BIOMIMETIC MECHATRONIC HAND 2018

Abstract

Most prosthetic limbs are controlled by the detection of nerve signals in the arm of the user, usually limiting their functions to simple opening and closing movements. The objective of this project was to develop a unique design for a bionic hand not limited by these control methods, wherein the design focus would be to match the system to be as similar to a real hand as possible in terms of movement speed, dexterity, ranges of motion and fluidity of movement. In order to demonstrate the model, the secondary objective was to develop a physical, wearable controller such that the model could be made to imitate a user's hand. In both objectives functional, partial prototypes were built which demonstrated the success of both designs.

The initial designs were created based on a thorough review of anatomy and biomechanics in real hands, then developed iteratively based on simulated and physical tests. The final prototypes were evaluated using several testing methods, taking inspiration from real-world assessment procedures for bionic hands and also novel tests to meet the unique requirements of the models. The tests quantifiably show that the design has more than double the proposed ideal contraction speed for prosthetic hands as found by Chappell (2016), very similar ranges of motion in each joint to real hands and an ability to assume all grip types in the abstract shapes section of the Southampton Hand Assessment Procedure. The control glove was shown through electronic testing and physical control of a simplified prototype to be a functional and precise controller for the bionic hand.

The designs and concepts developed in this project present an effective bionic hand framework as well as a precise and dextrous control glove for applications in prosthetics, telepresence robotics, hazardous materials handling and more. Through in-depth research into 3D printing technologies, the designs have also been made very affordable for manufacture on what are now widely accessible FDM 3D printers, enabling the potential for continued collaborative efforts to further develop the designs in the future.

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1 Project Plan

1.1 Aims and Objectives

The aim of this project is to design and build a bionic hand which mimics real human motion more closely than many of the current bionic hands in development. Where most designs for prosthetic limbs tend to be restricted by the limitations of myoelectric technology (using electrodes to detect nerve signals and using this to control the mechanism), this project will be developed alongside a wearable glove that will detect fine motion in the wearer's hand and act as a controller. In this way, the bionic hand should be able to quickly and accurately imitate the motion of the user's hand.

The final prototype will be well suited to situations in which fine motor skills are required but the operator cannot be physically present. This technology could be useful for a wide variety of different applications, ranging from handling of hazardous materials to telepresence robotics. Alternatively, the design could be useful for when nerve-control technology or EEG advances, such that the hand could be used as a real prosthetic that would allow full fine motor control – enabling amputees to have a higher level of functionality restored.

All of the components will be designed in CAD software and it is assumed that much of the prototyping and construction will use 3D printing, due to its speed and versatility. Where 3D printing is inappropriate, other construction methods such as machining may be used.

2 Functional Anatomy and Biomechanics of the Human Hand

In order to define clear parameters for the operation of the bionic hand, it is necessary to examine the anatomy behind a functional hand which allows it to move in the way that it does. The aim of the project is to produce a bionic hand capable of replicating movement of the hand as closely as possible, so the actual structures of the hand are a very important consideration.

The human hand has 27 degrees of freedom: 4 in each finger, 3 for extension and flexion and one for abduction and adduction; the thumb is more complicated and has 5 DOF, leaving 6 DOF for the rotation and translation of the wrist (ElKoura, Singh, 2003). There are a total of 27 bones with 36 articulations and 39 active muscles. Most manufacturers of prosthetic hands limit their designs to have a much lower number of degrees of freedom because of considerations about power, space, weight and control, but as a biomimetic mechatronic hand, this project should aim to imitate the hand as closely as possible.

Each finger (not including the thumb) consists of four bones. The visible finger segments which protrude from the palm are called phalanges: distal, middle and proximal from tip to base respectively. In the palm, metacarpals attach each phalange group to a group of bones called the carpals at the base of the palm and these bones allow the wrist to rotate and translate on the radius and ulnar bones of the forearm. These bone structures are shown in Figure 2.1. Much of the hand's actuation originates from muscles in the forearm, which move the hand using tendons attaching to the various bones of the hand, these are referred to as extrinsic muscles. Some motion comes directly from muscles inside the hand called intrinsic muscles.

