A Review of Myoelectric Prosthetic Arm Designs from 2011 to 2022

Prof. Dr. Shripad Bhatlawande

Pranav Belgaonkar, Department of Electronics Engineering, Vishwakarma Institute of Technology

***Abstract* – Prosthetic arms are used by people whose arms had to be amputated (cut-off surgically). Prosthetic arms can help users perform daily life activities and work-related activities with nearly the same functionality as a human arm. There are multiple designs for prosthetic arms depending on the user's requirement. This paper reviews the motivation, designs, and tests performed on prosthetic hands, wrists, and elbow from 2011 to 2022 from acknowledged journals and conferences. These papers describe the design of two prosthetic hands in SolidWorks with 1 degree of freedom and 13 degrees of freedom respectively. The hands were attached to a 1 degree of freedom wrist and a 1 degree of freedom elbow. The simplified designs will be further realized and tested.**

Keywords—Prosthetic Arm, Prosthesis, Artificial hand, Myoelectric hand.

I. INTRODUCTION

The human hand is capable of extremely gentle and precise actions like writing, painting, or threading a needle and on the other hand, lifting heavy weights, or performing intense labour work. It has evolved such that it can grasp, feel, hold, manipulate, and so much more. The brain dedicates a lot of resources towards the functioning of the hands as they help us express ourselves to the world [1]. That is why recovering from an amputation can lead to frustration and sadness [2]. Amputees can experience phantom pain, which is the pain that is felt coming from a body part that is missing [3]. This pain is much more intense for upper limb amputations. Complications can arise in patients who were amputated due to a medical condition like disease or injury. So maintaining physical health is important. Equally important is considering the patient's mental health, as their motivation and dedication is instrumental towards the recovery program. The amputee might not disclose his emotions in the beginning and the therapist will have to make sure that the patient is expressing those emotions. The amputees must also be provided with vocational training and placement if required and the physician must ensure that the patient is recovering well [4]. The stump starts to shrink after amputations and if the fitting is delayed for too long the patient might decide to not use a prosthesis at all. The patient should be shown that the best way for recovery is an early fitting. In that case, the patient should also be made aware that they may have to fabricate more than one socket and the additional costs that it requires.

The hand is divided into 3 parts – the finger bones (phalanges), the metacarpus, and the carpus [5]. The wrist has 3 degrees of freedom (DOF) radial/ulnar deviation, pronation/supination and flexion/extension. It is made up of 2 joints that work together. The metacarpus is the middle part of the hand. Each finger is attached to a bone in the metacarpus. Each finger except the thumb has 3 parts - DIP (Distal Interphalangeal Joint), PIP (Proximal Interphalangeal joint) and the MCP (Metacarpal Phalangeal joint) whereas the thumb has 2 parts. Due to the thumb's unique joint with the bone in the metacarpus, it has 2 DOF.

There can be several reasons for performing an amputation. They can be because of infections such as tetanus which can be prevented by taking a tetanus shot and a booster every 10 years [6]. It was noted that since the discovery of antibiotics, amputations due to infections are very rare. Amputations due to unsafe workplace equipment or workplace conditions are frequent in the low-income rural parts of India [7]. Frostbite is a condition that occurs in the extremities when they are exposed to very cold temperatures. It results in loss of colour and feeling in that area and can cause permanent damage. In some severe cases, frostbite can result in amputation [8]. In some extreme cases of primary bone cancer or soft tissue sarcoma, an arm or a leg can lead to amputation. Primary bone cancer is a rare type of cancer that starts in the bones as compared to secondary bone cancer that spreads to the bone from other parts of the body [9].

There are multiple types of prosthetics available in the market depending on the user's requirement. If the amputation is limited to the fingers or thumb it is referred to as partial finger amputation. Any part of the finger such as the DIP, PIP or the MCP can be replaced. Wrist disarticulation is the removal of the hand and the wrist, trans-radial amputation is the amputation below the elbow, elbow disarticulation is the removal at the elbow joint, transhumeral amputation is amputation through the humerus i.e. above the elbow and below the shoulder [10]. The scope of this paper is limited to the designs for amputations up to the shoulder.

Prosthetics that can be attached for aesthetic purposes with little or no mechanical parts are called passive prosthetics. They might have mechanisms that are adjusted using the other hand. Prosthetic tools such as a hook assist with activities that require 2 hands. They can be made of PVC, different qualities of silicone and they can be customizable to match the amputee's hands.

Newer models for prosthetic hands can be made of 3D printing material like plastic or steel. Amputees often use both passive and active hands depending on the situation. Passive hands provide a lifelike appearance and are more comfortable than active hands so they are used on social occasions to increase confidence. They offer psychological support to the user and forget about the handicap [11].

Body powered prosthetics are operated using harnesses and cables that are operated through the movement of the chest and shoulder. These prosthetics can be used by people who work in manual labour as these prosthetics can be durable and assist the other arm. The end effectors are usually hooks that can be normally open or normally closed. These hooks can be made from a variety of materials like plastic or titanium and be lined with rubber for better grip. One variation of body-powered prosthetics is called naked prosthetics that are used by people with partial hand or finger loss. The end effectors are modular and can be changed easily for specific tasks. As body-powered hands are lighter than myoelectric hands, they can be used for much longer and are more comfortable. They can be used for travelling activities for extended durations as they are not dependent on batteries [12].

The third type of prosthetics are electronically operated prosthetics. They are attached with sensors such as Electromyography (EMG) sensor or Electroencephalogram (EEG) sensor that detect signals from the user's body, interpret them as an action the user wants to perform and provide commands accordingly to the end effectors like motors. This type of prosthetic can be designed in multiple ways according to the user's needs. They can be attached with a simple gripper that can perform opening and closing actions or they can be attached with a complicated mechanism that can control individual fingers.

Amputation of upper limbs is more frequent in developing countries and usually, people from those countries cannot afford expensive myoelectric arms so it is important for the research community to come up with solutions that can help the population of these countries during work and also be affordable [13]. There are 3 million people worldwide who have an arm amputation and 2.4 million of those live in developing countries [14]. In 2019, the number of amputees in India who suffered amputations below the elbow was 0.11million and about 16, 500 people are added each year [6]. According to a 1975 study, 75% of amputees change their occupation from labour related jobs like processing and machining to clerical or sales [15]. This shows that amputation can lead to major lifestyle changes for amputees.

