rotates the lead and the MCP link slides, whereas the connecting rotates and closes and opens the finger links, where as connecting rods are used to convert the linear motion into rotary motion and keeps it steady at the locking point as well. A cam follower mechanism is used to rotate the knuckle as well which provides assistance in closing the fist of the patient. An inclusion of thumb with the same actuation mode is also been successfully implemented with different sizes of the MCP and DIP linkages. A harness is attached to the DIP joint which provides successful power transmission to the human finger. An independent wrist joint is also included to providing rehabilitation to the disabled wrist joint of the human finger as well. A worm gear and compressive spring is attached with the wrist joint to sustain the heavy torque applying on the wrist joint. The feedback control is carried through by current feedback being drained by the motors. A threshold is calculated within the controller that keeps a check on the current drainage by the motor. As soon as the motor drains more current than the threshold the motors locks at that point. This method is used to ensure the perfect gripping in both gripping and grasping techniques and it also varies from different materials which include plastic, metal and different other alloys and composites materials.

1.8 Resource:

Many researches and journal papers in humanoid robotics and exoskeleton provided with many calculations and different designing techniques prior to the development phase. Many medical journals provides with the causes and the solution to the hand paralysis and disabilities which greatly assisted in understanding the core of the major cause and the best possible solution to heal the disability. The allowable rotation of the human finger joints, the length of different phalange and the many gestures requires by the physiotherapist applied on the patient. The preliminary data and different future prospects in different research paper also provided some other areas to design and implement which included the designing of connecting rods which simplified the entire system greatly and also helped in efficient power distribution.

CHAPTER 2: LITERATURE REVIEW

2.1 Research methodology:

The primary objective of the research was to design an optimum and best possible hand-exoskeleton keeping in view the major mechanical prospects and attributes to fulfill the major necessity of the hand-exoskeleton and also compete with the other hand-exoskeletons available. The major 4 aspects which needs to be cater off prior to design the hand-exoskeleton are

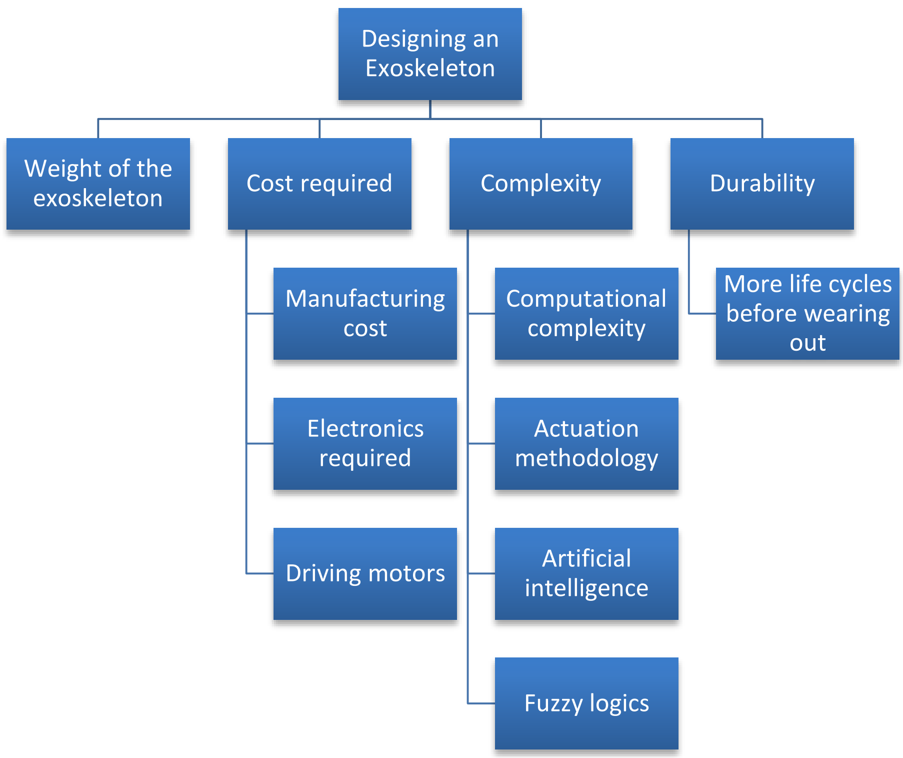

Figure-3: Flow chart of the pre-designing parameters of hand exoskeleton

2.1.1 Weight of the exoskeleton:

Hand-exoskeleton, as per explained in the previous chapters is an assistive humanoid robot which is a supportive harness attached to the disabled hand. The primary objective prior to design a hand-exoskeleton is to keep it as low weight as possible for the patient hand to lift the complete system and wear it. The weight however is linked with the cost, complexity and the durability of the exoskeleton. For-example if a lighter material is chosen for the finger links, sacrificing one of them is eminent, i-e the cost of the exoskeleton will increase or the durability or force will decrease or the system becomes more complex because of the mechanical properties.

Figure-4: Two different materials used entirely for finger links but same method of Force transmission

In figure-4, there are two different exoskeleton discussed with the same number of degree of freedom and force transmission (via extensive and flexion strings) but completely different materials used. The hand in the left side of the figure 4 uses different polymers and composites plastic for the finger links [17], which reduces the weight of the exoskeleton 10 times than the exoskeleton shown on the right side in figure-4 [18]. However the polymer requires extensive care during manufacturing as per the flexibility towards cutting tools during CNC machining. Along with this the flexibility greatly reduces the gripping hold strength during locking which provides slippage of the object.

2.1.2 Cost required:

The second constraints prior to design the hand-exoskeleton, which according to many authors and researchers, is correlated to the other remaining branches of the constraints discussed previously. The cost required for designing a complete hand exoskeleton mainly depends on the material required, the manufacturing cost, the complexity of the mechanical and electrical system, and piling up to a huge sum of the entire exoskeleton. The MIRI hand exoskeleton, [19] and the 2-Finger VR simulator [20] have the same driving mechanism and the system design but entirely different cost required for each system. Mainly because of the materials and the manufacturing processes are different from one another which results in the difference in the two systems respectively. The MIRI hand exoskeleton primarily focus on the driving mechanism through EMG signals while the VR hand exoskeleton use gesture recognition to plot its workspace. Their entire system revolves around the same recognition concepts but different cost of individual system.

2.1.3 Complexity:

Complexity of the system involves the mechanical, electronic and the computational complexity. This is the most vital and the most important branch prior to the design the hand exoskeleton. Each of the complexity of the system are correlated with each other and every single complex system is correlated to the remaining 4 branches as well. The complexity involves, different actuation modes, individual degree of freedoms, feedback controls and their performance based on the recognition or actuation modes. The haptic perception of the VR hand exoskeleton [21] and the rehabilitant hand exoskeleton [22] discusses the different complex system with the same mechanical design but different actuation modes all together. The haptic perception of the VR hand exoskeleton, use visual recognition of the hand movements and follows the same hand gestures, however the rehabilitant exoskeleton use string and pulley drive system to follow the path to the end point. Now the computational time required for the VR hand exoskeleton for one gesture takes around 56.7 seconds to complete the path which is longer compared to the rehabilitant exoskeleton, however in the continuous hand gestures motion, VR is more responsive than the rehabilitant exoskeleton.

2.1.4 Durability:

Durability of the hand exoskeleton depends on the life cycle of its working at maximum deliverable output. The durability of the hand exoskeleton mainly revolves around the mechanical structure and its sustainability to deliver the amount of load on the end-effectors. Therapy Wilmington Robotic Exoskeleton (T-WREX) discussed in [23] and Magnetorheological fluid (MRF) glove [24], are the adaptive hand-exoskeleton, used for astronauts for increasing the gripping during zero gravity. Both of the gloves have different materials; T-WREX is made of Ti copper alloy with low resistivity and high hardness deficiency however the MRF glove is an adaptable shaped polymer with very low gripping strength. However the MRF is easily adaptable with the human hand shape; irrespective of the sizes while T-WREX requires sufficient manufacturing hence decreasing the durability during cyclic working, while the MRF glove proves to be more durable compared to T-WREX.

After planning the best possible solution by keeping in view the 4 major aspects of pre designing techniques, we can move to the designing stages with provided constraints. The designing parameters defined in the pre design techniques should have the logic to meet the requirements of the goals set which primarily includes actuation modes, the degree of freedoms, individual finger links, the feedback controls of the system and the materials used for the hand exoskeleton.

CHAPTER-3: METHODOLOGY

The first design of the hand-exoskeleton consisted of rigid joints between the finger-links bended at an angle of 135° for the PIP joint and 105° for the DIP joint, as shown in Fig.5. The MCP joint was further connected to a 3 cams following mechanism driven by a high-torque motor, which required moving the 4 fingered exo-skeleton. The first design had the following features:

- 4 fingered hand-exoskeleton, each finger with only 1 degree of freedom which is the MCP rotating mechanism, labeled in the Figure 5.
- 3 cams rotating mechanism attached to the MCP joint.
- No thumb included in the design.