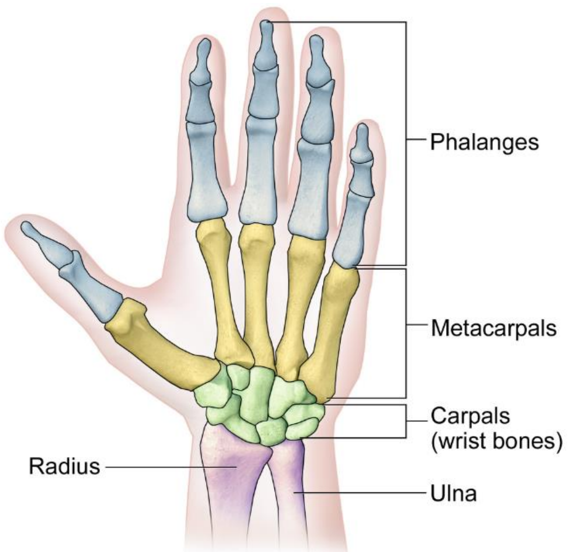


Figure 2.1 - Bones of the hand and wrist: Blausen.com staff (2014)

The Fingers

2.1 The fingers have several tendons which allow for flexion (bending motion which decreases angle between bones) of each segment, as well as tendons which allow them to extend (increasing angle between bones). There is a total of nine extrinsic extensor muscles in the hand, three of which extend the fingers, shown in Figure 2.2. These are:

- The extensor digitorum which extends all fingers from the distal phalanges, then the wrist
- The extensor digiti minimi which extends only the little finger
- The extensor indicis which extends the index finger

The complex way in which each of these extensors interact with each other and the ligaments affecting their motion is beyond the scope of this project because in the final product, motion will be directly measured from a fully-functional hand. However, as a simplification it can be noted that only the index and little finger can extend independently of the other fingers. These tendons oppose flexion to return the finger joints to a neutral position after being flexed, but also allow each finger to extend 40° from the back of the palm. When one of these muscles stops contracting, the fingers will be brought back to a neutral position by the opposing flexor muscles, the elastic ligaments between each phalanx or a combination of both, meaning that the fingers will return to a neutral position even if all muscles are relaxed.

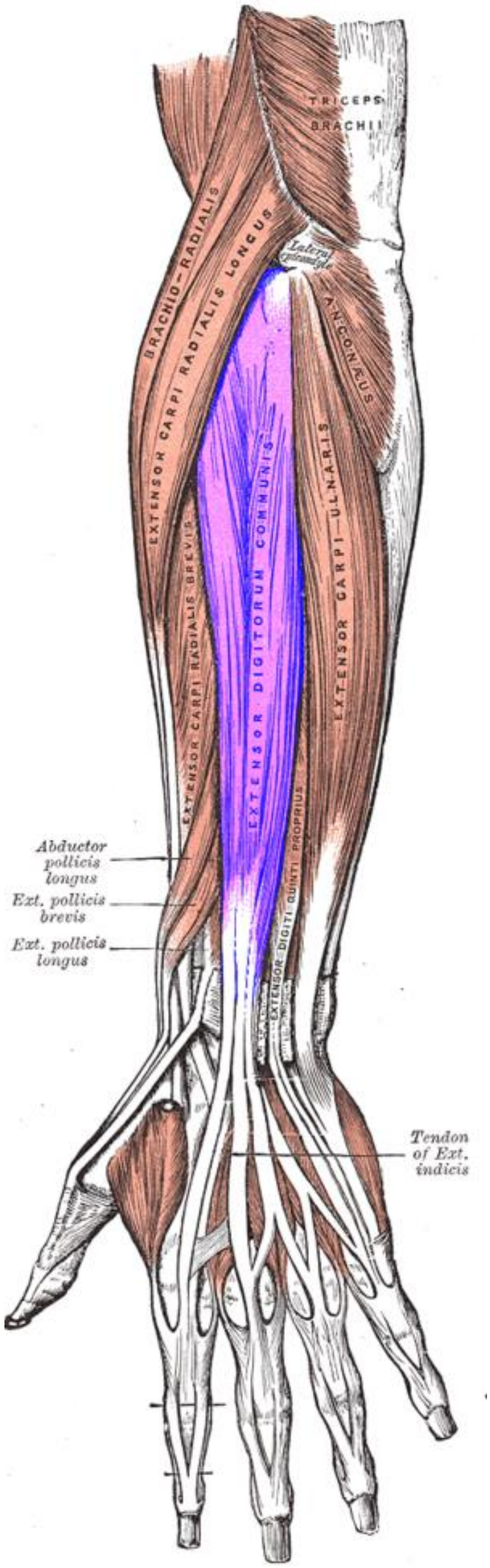


Figure 2.2 - Posterior surface of the forearm, extensor digitorum muscle labelled in purple: Häggström, Mikael (2014)