II. LITERATURE REVIEW

Galileo Hand [16] was a 3D printed hand with a simple yet functional design for transradial amputation with a lot of different options for customizations according to the user's needs and budget. This was possible because it was designed to be made with materials that were readily available in developing countries and its modularity made it easily modifiable to increase the range of target users. The cost was less than \$350 and weighed less than 350g. The hand was also fitted with a micro LCD screen that displayed a range of grips that the user can select. The complete mechanical assembly along with the micro LCD screen and the motors were attached inside the hand itself so that amputees with stumps of any length could use it. The palm was divided into 3 sections – The motors for the fingers excluding the thumb, the actuators for the thumb and the remaining components such as the micro LCD screen. An ARM Cortex-M4 based microcontroller was used, which consisted of SIMD extensions for its instruction set that could be utilized for signal processing and stack pointers for real-time applications using RTOS (Real-time operating system). The hand had 6 DOF. The Thumb had 2 actuators to provide it with 2 DOF. The actuator responsible for the flexion-extension was located inside the thumb. The mechanism for abduction-adduction consisted of a motor located inside the palm and a system of bevel and helical gear to change the axis of rotation. The outer shell was connected to the inner phalanx to provide extra grip in case the material is thermo-flexible. The length of the finger could also be changed to suit the user. This actuation design for the fingers was tendon driven. Waxed nylon cords were used as active tendons and elastic cords as passive tendons. The passive tendons were inserted from the outer (dorsal side) and the active tendons were inserted from the inner side and both were connected at the tip of the finger. The hand could be controlled in 2 ways, the first one was using an EMG band and the second way was using buttons and the MicroLED display. Tests were conducted to find out which interface would be more user-friendly and the results showed that the EMG version did slightly better as it required less effort by the user. The authors pointed out that there were some disadvantages to this method as well so they decided to provide the user with both user-interfaces

As per [17], the prosthetic design is based on the fact that the thumb is the most used finger in our daily lives and it is used 37.6% of the time followed by the middle finger at 21.2%, the index finger at 19.7% and ring and little finger at 5.6% and 2.4 % respectively [18]. So the design focused on attaining the maximum possible range of motion for the thumb, then the index and middle finger followed by the little and the ring finger. Attention was given to 2 types of grips namely power grip and precision grip as they are used a lot in daily life. The thumb was positioned in such a way that these grips were possible. A total of 2 motors are used, 1 for actuating the thumb to imitate the CM joint that moves the thumb towards the inside of the palm and the other is used for the rest of the fingers for flexion and extension. The fingertips were made of soft material to increase the contact area while picking up objects and grasping objects in a much more comfortable grip. The hand could also perform lateral grip. An added benefit was that it also allowed the user to pick up smaller objects as compared to what was possible before. The hand could provide 3 types of grips. The unique aspect of the design was its inclusion of a nail at the end of the finger presumably to make the prosthetic hand look more aesthetically similar to a human hand. Springs were added to the design in a newer version, to factor in any large impact to the hand that might damage the hand. The authors pointed out that if the impact was large enough, the deformation would be permanent without springs. These springs were put in at the MCP joint, where the finger was attached to the palm. The 'Pick and Place' experiment was conducted using objects used in daily life. They were to be lifted and placed at a target and back to the original point in 30 seconds. It was noted that the improved hand was able to pick up small objects better than the older version and the factors that contributed to this improvement was the shape of the nails and the spring.

Rehand [19] was a 3D printed prosthetic hand that looked realistic and had the same grasping functionality as a hand, with a simple mechanism using only a single actuator. As the hand was 3D printed it would be easy to make and maintain. The hand was modelled based on a passive prosthetic hand manufactured by SATO GIKEN corp. The mechanism for grasping was developed next based on the model in CAD. The mechanism was controlled by a linear actuator that is connected to a series of links and shafts. The control system was different from most on the prosthetic hand available. The socket that is attached to the stump had a distance sensor that measured the bulge of the muscles by measuring the distance between itself and the skin. The distance sensor was not in direct contact with the skin and was separated by a urethane spacer. The distance sensor measured the bulge of the muscles and proportionally calculated the amount of extension-flexion required for the prosthetic arm. EMG signals that were in contact with the skin could be affected due to sweat but this disadvantage was eliminated in Rehand. They are also much cheaper than EMG sensors. The calibration for the hand would be initiated by pressing a button on the control box for 1 s. In the next 1 second, the distance sensor would measure the distance when the arm was at rest and then averaged. The sensor then measured the values during contraction and the values were again averaged. The entire calibration would take around 5s. The wrist could be passively operated. The Southampton Hand Assessment Procedure was conducted for this hand [20] with the help of an amputee trained in commercial prosthesis and the distance sensor was placed on his carpi ulnaris. The tasks consist of 6 abstract object tasks and 8 simulated Activities in Daily Life (ADL) tasks that had to be completed in 100 seconds. The participant was able to move the three lightweight objects but could not complete the remaining abstract object task using Rehand. He was also able to complete most of the ADL tasks except the ones that needed fine manipulation like picking up coins.

The design in [21] was a 24 degree of freedom hand with hybrid actuation. The design was heavily inspired by the human hand by imitating the structure of a real hand, joints, muscles and tendons. Each part of the bone structure was studied carefully, recreated in CAD and scaled according to the requirements of the subject. Cylindrical joints were used for MCP, DIP, PIP of fingers and IP and CMC joint of the thumb, whereas spherical joint for MCP and CMC joint for the thumb. Constraints that the human hand provided were translated into the design. For example, the extension-flexion for the PIP joint in a human body is 0 degrees to 110 degrees and the design reflected that constraint. Shape memory alloy (SMA) actuators were placed on the lateral and medial sides of the metacarpal for abduction and adduction of the fingers. SMA was chosen for this purpose as they could imitate the actual muscles that are relatively weak and weigh less than motors. For flexion and extension of the prosthetic hand, brushless DC motors were used as they would provide similar functionality to an actual hand. 4 motor pairs were used for the hand and 2 more motors were used for flexion-extension and abduction-adduction of the wrist. Additional 3 motors were used to actuate the thumb. A total of 13 motors were placed in the forearm. Neural Networks were used to classify the EMG signals and create control commands. The Myo armband by Thalmic labs was used to gather data. Data was collected from 18 volunteers. The features extracted from the EMG signals were given as the inputs and 7 grip positions are the outputs. The neural network created in Matlab had 20 layers with a sigmoid activation function for all layers except the output layer which uses the softmax function. A labelled data set was used to train the model. The model was trained in two different ways, once using data from a single volunteer and the second time using the complete dataset. The accuracy was 95-98% in the first case and 80% in the second case. The motors were attached to tendons that pass through tunnel-like structures in the palm that was kept close to the skeletal structure to prevent bowstringing and better efficiency in the movement of the finger. The tips of the fingers were embedded with sensors that provide feedback about the location of the tips at all times.

Olympic hand [22] proposed a modular design that allowed for modularity of fingers, the hand and the wrist. The paper stated that many researchers have tried to solve the issue of reparability but those designs required delicate components or were not suitable for prosthetics hands with large weight or high mechanical complexity. Amputees who used prosthetic hands were unable to maintain and repair their prostheses which is a big problem in places without specialists. Olympic's design allowed the user to intuitively and quickly exchange components without the use of complicated instructions. It was capable of doing so because of joint coupling mechanisms at the finger and wrist level. The complete cost for the hand was around $193 and took 8 hours to assemble. The hand consisted of 3 joints per finger and 1 motor per finger. The motor for the thumb was located in the palm and the motors for the rest of the fingers were located at the back of the hand (the dorsal region of the hand). Bevel gears were used to transmit power in the direction perpendicular to the axis of the motor and pull the tendons present inside the finger. The high gear ratio prevented backdriving and the hand could stay in a position without power being supplied to the motors. The fingers would be properly aligned to the palm using magnetic markers and the fingers were attached using a swinging motion. A pivot latch inside the finger and a socket in the palm ensured proper coupling and a spring plunger was used to lock the fingers in place. Similar mechanisms were used for the thumb and the wrist.