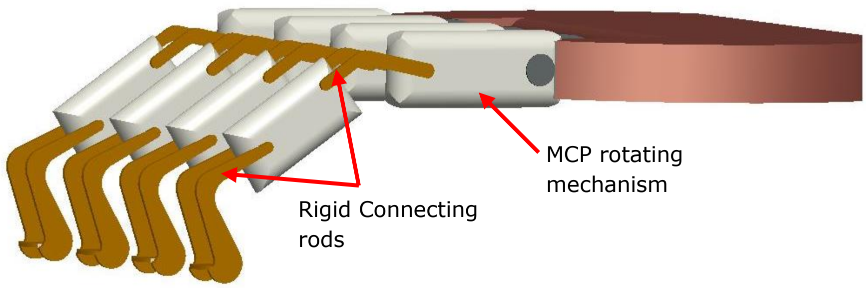

Fig.5. The first CAD model of the hand-exoskeleton with wrist joint, cam following mechanism and rigid connecting rods.

The following was a raw design without the inclusion of any other mechanism, which were used in the previous designs of the hand-exoskeletons. The space between each of the finger link greatly reduced the weight of the whole system, however it also created extensive load on the edges of the rigid connecting rods.

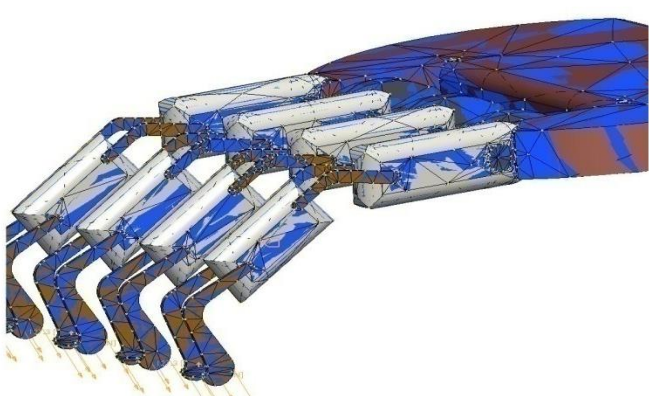

Fig.6. Mesh model of the hand-exoskeleton creating more than 5235 surfaces

Structural analysis was carried out on the hand-exoskeleton with a cumulative load of 50 N on each tip of the finger link. The analysis failed due to the fracturing of the connecting rod attached to the PIP joint. However the analysis was successful on applying 35.2 N loads, which is equivalent to holding a "pen" during pinch gripping. Keeping in view the sacrifice in the degree of freedoms as well as the low load sustainability, it was decided to redesign the finger link mechanism.

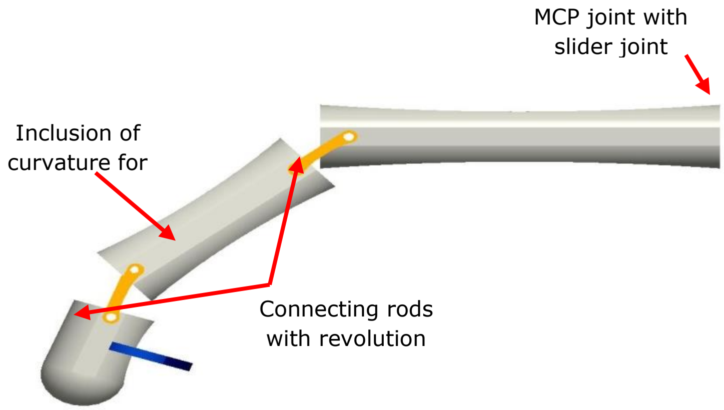

Fig.7. Redesign of the finger link of the hand-exoskeleton.

Fig.7 shows the improved design of the hand exo-skeleton. The rigid support plate links are replaced with cylindrical shaped solid links. Also the connecting rods had been changed to a single rotating connecting rod with a concave curvature in the lower end of the connecting rod. This design of the finger links includes the 3 degree of freedom of each individual finger links.

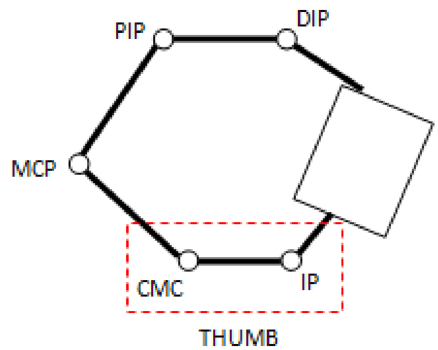

Fig.8. Mechanism of the human hand grasping the object with index finger and thumb coupled

A side view of the human hand is shown in Fig. 8. The index finger incorporates with the thumb to hold an object. The Thumb, however, has two joints, Carpometacarpaophalangeal CMC joint and the Interphalangeal IP joint [19]. The thumb and fingers are linked to the carpel bone which connects to the wrist.

If a hand exo-skeleton has to be designed that incorporates a thumb along with the finger link, an independent 2 D.O.F thumb link has to be included which must have a linkage with the remaining four fingers to operate independently.

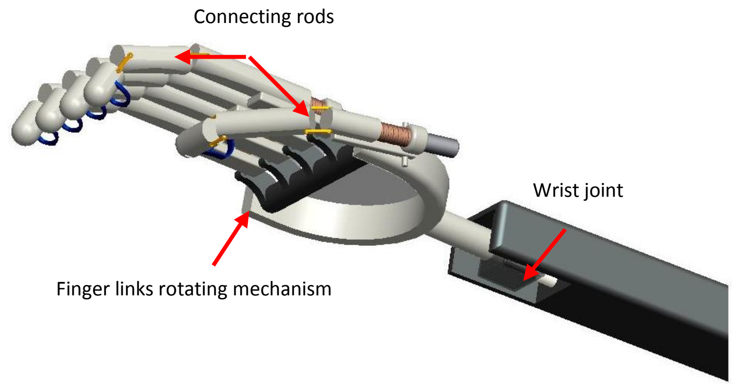

Fig.9. The Pro-Engineer design for the five fingered hand exo-skeleton

Fig. 9 shows the CAD design of the hand exo-skeleton. A five fingered hand exoskeleton with 3 degree of freedom of each link, and one motor is used for actuation. The mechanism used in this particular design is the lead-screw mechanism attached to the proximal phalange. The proximal phalange slides in a linear motion as the motor rotates the screw. 4 connecting rods serve the purpose of the PIP and DIP joints respectively as well as joining the middle and the distal phalange. The connecting rod has one D.O.F, the revolute motion around the axis. The thumb mechanism follows the same technique; however it also has an additional D.O.F because of its linkage with the carpel bone which also connects the 4 finger links respectively. The carpel bone is replaced by a cam like rotating shaft which helps the curling of the MCP joint as well. The wrist joint is connected to a solid rigid entity “base” which sustains most of the weight of the exo-skeleton.

3.1 Lead Screw Mechanism:

The screw profile chosen in this case is trapezoidal for high torque sustainability. The thread lead angle is 29°. Following are the parameters chosen for the lead-screw design.

- Length of the lead-screw=15mm
- Diameter of the thread profile ≈ 0.75mm
- Thread size=15 units.
- Linear Velocity of screw=0.545m/sec

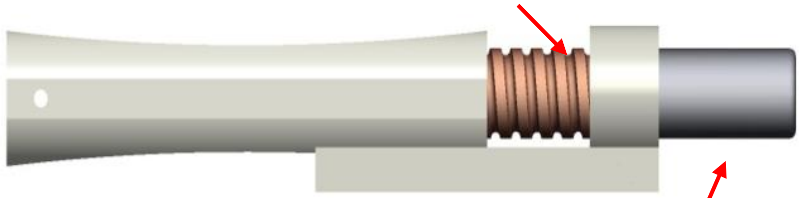

Fig. 10. Lead-screw trapezoidal profile with lead angle 29°

According to the designing parameters of Standard Acme thread pitches for customary diameters [24]. The ISO profile:

- Pitch profile in inches= 5/127 ≈ 1/16
- Diameter of the thread profile= 3/14 ≈1/4
- Thread size= 15 units ≈ 16

These parameters should be less than or equal to the standard ISO parameters of the given profile.

$$T_{raise} = \left(Force \times dm/_2 \right) \times \tan(\phi - \lambda) \quad (1)$$

- Traise is the torque required to raise the lead-nut.
- Force is the minimum load required to derive the lead-nut= 14 N (max pay-load on MCP).
- ϕ-λ is the angle between the lead-screw thread and the nut-thread≈5.43 degrees.
- dm is the mean diameter of the lead-screw =5 mm

$T_{raise} = \left(14 \times 5/_2 \right) \times \tan(5.43)$ =3.32Nmm

Total Torque= Traise x Thread size

Total Torque=3.32 $\times$ 15 = 0.498 Nm.

$$T_c = F \times \mu c \times dc/_2 \quad (2)$$

There Tc is the critical torque, required for single thread to endure for avoiding back-lash and friction between the lead-screw and nut.

- µc is the co-efficient of friction which is equal to 0.17 (standard). [24]
- dc is the critical diameter of the thread profile=0.75mm.

$T_c = 14 \times 0.17 \times 0.75 / 2$ = 0.8925Nm. Efficiency= (Traise-T_c)/ Traise =73.11% (3)

$$N = \left\{ (4.76 \times 10^6) \times dr \times C / L^2 \right\} \quad (4)$$

Where

- N is the maximum RPM required for the lead-screw to rotate
- d_r is the smallest diameter of the lead-screw thread.
- C is a standard value for the type of lead-screw assembly, in our case both end simple, so C=1.
- The value of L is the length of the lead-screw.

$$N = \left\{ (4.76 \times 10^6) \times 0.75 \times 1 / 0.015^2 \right\} = 2181.93$$

Hence, the value of N becomes 2182revolutions per minute. [25],

Linear velocity of the lead-screw is:

$V_{max} = \frac{1}{2}[travel\ distance] + \frac{1}{2}[accelration]$ V_{max}=0.545m/sec (5)

The angle of complete closing of the fingers is ϴ=57.5°, [25]

The radius of curvature is r=82.2385mm.

$$\omega = r.v = 6.627 \text{ degree/sec}$$

Where ω is the angular velocity, so time taken to close the fingers is:

$$T = \theta / \omega = 8.676 \text{ sec without friction.}$$

3.2 Wrist Joint and Rotating Mechanism:

The previous design in the hand-exoskeleton did not include an independent wrist joint. It was a rigid joint geared with the finger links which was adjusted according to the patient requirements. The inclusion of an independent wrist joint consists of following major problems:

- High bending stress on the shaft (due to extensive loading).

- Fracturing of the supporting shaft due to large torque acting on the shaft.
- High shear stress acting on the end of the wrist shaft.

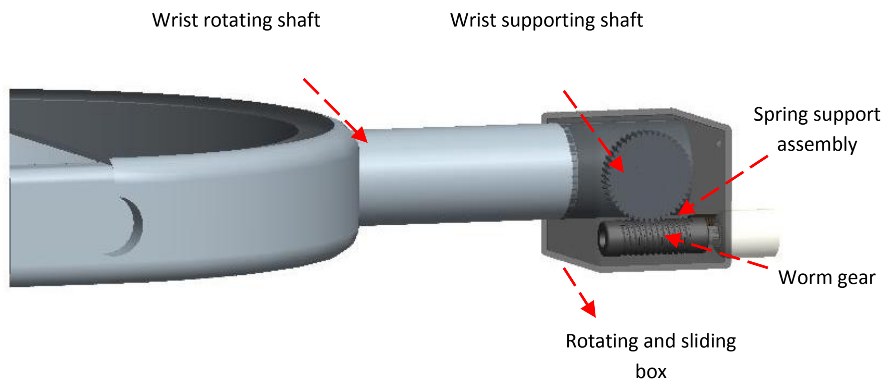

Fig.11. The wrist joint and mechanism

To achieve an independent joint and rotating mechanism, following designing parameters were included:

- Worm gear for the rotation of the wrist rotation. This technique is used to endure the high bending stress acting on the wrist rotating shaft which holds almost 90% of the weight of the hand exo-skeleton
- A wrist supporting shaft which endures the linear stresses acting on the hand-exoskeleton.
- A supporting extensive spring which assists in the clock-wise motion of the hand exo-skeleton rotation.
- The box enclosing the wrist rotating mechanism rotates along with the wrist-joint and while rotating it slides on the corner of the rigid base allowing distributed stress on the base itself.

3.3 Worm Gear Calculation:

The Fig. 12 shows the design of the worm-gear used to rotate the wrist joint (also shown in Fig. 9), before that the structural analysis also highlighted the shaft for the wrist rotating mechanism to be under heavy load during the revolution of wrist joint.

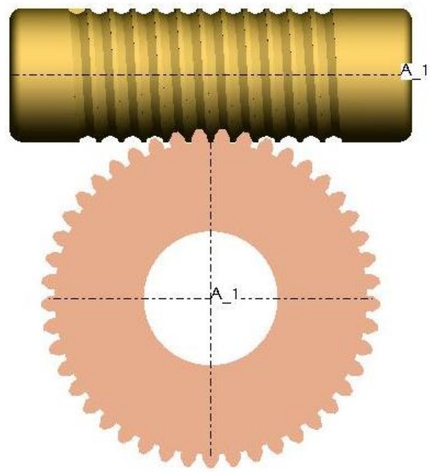

Fig.12. Worm gear mechanism for the revolution of the wrist joint.

In-order to minimize the load on the shaft, worm gear mechanism was included. Also this will allow the motor to lock the shaft at a particular position in the plane.

The following calculations for designing the worm gear are:

The Minimum force acting on the wrist joint of the exo-skeleton=700N [26].

Moment of arm=r=0.035m.

Minimum torque=0.035x700N=24.5 5Nm is the torque acting on the worm shaft.

For high torque worm gear, we choose the normal pressure angle acting on the worm gear is taken as ϕ_n=25° according to designing features given. [26]

3.3.1 The designing parameters are:

- n_d = 1.2,
- Materials and processes: case-hardened alloy steel worm, sand-cast bronze gear.
- K_w=worm-load factor=100
- For ϕ_n=25° the minimum number of worm teeth should be 15,
- The permissible angular rotation given for the wrist therapy is=-10 to 34°=44°
- So the minimum ratio for worm to gear teeth becomes $m_G=N_G/N_W$=15/3=5
- The ratio becomes 5:1.

- The axial pitch diameter is set to be p_x =0.059 in

The time taken to complete the revolution =15 sec

Angular velocity for this particular case is ≈2.93 deg/sec

So the minimum power required to drive the wrist =Torque x angular velocity= 71.785 Watts=0.0962 hp

3.3.2 Worm gear parameters:

If $N_W > 2$, ϕ_n=0.436 rad then [27]

- Addendum= a = 0.286p_x=0.016 in
- Dedendum= b = 0.349p_x=0.0206 in
- Whole depth= h_t=0.635p_x=0.0375 in
- Tangential pitch=$P_t = \pi/p_x = \pi/1.5$ = 0.0823 in
- Diameter=$D_n = N_G/P_t$=15/2.0944=0.281 in

Choosing mean diameter between the threads=d_n=0.078 in

- C= $(d_n + D_n)/2$=0.18 in
- $(d)_{lo} = C^{0.875/}3$=0.0496 in
- $(d)_{hi} = C^{0.875/}1.6$=0.0931 in

So 0.0496≤ d ≤ 0.0931 should be the designing parameters for choosing the diameter of the thread profile of worm gear

Length of the worm gear should be

- L=p_x x N_W = 0.059 x 3=0.177 in
- The lead angle=$\lambda = \tan^{-1}[L/(\pi d)] = \tan^{-1}(0.572)$=29.81°
- Which should be less than maximum permissible lead angle for ϕ_n=25° which is 35°.

$$V_s = \pi dnW/12 \cos\lambda = \pi(2)2250/12 \cos(29.81) = 53.45 \text{ in/min} \quad (6)$$

$$V_W = \pi dnW/12 = \pi(2)2250/12 = 46.38 \text{ in/min} \quad (7)$$

$$V_G = \pi DnG/12 = \pi(7.16)(2250/5)/12 = 33.2 \text{ in/min} \quad (8)$$

Where Vs is the sliding velocity, V_w is the worm velocity and V_G is the gear velocity.

$$\text{Material Factor}=C_s= 1190 - 477 \log d_G = 1190-477\log 7.16 = 782.2 \quad (9)$$

$$\text{Ratio correction}=C_m=0.02 \text{ x } \sqrt{(-m_g^2 + 40m_g - 76)} + 0.46 = 0.65 \quad (10)$$

Velocity Factor=C_v= $13.3V_s^{-0.571}$=0.2162 (11)

Co-efficient of friction=f=0.103x$e^{(-0.110V_s^{0.450})}$ + 0.012= 0.018

The transmission force to the gear:

W_G^t= $33000n_dH_0K_a/V_Ge$ =33000(0.047)0.0962(1.25)/2.76e= 634.71 lbf (12)

Face width of gear=F_e= $W_G^t/C_sD^{0.8}C_mC_v$=0.047 in (13)

$F_e \leq (F_e)_G \leq 2d/3$,=0.0496 in

- The minimum lateral area for gear= $A_{min}=43.2C^{1.7}$=0.87 in^2
- The normal gear diametric pitch=$P_n=p_x\cos\lambda$=1.5cos29.81=0.051 in
- Gear bending stress =σ_a= W_G^t/yp_nF_e = $W_G^t/0.15p_n1.195$=2721.6 psi

3.4 Calculation for the Extension Spring:

An extension spring has been included for sustaining the load during the wrist rotating motion. The spring attached to the base and the rotating box of the wrist joint showing in figure 9. The motor attached in the worm gear mechanism apply force against the tension in the spring during the motion in Fig. 13(i), however during the motion shown in Fig. 13 (ii), the energy stored in the spring will move the wrist joint.

Fig.13 Wrist rotating motion, (i) counter clockwise motion, (ii) clock-wise motion.