The authors decided to use a new protocol to measure the effectiveness of the hand using food, kitchen items and other tools as they are used in day to day life. Two marks were placed 500 mm apart and items from the Yale CMU Berkley Object [23] set were placed on one mark, lifted above a minimum height of 100mm, and placed on the second mark. This was repeated 10 times for each of the 20 objects. The hand achieved a score of 185 out of 200. The hand was able to lift all the items using a power grip but failed a few times while using the precision grip. The maximum load force was calculated by pressing a load cell perpendicular to the fingers till the fingers detached. This was done 10 times per finger. The maximum and minimum torque of 0.5Nm and 0.33 Nm was calculated with a median of 0.39Nm.

The Touch Hand 3 [24] was designed to be converted from a mechanical system to a mechatronics system if required. The previous version was called the Touch Hand 2 and was controlled using tendons but the Touch Hand 3 made use of the 4 bar finger system due to the friction between the tendons and the finger. The Touch Hand 3 also used micro linear actuators which are cheaper than other alternatives for manipulating fingers. They are located in the palm. The hand also had 2 microcontrollers instead of 1 so that each controller can focus on a specific task, one is used to process the EMG signals and the other is used to control the motors. The thumb in the prototype was designed for rotation only and cannot perform flexion/extension. It is held in place using a pin fastener that allows it to rotate. The wrist motor is attached to the palm using a standard prosthetic connector and connected directly to the palm. This design was then developed, tested and then optimized and in the final design, the fingers were modular and they could be opened or closed fully. The final mechanical design weighed 513g and cost around $81 while the mechatronic system weighed 593g and cost $1042. The chassis and the finger hinges were made out of 2 mm 304 stainless steel while the fingers and the cover were printed using 2mm ABS plastic. Three tests were conducted on the Touch Hand 3. The first one was the Yale Open Hand Test [25] which checks if the hand could pick up daily use objects and scored out of 5. The mechanical and mechatronics hands were able to successfully pick up one object. The second test conducted was the SHAP test [36] and the results were plotted to compare the results of the Abstract Object Test. A Dynamometer test was conducted to measure the grip strength of both the modes and it was observed that the mechanical version had a maximum strength of 2.8kg vs. 1.9 kg for the mechatronic version. The authors of this paper also noted the maximum human grip is 45.9kg.

The RIC arm [26] was designed by keeping comfort and cosmetics in mind. The weight of the arm was 1518g. The authors noted that since the 1940s, people have been trying to replicate the human hand and with the advance of robotics, research in multi-articulated hand design and control strategies have increased but they came at the cost of increased cost, weight, and complexity. Decreasing the weight and size of the prosthesis would lead to a better aesthetic appeal for daily use. This is not an easy task. The RIC arm consisted of a 2 DOF hand, 2 DOF wrist and a 1 DOF elbow. Custom motors were designed that could provide high torque at very low speeds to match the characteristics of a human hand. To assess the performance of the arm, inputs were given directly through the CAN bus and controlling the motor controller directly. The speed of joints was found out by moving the joints back and forth completely four times, except for the thumb. It was found out that the elbow was the slowest, followed by the finger MCP joints and the elbows was the fastest joint. The dynamic behaviour was tested by providing each joint with four-step inputs except for the thumb and the output velocities were recorded. The detailed analysis of that data was mentioned in the paper [26]. To measure the pinching force, a testbed with a load cell was created. The starting position was an open hand and the test stopped 1 second after the force interaction. The details of this test were noted down and can be seen in [26].

The open-source arm in [27] can be found on their website [28]. The main goal behind this arm was to create an arm that could be used for researching control techniques other than the current control techniques such as EMG. The authors wanted to create a hand that could be open source and inexpensive so that the control techniques could be implemented in the real world instead of just being designed and simulated on virtual hands. They suggested that the main bottleneck with the limited usability of a prosthetic hand was that the EMG sensors can only read signals from 2 sites and so only provide a single degree of freedom (flexion and extension). This leads to abandonment of upper hand prosthetic limbs and those numbers could be as high as 75% [29]. The design that they proposed had 6 degrees of freedom, one for each finger except the thumb while the thumb had 2 degrees of freedom. The metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints were fused. The thumb would be able to perform flexion-extension and rotation. Parameters such as the weight and the speed of the hand were kept as close as possible to commercial products. The components were 3D printable to keep the design affordable. The added benefit for end-users was that the design could be modified if needed. Each finger on the hand had the same design for simplicity. The motor at the base of the finger was attached to a bevel gear set that actuated the MCP joint. A timing belt system actuated the PIP joint. The movement of PIP and MCP joints were coupled. The thumb's flexion-extension mechanism was housed inside the finger and is similar to that of the other fingers. The motor placed inside the thumb rotated the first miter gear and this gear would drive a second miter gear that is attached to a shaft at the base of the thumb. This shaft would rotate the entire thumb. For the rotational motion of the thumb, a motor located in the palm rotors a miter gear. This gear transmitted the torque to a set of spur gears that rotate the base of the thumb. 2 Tests were on the hand. The first test measured the torque produced by the motors with and without the gearbox. The equipment used to measure the torque was a load cell that could measure forces accurately. The second setup was used to test the force at the fingertips. The tips were placed on the load cell, in a fully extended condition. The fingertip force was measured to be 4.12 N at 6.4 V. This value was lower than the calculated value due to the losses in transmission being one of the reasons.

Prosthetic hand in [30] utilized a single actuator but could provide multiple grips. As the design used a single actuator, the authors could make use of a much stronger actuator than other designs. The design could achieve the best of both worlds as the grip force is higher than commercial designs and could provide multiple grips that single actuator arms cannot. All four fingers have the same dimensions for reduced complexity. The hand had 6 revolute joints and 2 prismatic joints per finger, 8 revolute joints for the hand. The thumb was located between the index finger and the middle finger opposite to the palm. The hand was controlled using tactile buttons. The hand could perform the following actions – open hand, precision grip and power grip. Although the dimensions of the hand were acceptable, the weight of the hand was 2.5 times a human hand and so it could not be used for daily life. The pinch force was measured using a load cell while the hand performed precision grip. The hand could provide a grip up to 34.5 N at 2A current, which was the nominal current of the motor. The closing time for precision grasp and power grasp was found to be 1.4 and 1.7 seconds respectively. The hand could grasp spherical objects with diameters up to 96mm as compared to traditional could grasp objects with 100mm diameter. The hand could also pick up items used for ADL.

The Bebionic hand [31] is one of the most advanced prosthetic hands available to purchase. The hand is controlled by 5 6V motors, 1 for each finger. Each motor is located inside the palm for proper weight distribution. Each finger is also fitted with its own PCB with a microcontroller that monitors the parameters from its respective finger and provides the required control and feedback for smooth movement. The gripping positions for the Bebionic hand are programmed into the hand and the user can choose between 2 positions for the thumbs – opposed and not-opposed. The user has access to a total of 14 grip patterns out of which 10 are available at any point in time by adjusting the thumb position. The position of the finger is calculated by having a counter to measure the revolutions of the motor. This allows for repeatable results every time. The revolutions are measured every 50ms. Each hand is programmed with a software called Bebalance that allows for customization of parameters such as speed, grip force. It also provides options for real-time analysis and for users to practice using the arm using feedback. A Program switch is located on the back of the hand under a membrane that provides 4 functions that can be activated using BeBalance.