The calculations for the extension spring are as follows:

- The material chosen for the spring is "Hard-drawn steel spring wire" UNS G10660, AISI 1066, ASTM A227 used between -200 to 250 °C, stock number 5172 [29]

3.4.1 Designing Parameters:

Spring type: Machine half loop open [28]

The wire diameter for the spring is=d_w=0.81 mm

- The outside diameter=OD=5.94 mm

- The initial tension is given as Fi= 4N
- The number of body turns N_b=12 turns
- The hook radii are given as r_1 and r_2 as 2.69 and 2.2606 mm respectively
- The diameter D becomes=OD- d_w=5.94-0.81=5.13 mm
- The spring index=C=D/d_w=6.33
- K_B=$^{4C+2}/_{4C-3}$=1.224
- Total number of turns N_a= N_b + G/E=12.4 turns
- Spring constant=k=$^{d^4G}/_{8NaD^3}$=0.67 N/m (14)
- The optimal length of the spring=L_0 = (2C − 1 + N_b)d= 19.48 mm (15)

3.4.2 Force and stress calculations:

- The maximum allowable load=24 N [25].
- Maximum deflection=y_{max}= (Fmax-Fi)/k=29.8 mm which lies within the range. [25]
- The uncorrected Initial stress=σ_i=$^{8FiD}/_{\pi d^3}$=15.62 MPa
- The preferred range=$^{33500}/_{e^{0.105C}} \pm 1000(4 - \frac{C-3}{6.5})$=17.23±3.4876=13.746,20.721 MPa
- Initial stress lies between the preferred ranges.
- S_{ut}=A/d^m=2065/ $(0.81)^{0.19}$=2149.35 MPa
- For hard-drawn wire S_{sy} = 0.45S_{ut}=967.2 MPa
- The maximum stress=σ_{max}=$^{8KbFmaxD}/_{\pi d^3}$=731.5 MPa (16)
- Factor of safety becomes= S_{sy}/ σ_{max}=1.322

3.5 Design of the connecting rods:

The connecting rods are the part that converts the linear motion into circular motion. Two of connecting rods are attached to the distal and the proximal phalanges respectively which convert the linear motion of intermediate phalange into circular motion.

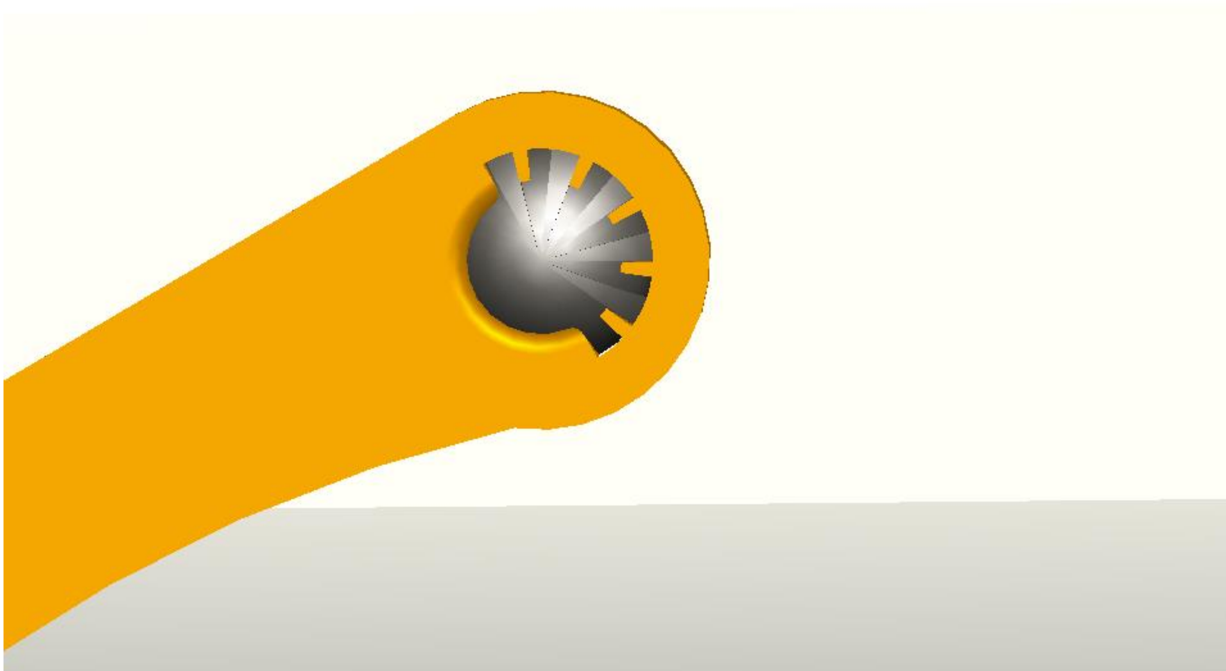

Figure-14: Connecting rods with the internal teeth with the conical shaped shafts.

In figure-15, the connecting rods are linking the two MCP and PIP joints respectively with an internal half circled teeth profiles. The shafts holding the connecting rods are in conical shape with the same teeth profile as per the connecting rods with a gear ratio of 2:1. The purpose of this technique was to ensure two major activities:

- The gear will sustain heavy torque when converting the linear motion of the intermediate phalange. The gear will transmit the power through the linkages by sustaining maximum torque transmitting from the motor
- The teeth of the conical shaft will also hold the finger links to a certain position, providing the locking during the operation of the finger links, the fin like teeth profile will allow the maximum concentration of the stress on the open area of the connecting gear profile and the shaft gear profile.

CHAPTER-4: ANALYSIS AND CALCULATIONS

4.1 KINEMATICS AND ANALYSIS OF FINGER LINKS:

The kinematics and the analysis of the 3 Degree of Freedom finger links includes:

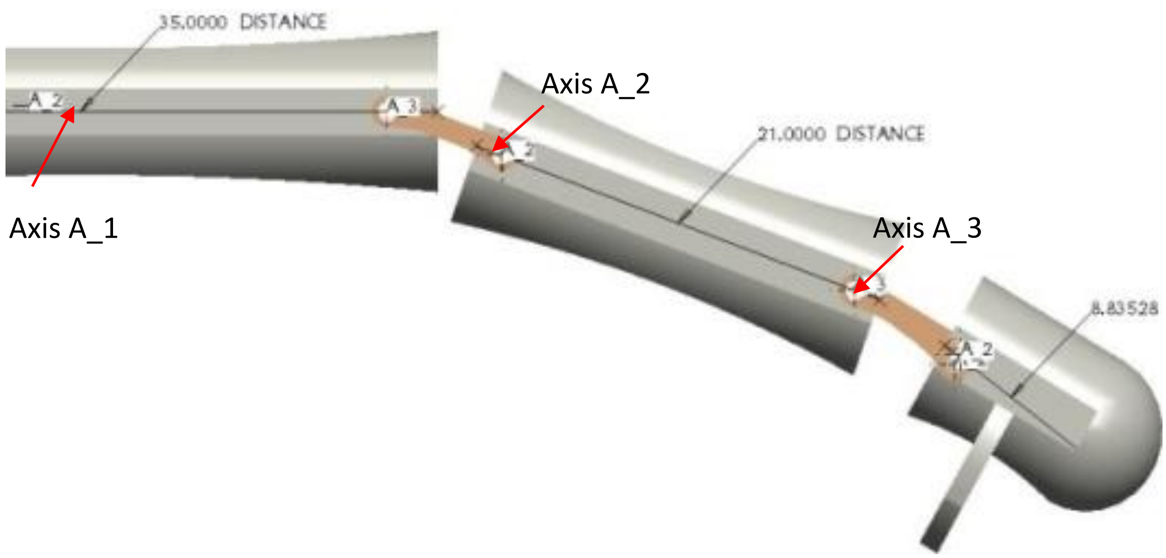

Fig.15. CAD image of 3 D.O.F finger link of the hand-exoskeleton

The specifications of the three links are as follows:

- The first link, correlated to the human distal phalange, is connected to the lead-screw mechanism and it slides over to the axis of rotation A_2. This makes it a slider joint. The maximum and minimum translation provided -10 to 15 mm in the same axis.
- The second link, correlated to the human intermediate phalange, is a simple rotary joint, consisting of two connecting rods connected on the axis of rotation A_3. The maximum and minimum rotation provided to the joint is -5° to 40°. [28]
- The third link, correlated to the human proximal phalange, is a rotary joint, consisting of two connecting rods with the similar specifications to provide rotations around A_3 as per shown. The maximum and minimum rotation given to the joint is -8° to 55°.

The equation of motion of the finger links are:

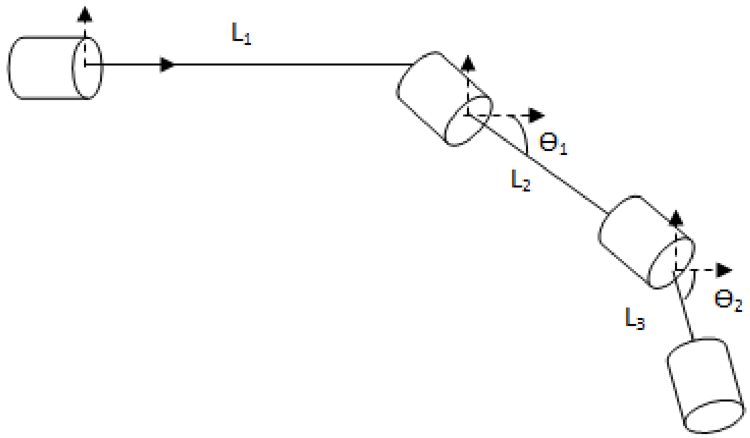

Fig.16. Kinematics of the 3 D.O.F finger links

The three links are as follows {L1, L2, and L3} the two links L2 and L3 are fixed and their value does not change. The two angular motions of the links are {Θ1 and Θ2}. Keeping in view the planar motion of the finger links the equation of motion becomes:

$$X = L1 + L2cos\theta1 + L3cos\theta2 \quad (17)$$

$$Y = -L2sin\theta1 - L3sin\theta2 \quad (18)$$

So in order to reach a particular point in the workspace the values of Θ1 and Θ2 are to be inserted. Taking derivative with respect to time:

$$V_x = V1 - L2sin\omega1 - L3sin\omega2 \quad (19)$$

(Where V2 and V3 are =0)

$$V_y = -L2\ cos\omega1 - L3cos\omega2 \quad (20)$$

ω_1 and ω_2 are the angular velocities of the PIP and DIP joints respectively. The direction normal to linear motion of the finger links.

And likewise the acceleration becomes:

$$Ax = \alpha1 - L2\ cos\alpha1 - L3cos\alpha2 \quad (21)$$

$$Ay = L2sin\alpha1 + L3sin\alpha2 \quad (22)$$

Where a1 and a2 are equal to zero and α1 and α2 are the angular accelerations directed in the normal of the linear motion.

4.2 Matlab Function For Workspace:

A MATLAB function has been made to map the finger link's final position by giving the parameters, length of extension L1, ϴ1 is the angle given for the rotation of the MCP joint;

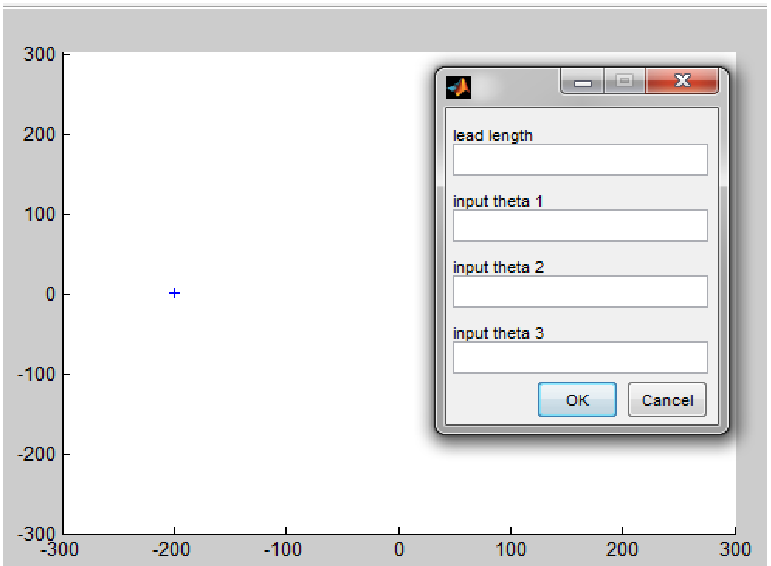

Fig.17. Matlab function with 4 parameters to map the workspace of the finger link

ϴ2 and ϴ3 are the PIP and DIP joint respectively. By entering the values of these parameters we can determine the position of the tip of the distal phalange in the planar space.

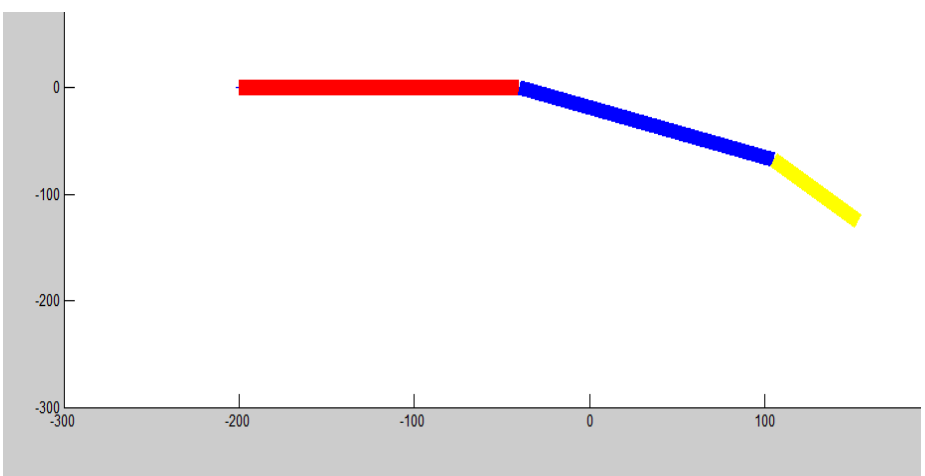

Fig.18. Finger links mapped in the plane

By entering the parameters defined in Fig. 17, the MATLAB functions map the finger links accordingly, giving an overview of the position of the finger-tip. This allows the therapist to pre-process the simulation of a particular therapy before implementing it on the patient.

4.3 Structural analysis and results:

Structural analysis has been carried out on the finger link to ensure the structural stability and sustainability for the applied load.

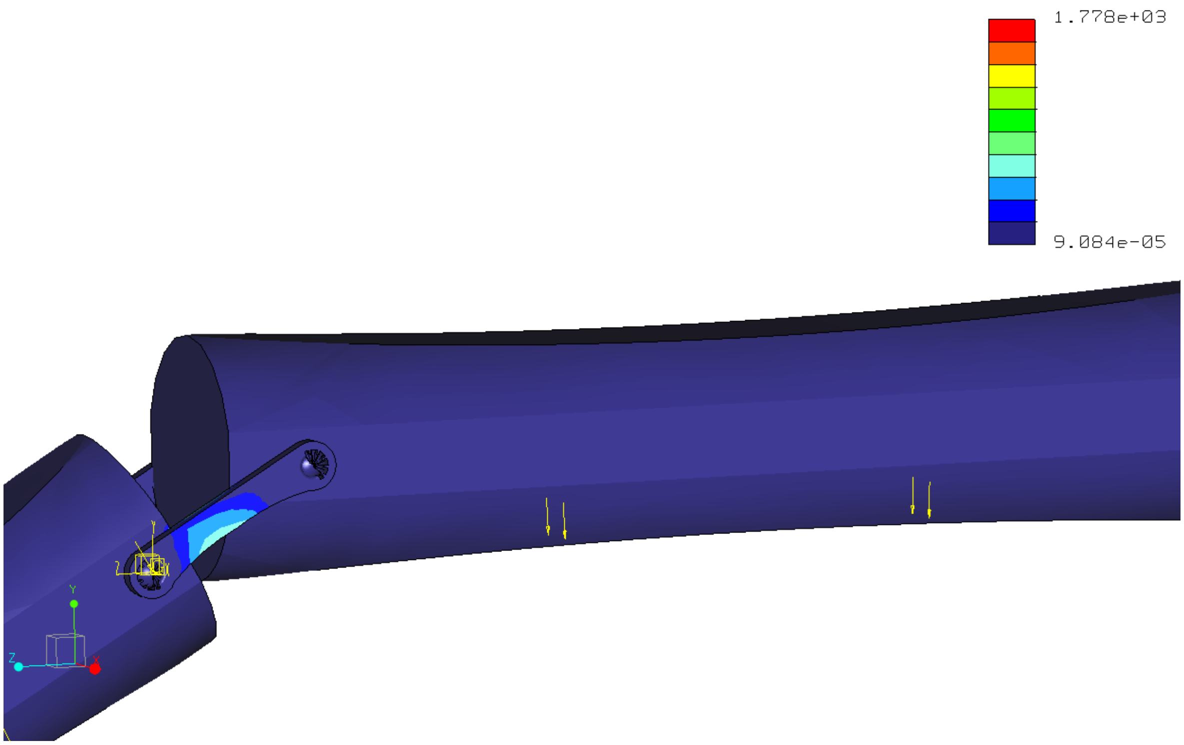

Fig.19. Fringe of Max principle stress analysis of the finger link

It is clear from the image that the region around the connecting rods experiences high stress (approximately $2.36\text{x}10^4$ Pa) on the upper region of the connecting rods. By increasing the thickness and decreasing the curvature of the connecting rod, we can decrease the structural stress; also we can always opt for a better material for the task e.g. Ti-Al alloys can be used instead of Al2024.

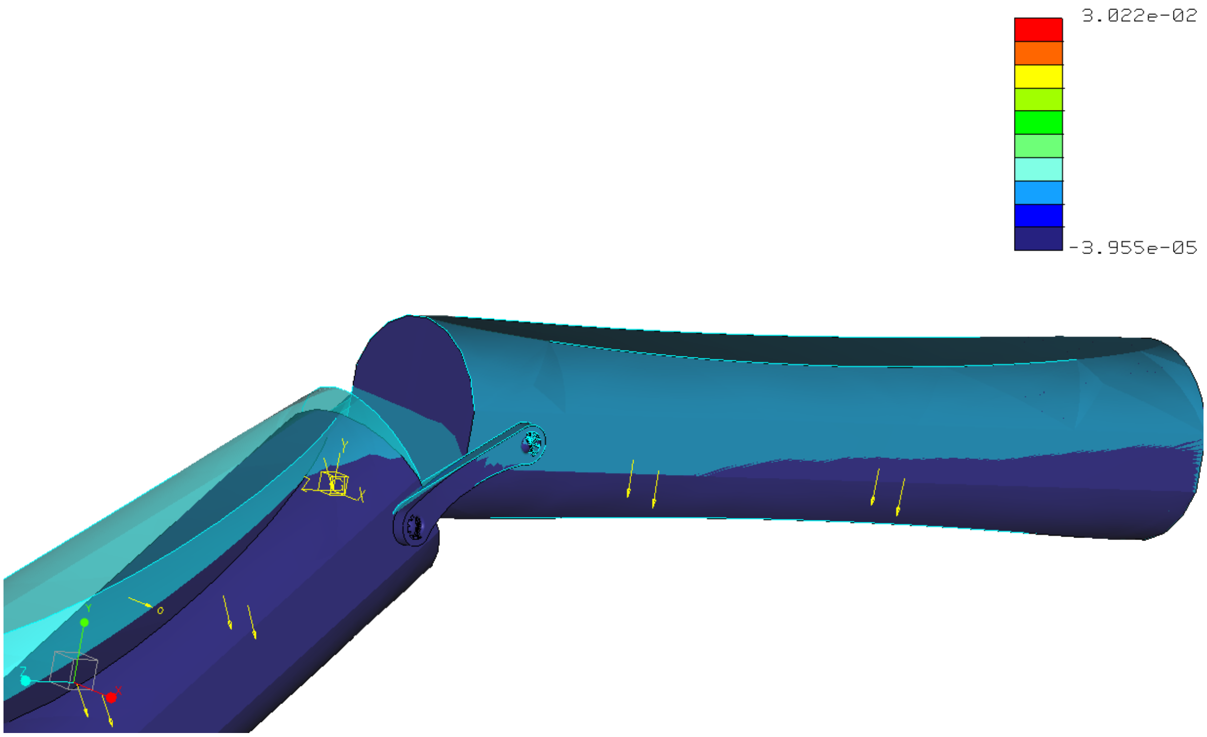

Fig.20. Fringe of strain analysis of the finger link

The strain analysis shows minimal strain and displacement occurring on the connecting rods joining the finger-links. This nullifies the error arising due to vibration and damping during power and pinch gripping and grasping.