SSSA-myhand [32] design wanted to solve issues with current off the shelf prosthetics. It made use of 3 actuators only and was capable of most of the grasps which could be used for ADLs. The authors of [32] also wanted the arm to stand out and not blend in, so the aesthetics were designed to do the same. The fingers were designed to be long and included 2 joints. The thumb was designed without an interphalangeal joint. It could flex or extend around an equivalent MCP joint and abduct or adduct around an equivalent trapezio-metacarpal (TM) joint. 8W BLDC motors were used as actuators with integrated planetary gears. The output of each motor was connected to a worm gear to make it non-backdrivable. Sensors would be attached for automatic grasping and for providing feedback to the user as a future application. A single actuator was used for the flexion/extension of the index finger and the adduction/abduction of the thumb. The mechanism used a Geneva drive for the thumb and a four-bar linkage for the finger, where both these mechanisms were driven by a worm gear connected to a motor. The prosthesis could hold objects without additional power to the battery. The power consumption was such that a lightweight 12V 1AH battery was sufficient to power the hand. The authors noted that SSSA-myhand's speed was faster as compared to some of the commercial prostheses.

The hand designed in [33] uses 4 motors to provide precision and conformal grips. To provide both types of grasps, the thumb and the index were used mainly responsible for precision grasp and the other fingers were responsible for the conformal grasps, to stabilize the object during grasping. To handle precision grasps, 3 actuators were used to provide 3 DOFs and the remaining fingers were actuated using a single motor using a coupled differential. The PIP and the MCP were fused for all fingers. The first motor was used for abduction-adduction of the thumb using tendons. The second motor used tendons to provide the thumb with flexion-extension actuation. The third motor is used for flexion and extension of both the index and the fourth motor is used for actuation of the remaining fingers. The middle, ring and little fingers have unidirectional actuation only and could be extended using torsional springs whereas the thumb and index are actuated bidirectionally. Using 3 motors for controlling 3 DOF for the index and thumb allows the user to have much better control.

MSC prosthetic hand [34] proposed a twofold solution for hardware and software. The actuation mechanism was called 2-speed twisted string actuator or TSA for short. The actuator could provide 2 modes, one for quickly grasping objects (speed mode) or having a high grasping force (force mode). The software included a new method for detecting intent using EMG. This control system used a neural network model that had reduced inputs which were adapted to be used by a microcontroller inside the hand. The complete system was optimized to be highly portable and independent. The authors said that the reason conventional prosthetics were not able to achieve grasping speeds equivalent to that of a human was because of the use of transmission that could provide high torque or speed but not both. The index and the middle finger were given one DoF each whereas the ring and the little finger shared a single tendon actuator. The thumb was provided with two DOF. The Abduction/Adduction movement was due to a motor embedded inside the finger connected to a worm gear. Flexion/extension was provided due to a 4 bar linkage between PIP and MCP joints. The hand could be controlled using position-based or force-based systems.

As per, [35] the design was optimized for swinging in sports activities. The anthropomorphic prosthetic hand was dedicated to achieving a power squeeze grip and changing the phase during swinging to get an efficient swing. This was done by adjusting the stiffness of the fingers and the wrist. Fibre ropes with high stiffness were used as ligaments to reduce the flexion rotational motion. Differential actuation was used as it reduced the number of actuators and force distribution is equalized amongst fingers.

A clutch was used for actuating the wrist. The wrist would be stiff at the top of the backswing and would be loosened at a certain point while swinging.

A hand that could magnify grasping force using a tendon driven mechanism was designed in [36]. The hand was light-weight and could be controlled using flexion drives for fast movement and force magnification drive for a strong grasp. The thumb was controlled using 3D linkages. Each finger used one motor including the thumb. The motors were rated at 1.2W but they were connected to a force magnification drive and the final output was 3W. The motors for the fingers drove the feed screw with the spur gears. The feed screw for the thumb and the motor for that thumb was connected using a universal joint. The average time for the fingers to move 90 degrees was found to be 0.47s because of the flexion drive. The worst-case scenario for the fingers would be when they were stretched out and their force at the tips is the minimum. Without force magnification, the force was 2.9N and with the magnification, the force was found to be 22N. The Thumb could lift a 10kg object which was hung 55mm away from the thumb joint. Tests were also conducted to find out the electrical parameters during a grasping operation and to find out how firm the grip could be, using all 5 fingers. The detailed results of these experiments were shown in the paper.

A pneumatically actuated hand was designed in [37]. The authors noted that the devices used today are complex and require a lot of sophisticated mechanisms. If any compliance was to be added to these structures, additional parts had to be included which increased cost and complexity. Their approach was to use soft robotics i.e. robots made of soft and flexible materials that are compliant by design. They would adapt to their environment easily without a lot of sensors and the flexible structures adapt to the object passively. The hand had 6 DOF, with 2 for fingers and 1 for remaining fingers. Each finger had an actuator and the thumb had 2. The hand was made from 2 types of silicone with polyester thread reinforcement. The rubber exoskeleton was made with stiff silicone. These materials could be programmed to have the required mechanical properties that allow the hand to curl [38]. Tests showed that the hand was even able to grasp small objects, and actuated fingers influenced other fingers which provided a natural feel to the motion. The current version of the design required a relatively large pressure of 3MPa and the design will be improved in further iterations with the inclusion of an EMG controller as well. The design and its code is open source. To measure the bending angle vs. the pressure, the hand was attached to a vise in such a way that the bending plane was parallel to the plane of the camera and a coloured marker was tracked on the finger using image processing. This experiment was conducted 6 times for individual fingers and the entire arm. A custom force sensor was used for measuring force using the same setup for each finger and the entire hand. The results for these tests were plotted in [37] Grasping tests were performed on various objects and the results are also displayed in [37].

The wrist mechanism design in [39] was inspired by the human wrist rather than mechanical techniques. The design adopted a tensegrity structure, resulting in a much lighter design than its mechanical counterparts. The mechanism used tendons and the actuators were mounted in the forearm. Rolling contact joints [40], [41] were used, containing 2 links that were in constant contact with each other, they did not have a lot of friction between those links, had a wide range of motion and had high force capabilities. Tensegrity is a design principle that is applied to 2 pieces that are connected using opposing tensile force that stabilizes the structure. Compliant mechanisms are mechanisms that can gain some movement due to deflection. This would not only reduce the number of parts [42] but the authors stated that these mechanisms would reduce damages to the hand and the user during the event of a mishap. The compliant property was introduced in the structure due to the elastic strings. The wrist was made of 3 pieces that were connected using 12 pieces of string. They were in equilibrium with each other. The compliant feature was maintained in all directions unless the pieces came in contact with each other. A prototype was manufactured, and it was assembled using SAVA cables. The stiffness was measured to be around 100N/mm. A testbed was designed to measure the force with respect to the position in the longitudinal direction. The testbed consisted of two lead screws in parallel to each other, rotated by stepper motors. A horizontal plate was equipped with a load cell to measure pulling or pushing forces. The prototype was kept upright to measure compliance against compressive forces and kept horizontally to measure compliance against lateral forces. The resultant stiffness was measured to be 419N/mm for compressive forces and 3.5 N/mm for lateral forces. The relationship between the input torque and output force was measured using a testbed made from a load cell. The experiment was performed only at the neutral position of the wrist. The experiment had two variations, one where the strings were tightly pulled and the other where the strings were loosely pulled.