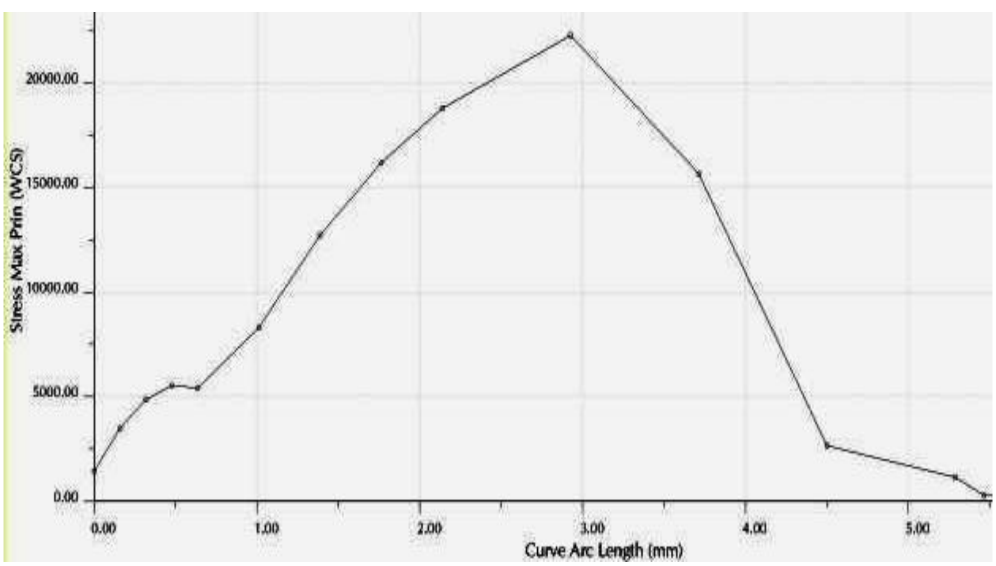

Fig.21. Graph of the stress occurring on the curvature of the connecting rod

The graph shows the stress occurring on the lower side of the curvature of the connecting rod. By this method, the region under heavy stress can easily be calculated. According to Fig. 21, the curve arc length of the connecting rod, ranging from (2.4-3.2) mm undergoes high stress.

By the data collected through various analysis techniques carried out to calculate stress and strain acting on various region of the finger links, it is evident that the “connecting rods” endure the maximum stress and it is under heavy influence of “fatigue loading”. The stress acting on the connecting rods varies from σ_{max}=63.2 kpsi and σ_{min}=28.34psi. The S-N graph for Al-2024 T3 treatment is plotted as [32].

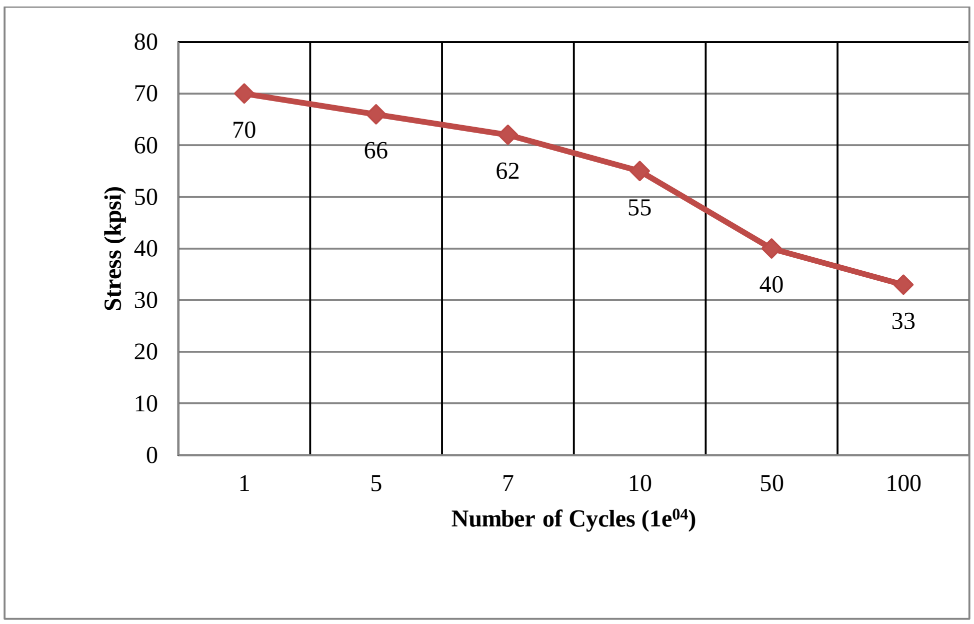

Fig.22. The S-N graph for Al-2024 T3 treated graph

The S-N graph in Fig. 22 depicts the non-linear decay of the life cycles of the Al-2024 T3 material under the given stress, the graph shows that the life cycle lies at approximately 2000 cycles for σ_{max}=63.2 kpsi, and keeping in view the stress graph plotted in Fig. 20, the region likely to be under failure is (2.8 to 3.1) mm of the connecting rod.

4.4 DH-Table and transformation matrices:

The DH-Table and transformation matrices for the 5 linked wrist to end-effecter is as follows;

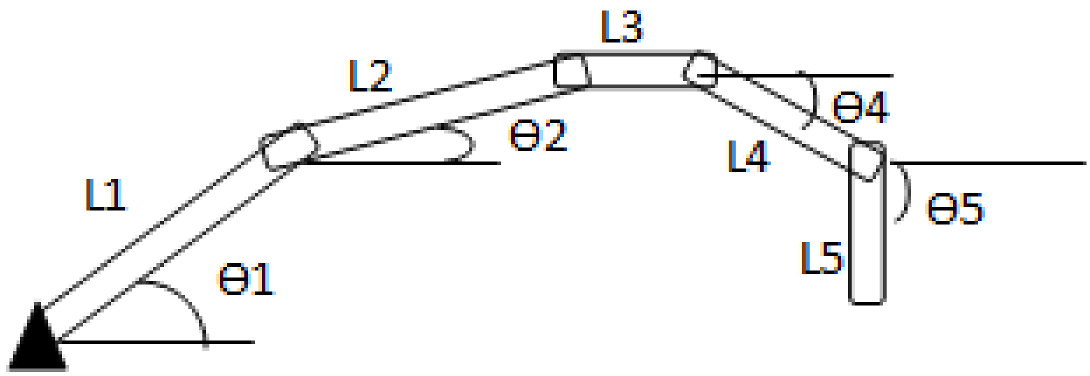

Figure-23: 5 linked hand exoskeleton with respective links and their angles

DH Table:

	αi-1	ai-1	di	ϴi
1	0	0	0	ϴ1
2	0	L1	0	ϴ2
3	0	L2+ΔL2	0	0
4	0	L3	0	ϴ4
5	0	L4	0	ϴ5

Table-I: DH Table of the hand-exoskeleton

The third link is prismatic joint (lead-screw) while all the other 4 joints are revolute joints. The whole exo-skeleton is planar robot.

$$ {}^{0}_{1}T = \begin{vmatrix} c\Theta1 & -s\Theta1 & 0 & 0 \\ s\Theta1 & c\Theta1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} $$

$$ {}^{1}_{2}T = \begin{vmatrix} c\Theta2 & -s\Theta2 & 0 & L1 \\ s\Theta2 & c\Theta2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} $$

$$ {}^{2}_{3}T = \begin{vmatrix} 1 & 0 & 0 & L2+\Delta L2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} $$

$$ {}^{3}_{4}T = \begin{vmatrix} c\Theta4 & -s\Theta4 & 0 & L3 \\ s\Theta4 & c\Theta4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} $$

$$ {}^{4}_{5}T = \begin{vmatrix} c\Theta5 & -s\Theta5 & 0 & L4 \\ s\Theta5 & c\Theta5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} $$

$$ \mathbf{{}^{0}_{5}T = {}^{0}_{1}T \times {}^{1}_{2}T \times {}^{2}_{3}T \times {}^{3}_{4}T \times {}^{4}_{5}T} $$

By entering the parameters and multiplying the 5 transformation matrices we can calculate the end-effecter

4.5 Stress analysis on the connecting shaft:

The connecting shaft connecting the linkages with the connecting rod with the conical teeth profile undergoes high stress and torque. The main purpose of the entire shaft was to sustain the bearing load of the rotating linkages and the structural stress acting on each of the connecting rod during locking of the linkages.

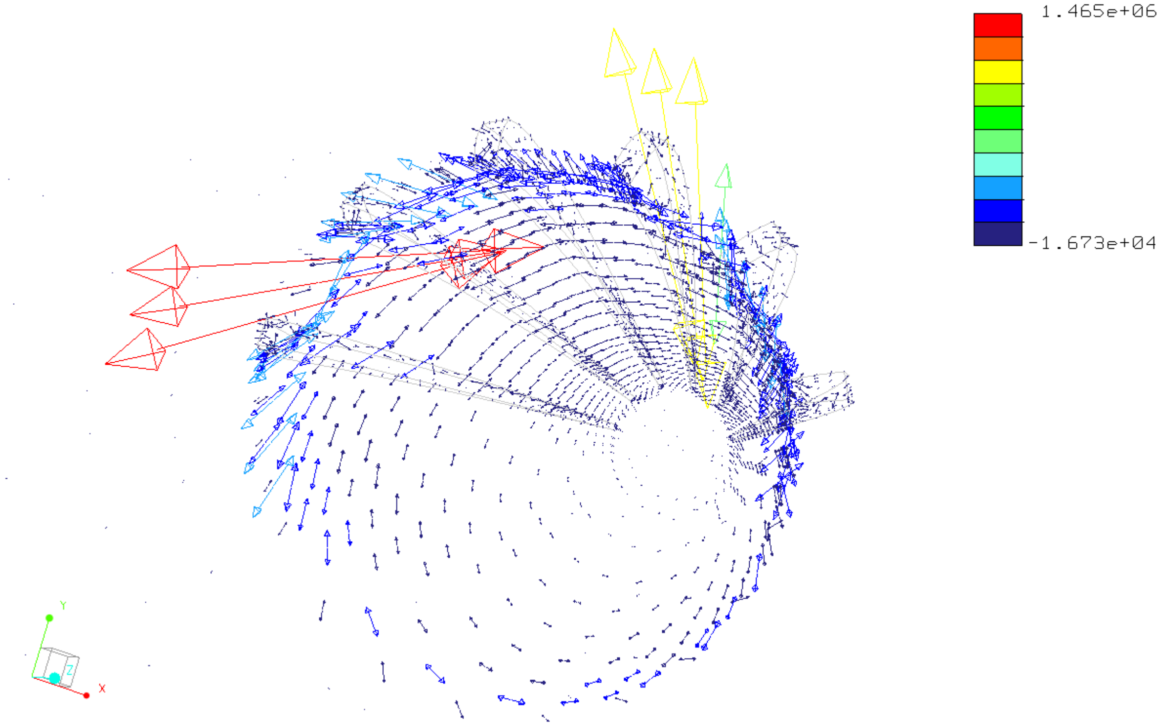

Figure-24: Vector analysis type on the connecting shaft with the applied moment and connection force loads.

By using the dynamic analysis technique in Pro-Engineer, dynamic loads are imported which are applied on the teeth profile and the connection force and moment loads on the face of the shaft. The analysis predicts minimal torque and centrifugal connecting forces and stress follows through the shaft face and teeth profile. However the connecting faces undergoes heavy stress perpendicular to the motion of the finger links. The maximum forces acting on the face of teeth profile is 1.456 MPa and the minimal stress acting turns out to be 16.37 kPa. The data in figure-23, indicates the region under high stress and the breaking the forces and the direction of the fracture points.

4.6 Singularity:

By applying angular and linear velocities to the table-I DH table, we have the angular and linear velocities as

$$ {}^{1}\omega_{1} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} $$

$$ {}^{1}v_{1} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} $$

$$ {}^{2}\omega_{2} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 \end{bmatrix} $$

$$ {}^{2}v_{2} = \begin{bmatrix} c2 & s2 & 0 \\ -s2 & c2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ l1\dot{\theta}_1 \\ 0 \end{bmatrix} = \begin{bmatrix} l1s2\dot{\theta}_1 \\ l1c2\dot{\theta}_1 \\ 0 \end{bmatrix} $$

$$ {}^{3}\omega_{3} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 \end{bmatrix} $$

$$ {}^{3}v_{3} = \begin{bmatrix} l_1 s_2 \dot{\theta}_1 \\ l_1 c_2 \dot{\theta}_1 + (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) \\ 0 \end{bmatrix} $$

$$ {}^{4}\omega_{4} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \dot{\theta}_4 \end{bmatrix} $$

$$ {}^{4}v_{4} = \begin{bmatrix} c_4 l_1 s_2 \dot{\theta}_1 + s_4 l_1 c_2 \dot{\theta}_1 + s_4 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + s_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \\ -s_4 l_1 s_2 \dot{\theta}_1 + c_4 l_1 c_2 \dot{\theta}_1 + c_4 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + c_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \\ 0 \end{bmatrix} $$

$$ {}^{5}\omega_{5} = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \dot{\theta}_4 + \dot{\theta}_5 \end{bmatrix} $$

$$ {}^{5}v_{5} = \begin{bmatrix} c_5 (c_4 l_1 s_2 \dot{\theta}_1 + s_4 l_1 c_2 \dot{\theta}_1 + s_4 c_2 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + s_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)) \\ -s_5 (c_4 l_1 s_2 \dot{\theta}_1 + s_4 l_1 c_2 \dot{\theta}_1 + s_4 c_2 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + s_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \\ 0 \end{bmatrix} + $$

$$ \begin{bmatrix} s_5 (- s_4 l_1 s_2 \dot{\theta}_1 + c_4 l_1 c_2 \dot{\theta}_1 + c_4 c_2 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + c_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)) \\ c_5 (l_4 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \dot{\theta}_4) - s_4 l_1 s_2 \dot{\theta}_1 + c_4 l_1 c_2 \dot{\theta}_1 + c_4 c_2 (l_2 + \Delta l_2)(\dot{\theta}_1 + \dot{\theta}_2) + c_4 l_3 (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) \\ 0 \end{bmatrix} $$

Now by applying the Jacobian to the finger links of frame [3]

$$^{3}J(\Theta) = \begin{bmatrix} (l1 + \Delta l1)s2 & 0 \\ (l1 + \Delta l1)c2 + l2 & l2 \end{bmatrix}$$

And applying Jacobian to the frame [0]

$$^{0}J(\Theta) = \begin{bmatrix} -(l1 + \Delta l1)s1 - l2s12 & -l2s12 \\ (l1 + \Delta l1)c1 + l2c12 & l2c12 \end{bmatrix}$$

By taking determinant of $^{3}J(\Theta)=(l_1+\Delta l_1)s_2.l_2$

This explains the fact that when θ_2=0 or 180 the finger links become singular. The finger is stretched out. At 0 and 180 degree, the finger link will lose one of its degree of freedom. [33]

So to resolve this issue, we will apply angular constraints to the finger links by not allowing reaching the 0 or 180 degree, where as the motion of the MCP and the wrist joint, the angular constraint already lies outside the singularity constraints.

CHAPTER-5: COMPARISON AND DISCUSSION

Table-II shows the comparison of different hand exoskeleton used up to this date. These hand-exoskeletons have different pros and cons. Few of these papers are compared with this design. The parameters used for comparison are the number of finger links used in the exo-skeleton and the individual degrees of freedom of each finger link, along with the maximum force acting on the end-effectors on each finger links and the maximum torque acting on the finger links. The last comparison used is of different grasping modes; the power grasp and the pinch gripping

Sr. No	*Papers/ Journals*	*Published date*	*Number of Finger Links*	*Individual Degrees of freedom*	*Force, Payload on end-effectors (N)*	*Maximum torque (Nm)*	*Grasping modes*		*Wrist joint*
							Power grasping	Pinch Gripping	
1	An Anthropomorphic Hand Exoskeleton to Prevent Astronaut Hand Fatigue During Extravehicular Activities	1997	3	3	n/A	2-3.8	Yes	Yes	No
2	Design of a 2-Finger Hand Exoskeleton for VR Grasping Simulation	n/A	2	3	15	0.28-0.65	n/A	n/A	No
3	An Orthotic Hand-Assistive Exoskeleton for Actuated Pinch and Grasp	n/A	4	3	8	0.3	Yes	Yes	No
4	HANDEXOS: towards an exoskeleton device for the rehabilitation of the hand	2009	5	4	10	n/A	Yes	Yes	Yes
5	Mechanical design of a novel Hand Exoskeleton for accurate force displaying	2009	2	4	5	9	No	Yes	No

6	An overview of the developmental process for the modular prosthetic limb	2011	4	3	44.1	1.75	Yes	Yes	No
7	Orthotic Hand-Assistive Exoskeleton	2011	5	3	44.48	n/A	Yes	No	No
8	Jointless Structure and Under-Actuation Mechanism for Compact Hand Exoskeleton	2011	3	2	18	0.45	Yes	Yes	No
9	Development of a Hand-Assist Robot With Multi-Degrees-of-Freedom for Rehabilitation Therapy	2012	4	3	n/A	0.51-3.72	Yes	Yes	No
10	Design of a Low Cost Multi Degree of Freedom Hand Exoskeleton	n/A	5	3	14	0.498	Yes	Yes	Yes