The authors of [43] were inspired by work done in [44] by Kyberd and colleagues on a compliant wrist with 2 DOF. The goal was to create a wrist whose stiffness would vary according to the EMG signals that were used by the hand for flexion-extension. The wrist consisted of a differential in the centre and an elastic joint attached to either side. The elastic joint was made up of 2 compliant modules with different stiffness and the desired module was selected using a selector. The central bevel gear was connected to the hand. Each elastic joint was composed of 2 outer rings and 2 polymeric springs with different stiffness on either side of the central compression plate. The outer ring had plugholes that would be used to connect to the selector. The selector was parallel to the plane of the elastic joint and could be engaged with one of the elastic joints at a time by inserting the pins on the selector with the plugholes. The selector was attached to an adjusting spring and an actuation slider. While reaching for an object, the wrist would become compliant, so that the wrist could easily align with the object by pushing the hand against the constraints (such as a wall). Once the hand grasped the object in a stable grip, the wrist would become stiff. The prototype was created by machining parts like lead screws, gears and shafts using stainless steel and non-critical parts using aluminium to reduce weight. The slider for the lead screw coupling was made from brass to minimise coupling friction. The output was connected to an

Instron tensile tester to measure the linear displacement and a load cell to measure the reaction forces. The resultant graph can be seen in [43] wherein the complaint mode the response was equal for both the DOF and there was negligible difference between only flexion-extension movement, only abduction-adduction and combined movement.

A bio-inspired wrist designed in [45] was made with 2 ellipsoidal structures stacked on top of each other and tunnels for ligament routing that made the wrist stiffer and more compact. The design reduced the weight of the wrist without compromising its range of motion or performance. The ligaments in the human wrists connect the carpal bones to provide high non-linear stiffness and a high range of motion. To emulate the same, tunnels were designed in the wrist and implemented using 3D printing. Manufacturers had not made ellipsoid artificial wrists as advantages of this design were not yet clear. The authors found out that the ellipsoidal two-row structure helped decrease the stress and thus reduce the load capacity for the tissues of the hand. They found out that the human wrist requires a large ROM during flexion-extension and a small ROM during radial-ulnar deviation. The ellipsoid joint could increase the contact area which leads to a larger load capacity. Tendons with linear elasticity had a lot of disadvantages and to solve this non–trivial task the authors designed a closed-loop routing system with high stiffness tendons. The closed-loop would slide along the path when the bone rotated without any increase in the length of the tendon. A prototype was fabricated using polylactic acid which weighed 30g. Open Source human dynamics simulator [46] was used to compare the energy consumption with respect to conventional joints. Due to the high DoF and its low inertia, the wrist was much more energy efficient. The RoM was calculated using an embedded gyroscope by pulling the wrist completely in the flexion-extension (FE) and radial-ulnar (RU) directions and measuring the angles. For measuring the RoM in FE and RU coupled direction, the wrist was rotated in an elliptical path. The authors were satisfied with the RoM as the results showed that it was enough to perform daily tasks. To find out if the routing method was better than conventional point to point routing, 6 prototypes were created, 3 with point to point routing and 3 with tunnel routing.The routing systems were created using 3 wire types – steel wire, fishing net and rubber band. A force gauge was used to measure the force-displacement curves for all joints. It was concluded that ligament tunnel routing can increase stiffness and have a large ROM.

The elbow designed in [47] used a belt, cable transmission and a DC motor and is similar to the size and weight of the human elbow. Very clear targets of torque, weight, range of motion were set by the authors for the elbow. They wanted the proximal and distal sections to be as small as possible to accommodate the maximum number of users. The transmission had 3 stages – 2 of which used chain drives and the last section used cable drives. Chain drives had the advantage of high efficiency, compactness and were back driveable whereas cable drives were not back drivable and did not have any chordal action. The total prosthesis weighed 1.2kg which was less than the target weight. The elbow had a maximum flexion of 15 degrees and a maximum extension of 145 degrees. The torque was measured by supplying 20A of current to the motor and a force gauge was attached 225 mm from the axis of the rotation for the elbow. An average of 18.4 Nm was calculated for 10 trials. The backdrive torque was measured by supplying 0A of current using the same setup but and the result was measured to be 1.5Nm. The maximum velocity of the elbow was calculated using motion control bandwidth. The motion of the elbow was controlled using an absolute encoder to provide feedback and the velocity was calculated using the hall sensors in the motor. The minimum time required to cover the full range of motion was 0.36 sec and the maximum speed was 360 degrees/sec.

Each of the papers reviewed was effective in solving the problem statement that was selected like modularity, weight, ease of implementation and so on. Most of their actuation mechanisms for the hand were either tendon based or 4 bar linkage based mechanisms. The authors for most of the papers also agree that 3D printing is a viable option for creating a prosthetic hand or for prototyping and experimenting with designs. Each of those designs had their own challenges that the authors have solved. The wrist designs were very different from each other, innovative in their own ways and found methods to increase the DoF and usability for the wrist than most of the available solutions which indicates that there is a lot of potential in research of prosthetic wrists.

III. DESIGN OF PROSTHETIC HAND

All the designs in the review that used a 4 bar linkage mechanism had fused the upper two sections of the finger and there might be a requirement for movement of the last joint for precision movements and the wrists and elbow that were reviewed had very complicated structures. To address those issues, a complete prosthetic arm was designed in such a way that it was 3D printable and had a very simple design philosophy. Along with the bionic version of the hand, a gripper type prosthetic hand was also designed to provide 1 DoF movement. The complete design was done in SolidWorks 2020.

A. Design of Prosthetic Finger

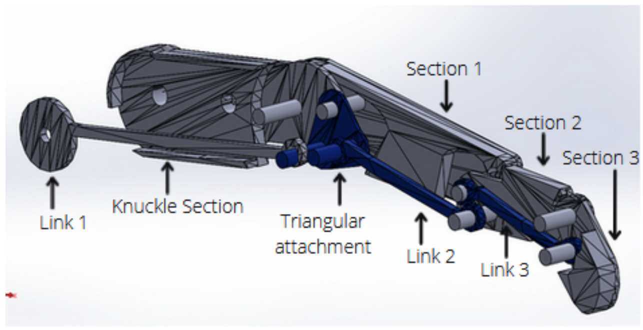

Fig.1. Internal design for prosthetic finger

The fingers that would be used for the bionic hand had to mimic a human hand so they needed to have three sections and the same type of movement. Three different sections of the finger were connected using linkages. The original design [48] contained pins used to connect links in a position where it was harder to connect all the sections so the location of the pins were changed. The finger shown in Figure 1 was used for demonstration purposes. The Triangular part (Fig 2) was attached to the first section through the hole at one end. One of the extensions/pins were connected to the worm gear through a link and the second section was connected to the furthest pin of the next section respectively.

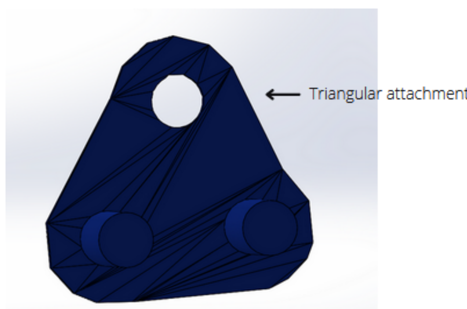

Fig.2. Attachment for the first section

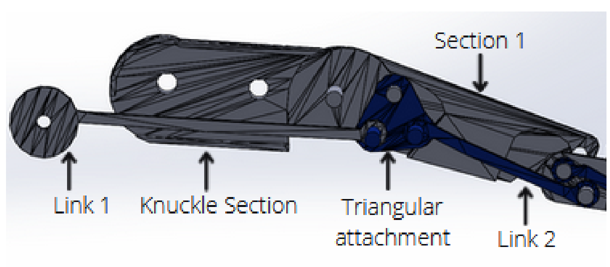

Fig.3. Knuckle section connected to the first section

The first pin from the middle section was used to connect to the final section of the finger. The finger moved when the worm gear pulled the first link towards itself, the triangular section (Fig 3) rotated and pulled the second link. This second link would pull the second section and the clockwise motion generated rotated the third section as well.

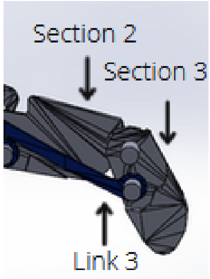

Fig.4. The tip of the finger

The actual finger looked like the figure shown below. The finger was connected to the palm as the third section is connected to a 'knuckle section' that has a hole in it. The knuckle would be connected to the backplate using screws.

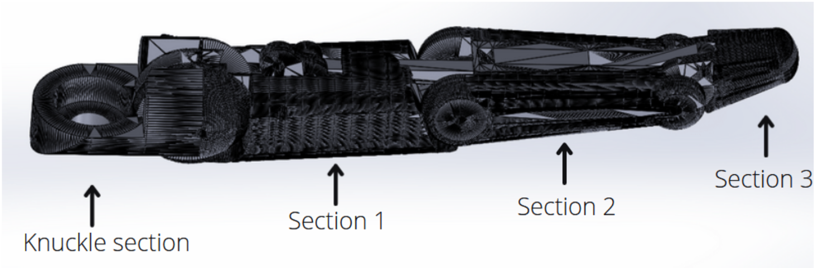

Fig.5. The prosthetic finger as seen from below

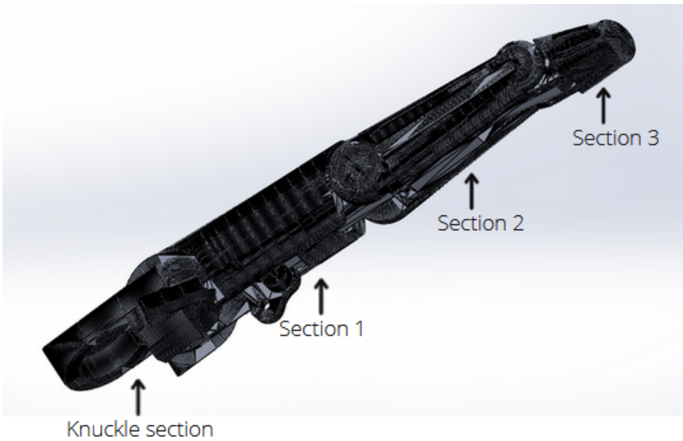

Fig.6. The prosthetic finger as seen from above

The finger link at the start of the finger would be connected to a worm gear [49] that was driving it. The mechanism was similar to the gripper mechanism shown in Figure 7. The major advantage to having a worm gear was that the hand would be locked in any position unless the user wants to move it. They are also low maintenance and are used in situations that require a low gear ratio resulting in more torque.

Worm	48 pitch, 3/16” bore, 5/16” outer diameter
Gear	24 gear, brass, 3/16” bore

Table.1. Required dimensions for the worm gear

A list of commercially available worm gears has been compiled.

B. Design of Prosthetic Gripper

Figure 7 shows the design for the gripper [50]. It had the same working principle that was used to actuate the finger. The worm gear had 2 parts - a worm or a screw and a gear. The worm is rotated by the motor. The gear is inserted inside the grooves of the worm such that the gear rotates when the worm rotates. A potentiometer can be attached to the gear to measure its rotation to measure the angle of the gripper. The same model of motor that is used for the elbow can be used for the gripper.

Opening span	100mm
Speed	110mm/s

Table.2. Target values for the gripper

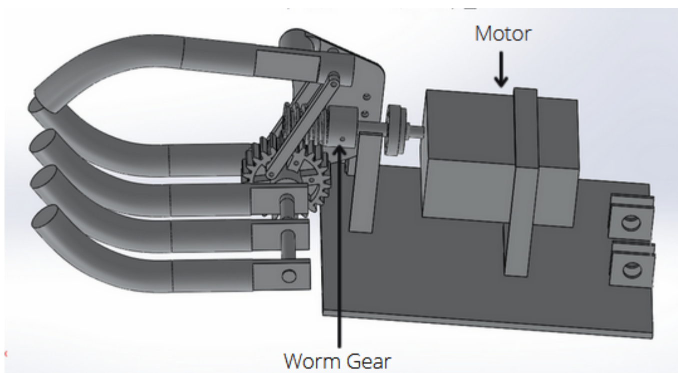

Fig.7. Prosthetic Gripper from side

C. Design of Prosthetic Wrist

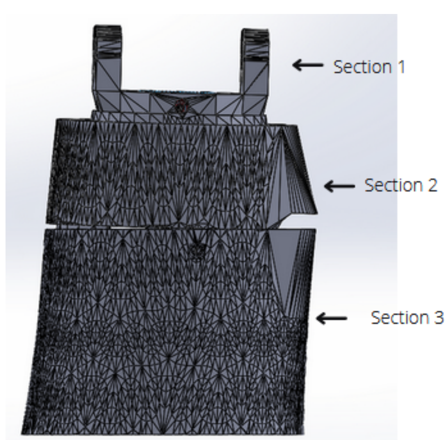

Fig.8. Complete prosthetic wrist

The prosthetic wrist has been designed so that it can rotate along the axis of the forearm thus mimicking the pronation-supination movement. The smaller gear is connected to the motor and is the driver gear. The larger gear is connected to the wrist and will be used to rotate the wrist. This design could have been improved by connecting the outer side of the wrist to a ball bearing to reduce friction during motion.

Mass	<100 g
Speed	≥1.42 rad/s (13.5 rpm)

Table.3. Design specifications for the wrist

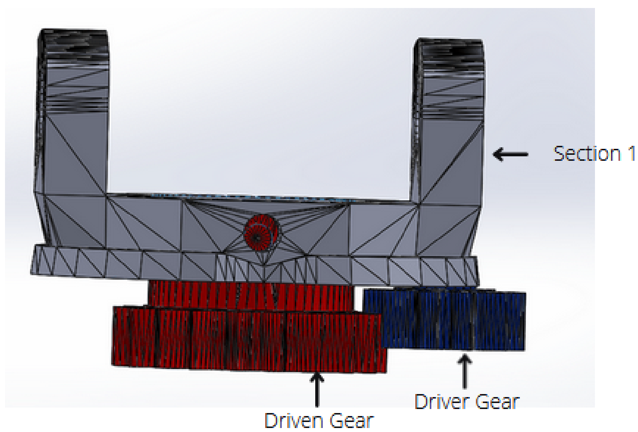

Fig.9. The upper part of the prosthetic wrist

D. Design of Prosthetic Elbow

The artificial elbow design in [51] had moving parts above the elbow, which was not a fit for amputees that might have larger stumps. To lift the arm using a single servo, a gear system had to be used [52][53]. Gears would allow the arm to generate more torque (turning force) at the cost of speed. A small gear was pressed onto the bicep servo to drive a larger gear section connected to the forearm. The designed gear system [49] increases the torque from the servo by a factor of 2.10. This Elbow has been designed to provide 110 degrees of rotation. This allows for a straight orientation and a right angle bend. With the addition of the gears, the servo now has to rotate the small gear by 290 degrees to completely bend the elbow. As previously mentioned a standard servo can only rotate through 180 degrees so modifications have to be made to increase the servo's rotational range. One potential solution would be to remove the potentiometer from the motor and attach it to the driven gear. Thus, the potentiometer would rotate as the driven gear is rotated and not the driver gear.