Table-II: Comparison of Hand exoskeleton

Each of these nine papers has used different techniques in achieving the hand-like movement and gestures of the human hand. However with each advantage of the particular techniques, several disadvantages also occur simultaneously. Many of these designs have cost and weight constraints which makes it difficult to be commercialized or manufacture respectively. Others have bulk design and complexity to achieve maximum force on the end-effectors. Keeping in view the cost, weight and the simplicity constraints, and to achieve the primary objectives of a hand-exoskeleton, this paper presents the particular hand exoskeleton which performs the necessary hand gestures with minimum actuation power. The simple design also minimizes the cost and weight of the hand-exoskeleton. The additional wrist joint also helps the amputee hand with gestures involving wrist as well. Its low cost and simple design ease the chances of its manufacturing and commercializing

5.1 Cost for the hand-exoskeleton:

The cost for the hand exoskeleton with estimation is as follows:

Sr No.	Items	Details	Size/units/time	Price List
1	Material Cost	Aluminum Alloy Al-6061 hardened extrusion scrap	240x240x50 cm sheet	3,008 Rs
		Titanium Aluminum alloy, Case Medium temperature	20x20x5 cm sheet	1,500 Rs
		Case-hardened alloy steel worm, sand-cast bronze gear.	-	2,500 Rs
		Nylon	6 inch dia roll	600 Rs
		Acrylic Sheet	10x10x3 cm	150 Rs
		Hard-drawn steel spring wire	-	1,200 Rs
		Stainless steel 2014	240x30 cm cylindrical shaped	3,300
2	Manufacturing Cost	CNC Machining	10 hrs	15,000 Rs
		Assembling	5 hrs	5,000 Rs
3	Motor Cost	Maxon DC Motor Provisoric 4.5 V	5	14,200 Rs
		Maxon DC Motor Presi 700 Nm torque	1	3,700 Rs
4	Electronics	Micro-controller, wiring, battery, IC etc	-	3,000 Rs
Total cost				53,158

Table-III Cost of the entire hand exoskeleton

5.2 Figure of merit:

The figure of merit is a quantitative analysis required to find out the “best” design per given list which in our case, is the 10 papers given in table-II. The methodology is to devise a formula in which each quantity is given certain percentile score and each of the paper is rated according to that score.

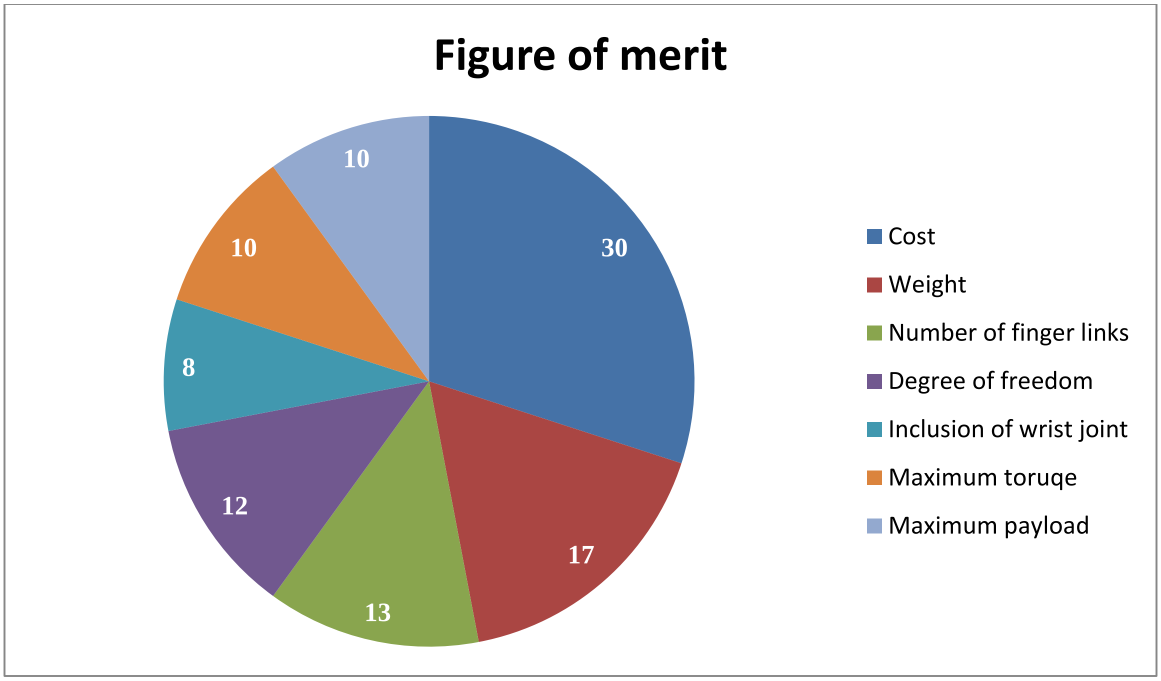

Figure-25: Figure of merit of different quantity out of 100

Now by entering the scores of different quantities as per the figure-25 we can develop a score of over-all best exoskeleton design.

Sr. no	Papers	Cost	Weight	Number of finger links	Degree of freedom	Inclusion of wrist joint	Maximum torque	Maximum payload	Total out of 100
1	An Anthropomorphic Hand Exoskeleton to Prevent	12.5	12.3	10.11	9.82	0	5.25	5.258	55.238
2	Design of a 2-Finger Hand Exoskeleton for VR	18.1	15.5	8.62	5.621	0	7.25	3.25	58.341
3	An Orthotic Hand-Assistive Exoskeleton for Actuated	15.3	14.3	8.33	6.32	0	5.25	3.62	53.12
4	HANDEXOS: towards an exoskeleton device for the rehabilitation	17.8	10.32	7.98	9.56	8	6.75	3.25	63.66

5	Mechanical design of a novel Hand Exoskeleton for accurate force	15.55	12.32	6.23	5.23	0	7.25	8.2	54.78
6	An overview of the developmental process for the modular prosthetic limb	20.22	13.67	5.36	6.52	0	9.12	5.5	60.39
7	Orthotic Hand-Assistive Exoskeleton	22.36	14.56	6.33	9.23	0	9.22	3.25	64.95
8	Jointless Structure and Under-Actuation Mechanism for Compact Hand Exoskeleton	11.25	13.62	10.11	8.25	0	7.7	3.75	54.68
9	Development of a Hand-Assist Robot With Multi-Degrees-of-Freedom for	13.12	12.11	8.621	7.01	0	3.25	8.2	52.311
10	Design of a Low Cost Multi Degree of Freedom Hand Exoskeleton	27.35	15.32	10.11	8.35	8	5.5	4.25	78.88

Table-IV Figure of merits of 10 papers of exoskeleton

CHAPTER-6: CONCLUSION & FUTURE WORK

The mechanical design of the hand-exoskeleton satisfies the primary prospects required for a passive hand amputee. By using different feedback connectors, error generated in mapping the position of the finger-links can be minimized. Using different methods of machine elements, shapes for connecting rods and lead-screw can be redesigned to endure more stress. Also, by defining different classes of different hand-gestures, we can reduce the session time and the subject can also carry the equipment to carry out therapy session at home. The simple design of hand exoskeleton will play vital role in the manufacturing and assembly processes. The extension spring and worm- gear mechanism allows the wrist movement to sustain heavy load during power grasping of comparatively heavy objects. The shape adaptive design of the finger links allows perfect and powerful gripping during different modes of grasping many shaped and shapeless objects. The curvature in the connecting rods allows the finger links to completely adapt the shape of the object and apply maximal forces on the concentration area respectively. Improvements can be made introducing pressure sensors on the DIP, PIP and MCP joint to identify the different stress levels during different modes of gripping and grasping. For-example, the position for pinch-gripping can be identified by allowing the maximum level of stress concentration on the index, middle and the thumb fingers, therefore allowing the exo-skeleton to provide perfect gripping respectively. It can also help to identify the level of power transferred to the finger links by calculating the strength of the materials that are under process. The hardness varies from different material with same size and shape, a cylinder made up of glass or steel, having the same size and shape, but different material. The resistive force that occurs during grasping the cylinder will identify the material strength, allowing the controller to apply more force onto the object during grasping firmly.

6.1 Future Work:

By plotting the workspace of different finger links and reducing the error generation during the motion of the individual finger links, the performance can be greatly increased. Polymers can be replaced with aluminum 2024 T-3 treatment, with higher concentration of different metals like alumina, copper and titanium. Different techniques of electronics can be used to reduce the power losses between each of the finger link and to transmit maximum output power to the end effecter and this will also ensure the safety of the lead-screw the nut of the proximal phalange. EMG controlled actuation can also be implemented which will enable to add more linkages up to elbow or even complete arm and the same techniques to the lower limb amputee’s as well. The Jacobian formulated can be used to program the workspace of the hand exoskeleton and to predict the forward and inverse kinematics of the finger links and wrist joint. The inverse kinematics will allow the patient to devise the gesture and its control for different power and pinch gripping hand gestures as per described by the physio-therapist respectively.

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Completion Certificate

It is to certify that the thesis titled "**Design of a low cost multi degree of freedom hand exoskeelton**" submitted by Regn. No. **2011-NUST-MS-PHD-Mts-32**, **Talha Shahid** of **MS-70 Mechatronics Engineering** is complete in all respects as per the requirements of Main Office, NUST (Exam branch).

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