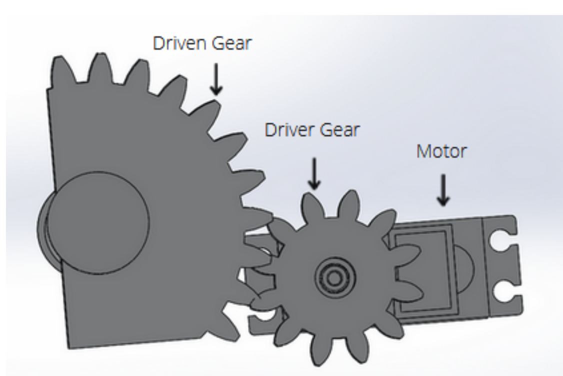

Fig.10. The mechanism for prosthetic elbow

IV. CONCLUSION

In this paper, sections of a prosthetic arm such as the hand, wrist and elbow were reviewed. A summary of each paper was created according to their problem statement and the designs created to tackle those problems. Each design was tested using a series of experiments designed by the authors of the respective papers and the effectiveness of each design was concluded based on the data from the experiments. Two variations of a prosthetic hand were then designed which were inspired by various designs from the literature review and other sources according to the design requirements. The entire bionic arm can be 3D printed. The gripper can be machined. Electronic parts such as motors can be bought off the shelf. A wrist and elbow mechanisms are also simple and so can be assembled by any user easily.

REFERENCES

[1] “Grasping the Importance of Our Hands” . Accessed on:Sep,22.2021. [Online].Available:https://orthop.washington.edu/sites/default/files/files/16-6-document.pdf

[2]“Limb Loss”. Accessed on: Sep. 25, 2021. [Online]. Available: https://medlineplus.gov/limbloss.html

[3] “Phantom pain”. Accessed on: Sep. 28, 2021. [Online]. Available:https://www.mayoclinic.org/diseases-conditions/phantom-pain/symptoms-causes/syc-20376272

[4] “Some Problems in the Management of Upper Extrem- ity Amputees”. Accessed on: Oct. 2, 2021. [Online]. Available:http://www.oandplibrary.org/al/1955_02_036.asp

[5]“How do hands work?” Accessed on: Sep. 5, 2021. [O- nline].Available: https://www.ncbi.nlm.nih.gov/books/NBK279362/

[6] “Reasons for amputating”. Accessed on: Oct. 11, 2021.[Online].Available:https://www.ottobock.africa/en/your-individual-fitting/lower-limb/info-for-lower-limb-amputees/before-the-amputation/amputation-causes/

[7] “Prosthetics designers harness AI to assist India’s amp- utees”. Accessed on: Sep. 19, 2021. [Online]. Available: https://www.scidev.net/global/features/prosthetics-designer s-harness-ai-to-assist-india-s-amputees/

[8]“Frostbite”. Accessed on: Oct. 12, 2021. [Online]. Available: https://orthoinfo.aaos.org/en/diseases--conditions /frostbite/

[9] “Bone cancer”. Accessed on: Oct. 11, 2021. [Online]. Available:https://www.macmillan.org.uk/cancer-informa-tion-and-support/bone-cancer

[10] “Arm & Hand Prosthetics: The complete guide from the prosthetic experts at MCOP”. Accessed on: Sep. 8, 2021. [Onli-ne].Available:https://mcopro.com/blog/resources/arm-hand-prosthetics/

[11]“Passive prosthetic hands and tools: A literature review”. Accessed on: Oct. 12, 2021. [Online].Available: https:// www.ncbi.nlm.nih.gov/pmc/articles/PMC5810914/

[12] “Body-powered upper limb prostheses”. Accessed on: Oct.13,2021. [Online].Available:https://www.ottobock.in/artificial-limbs/upper-limb/solution-overview/body-powered-upper-limb-prosthesis/

[13] Godfrey SB, Piazza C, Felici F, Grioli G, Bicchi A and Catalano MG (2021) Usability Assessment of Body Contr- olled Electric Hand Prostheses: A Pilot Study. *Front. Neur- orobot.* 15:683253. doi: 10.3389/fnbot.2021.683253

[14]“Limb Loss Stats” Accessed on: Sep 7.2021. [Online]. Available: https://u.osu.edu/fitness4all/loss-limb-stats/

[15] Millstein, S., Heger, H., and Hunter, G. (1986). Prosth- etic use in adult upper limb amputees: a comparison of the body powered and electrically powered prostheses. *Prosth- et. Orthot. Int*. 10, 27–34.doi:10.3109/03093648609103076

[16] J. Fajardo, V. Ferman, D. Cardona, G. Maldonado, A. Lemus and E. Rohmer, "Galileo Hand: An Anthropomor- phic and Affordable Upper-Limb Prosthesis," in *IEEE Access*, vol. 8, pp. 81365-81377, 2020, doi: 10.1109/AC CESS.2020.2990881.

[17] X. Jing, X. Yong, Y. Jiang, H. Yokoi and R. Kato, "A low-degree of freedom EMG prosthetic hand with nails and sprin- gs to improve grasp ability," *2014 7th International Conference on Biomedical Engineering and Informatics*, 2014, pp. 562-567, doi: 10.1109/BMEI.2014.7002837.

[18] Tatsuro NAGAO, M.D, “Analysis of Normal Finger Functions in Activities of Daily Life,” Rehabilitation Center, Kyushu Rosai Hospital, Kita Kyushu City, Japan, 1971.

[19] M. Yoshikawa, R. Sato, T. Higashihara, T. Ogasawara and N. Kawashima, "Rehand: Realistic electric prosthetic hand created with a 3D printer," *2015 37th Annual Interna- tional Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2015, pp. 2470-2473, doi: 10.1109/EMBC.2015.7318894.

[20] C. Metcalf, “Southampton hand assessment procedure (SHAP),” http://www.shap.ecs.soton.ac.uk, 2015.

[21] A. Atasoy, E. Kaya, E. Toptas, S. Kuchimov, E. Kaplanoglu and M. Ozkan, "24 DOF EMG controlled hybr- id actuated prosthetic hand," *2016 38th Annual Internation- al Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2016, pp. 5059-5062, doi: 10.110 9/EMBC.2016.7591864.

[22] L. Liow, A. B. Clark and N. Rojas, "OLYMPIC: A Modular, Tendon-Driven Prosthetic Hand With Novel Fin- ger and Wrist Coupling Mechanisms," in *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 299-306, April 2020, doi: 10.1109/LRA.20 19.2956636.

[23] B. Calli, A. Singh, A. Walsman, S. Srinivasa, P. Abbe- el and A. M. Dollar, "The YCB object and Model set: Tow- ards common benchmarks for manipulation research," *2015 International Conference on Advanced Robotics (ICAR)*, 2015, pp. 510-517, doi: 10.1109/ICAR.2015.7251504.

[24] R. Fourie and R. Stopforth, "The mechanical design of a biologically inspired prosthetic hand, the touch hand 3," 2017 Pattern Recognition Association of South Africa and Robotics and Mechatronics (PRASA-RobMech), 2017, pp. 38-43, doi: 10.1109/RoboMech.2017.8261120.

[25] Raymond M.A; Dollar; (2017); Yale Open hand Project; IEEE Spectrum Robotics and Automation Maga- zine, Vol. 24, No.1 March 2017, pgs

[26] T. Lenzi, J. Lipsey and J. W. Sensinger, "The RIC Arm —A Small Anthropomorphic Transhumeral Prosthesis," in IEEE/ASME Transactions on Mechatronics, vol. 21, no. 6, pp. 2660-2671, Dec. 2016, doi: 10.1109/TMEC H.2016.259 6104.

[27] N. E. Krausz, R. A. L. Rorrer and R. F. f. Weir, "Desi- gn and Fabrication of a Six Degree-of-Freedom Open Sour- ce Hand," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 24, no. 5, pp. 562-572, May 2016, doi: 10.1109/TNSRE.2015.2440177.

[28] "Open Source Hand: A 6 Degree-Of-Freedom Open Source Prosthetic Hand". Accessed on: Oct 24, 2021. [Online]. Available:https://opensourcehand.wordpress.com/

[29] Biddiss, Elaine A., and Tom T. Chau. "Upper limb prosthesis use and abandonment: A survey of the last 25 years." Prosthetics and orthotics international 31.3 (2007): 236-257.

[30] P. Wattanasiri, P. Tangpornprasert and C. Virulsri, "De- sign of Multi-Grip Patterns Prosthetic Hand With Single Actuator," in IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 26, no. 6, pp. 1188-1198, June 2018, doi: 10.1109/ TNSRE.2018.2829152.

[31] Medynski, Courtney and Bruce Rattray. "Bebionic Prosthetic Design." (2011).

[32] Controzzi, Marco; Clemente, Francesco; Barone, Diego; Ghionzoli, Alessio; Cipriani, Christian (2016). *The SSSA-MyHand: a dexterous lightweight myoelectric hand prosthesis. IEEE Transactions on Neural Systems and Rehabilitation Engineering ,() ,1–1*.doi:10.1109/tnsre.2016 .2578980

[33] D. A. Bennett, S. A. Dalley, D. Truex and M. Goldfarb, "A Multigrasp Hand Prosthesis for Providing Precision and Conformal Grasps," in *IEEE/ASME Trans- actions on Mechatronics*, vol. 20, no. 4, pp. 1697-1704, Aug. 2015, doi: 10.1109/ TMECH. 2014. 234 9855.

[34] Y. Cho, Y. Lee, P. Kim, S. Jeong and K. -S. Kim, "The MSC Prosthetic Hand: Rapid, Powerful, and Intuitive," in *IEEE Robotics and Automation Letters*, doi: 10.1109/ LRA .2022.3140444.

[35] M. H. Chang *et al*., "Anthropomorphic Prosthetic Hand Inspired by Efficient Swing Mechanics for Sports Activities," in *IEEE/ASME Transactions on Mechatronics*, doi: 10.1109/TMECH.2021.3084311.

[36] T. Takaki and T. Omata, "High-Performance Anthro- pomorphic Robot Hand With Grasping-Force-Magnificat- ion Mechanism," in *IEEE/ASME Transactions on Mechatr- onics*, vol. 16, no. 3, pp. 583-591, June 2011, doi: 10.1109/TMEC H.2010.2047866.

[37] N. Kim, S. Yun and D. Shin, "A Bioinspired Lightwe- ight Wrist for High-DoF Robotic Prosthetic Arms," in *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 6, pp. 2674-2683, Dec. 2019, doi: 10.1109/TMECH.2019.294 1279.

[38] J. Fras, M. Macias, F. Czubaczynski, P. Salek, and J. Glowka. Soft flexible gripper design, characterization and application. In International Conference SCIT, Warsaw, Poland. Springer, 2016

[39] G. Lee, G. Y. Hong and Y. Choi, "Tendon-Driven Compliant Prosthetic Wrist Consisting of Three Rows Based on the Concept of Tensegrity Structure," in IEEE Robotics and Automation Letters, vol. 6, no. 2, pp. 3956 -3963, April 2021, doi: 10.1109/LRA.2021.3067237.

[40] S. Kim, H. In, J. Song, and K. Cho, "Force characte- ristics of rolling contact joint for compact structure," in Proc. IEEE Int. Conf. Biomed. Robot. Biomechatronics, pp. 1207–1212, 2016.

[41] Y. Kim, "Anthropomorphic low-inertia high-stiffness manipulator for high-speed safe interaction," IEEE Trans. Robot., vol. 33, no. 6, pp. 1358–1374, Dec. 2017.

[42] "COMPLIANT MECHANISMS EXPLAINED" Aug. 15, 2014. Accessed on: Oct 25, 2016. [Online]. Available: https://www.compliantmechanisms.byu.edu/about-compliant-mechanisms

[43] F. Montagnani, M. Controzzi and C. Cipriani, "Prelim- inary design and development of a two degrees of freedom passive compliant prosthetic wrist with switchable stiffness" *2013 IEEE International Conference on Robotics and Biomimetics (ROB IO)*, 2013, pp. 310-315, doi: 10.1109/ROBIO.2013.6739477.

[44] Motion Control, Inc. 115 N. Wright Brothers Drive, Salt Lake City.

[45] N. Kim, S. Yun and D. Shin, "A Bioinspired Lightwe- ight Wrist for High-DoF Robotic Prosthetic Arms," in *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 6, pp. 2674-2683, Dec. 2019, doi: 10.1109/TMECH.2019.294 1279.

[46] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen, "Opensim: open-source software to create and analyze dynamic simulations of movement," IEEE transactions on biomedical engineering, vol. 54, no. 11, pp. 1940–1950,2007. UT, 84116, USA

[47] Bennett DA, Mitchell J, Goldfarb M. Design and characterization of a powered elbow prosthesis. Annu Int Conf IEEE Eng Med Biol Soc. 2015; 2015:2458-61. doi: 10.1109/EMBC.2015.7318891. PMID: 26736791

[48] "DARA Robot Fingers - InMoov updated fingers". Accessed on: Oct. 30, 2021. [Online].Available: https://ww w.thingiverse .com/thing:2551671#How%20I%20Designed%20This

[49]"Worm Gear".Accessed on: Nov.27, 2021. [Online]. Available: https://grabcad.com/library/worm-gear-112

[50] "Robotic 3 hand with worm gear and servo 360°". Accessed on: Oct. 30, 2021. [Online].Available: https://gra- bcad.com /library/robotic-3-hand-with-worm-gear-and-servo-360-1

[51] "Hand and Forarm". Accessed on: Nov. 23, 2021. [Online]. Available: https://inmoov.fr/hand-and-forarm/

[52] "Low Cost Myoelectric Prosthetic Arm". Accessed on: Nov.13,2021.[Online].Available :https://mdesigns.space/projects/ project-three-2jhsa

[53] "Prosthetic Arm". Accessed on: Nov. 26, 2021. [Online].Available:https://grabcad.com/library/prosthetic-arm-14