The fingers are flexed primarily with the flexor digitorum muscle which splits into the flexor digitorum profundus tendon and the flexor digitorum superficialis tendon. The FDP tendon attaches to the distal phalanx and the FDS tendon attaches to the medium phalanx, splitting to allow the FDP tendon to pass directly through the core of the tendon without impeding movement as shown in Figure 2.3. The proximal phalanx can be flexed independently with the lumbrical muscles located in the palm and shown in Figure 2.4. It is worth noting that although each muscle attaches at a different point, the furthest tendons actually flex all joints of the finger before it because of the way the tendons tie into the ligaments and tendon sheaths in the finger. This means that the flexor digitorum profundus tendon, which flexes the distal phalanges, also increases the flexion force at the medium and proximal phalanges. The arrangement of these muscles means than, in general, any segment of any finger can be flexed independently. There is some genetic variance and neuromuscular considerations (the mental connection that a person has with the musculature via the nerves) that play into specifically what movements the hand is able make, but the safest model to ensure maximum manoeuvrability/flexibility would be to assume that each phalanx is entirely independent.

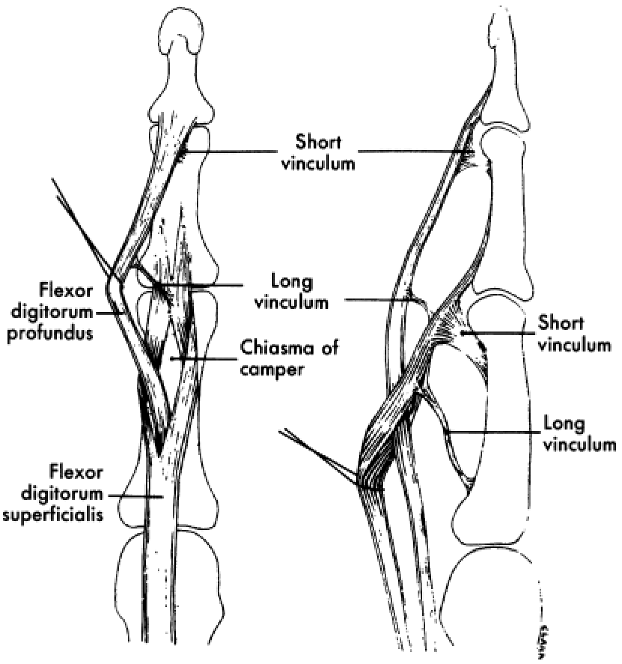


Figure 2.3 - Flexor tendons of the fingers: Flinn, S & Beckley, M, N (2007)

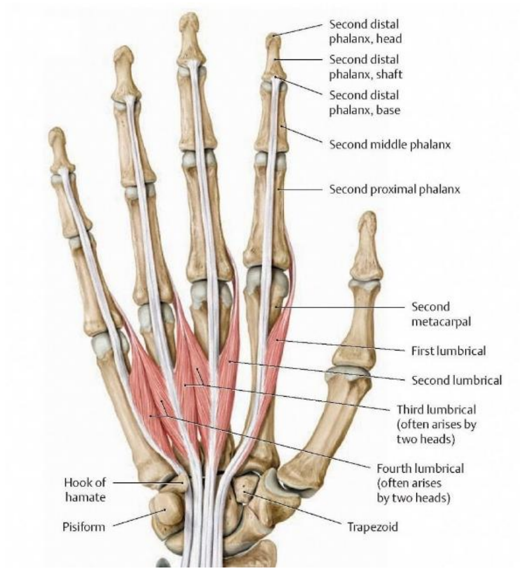


Figure 2.4 - Lumbrical muscles of the hand which extend the fingers as well as laterally rotating the proximal phalanges at the MCP joints. Gilroy et al (2016) Illustration by Karl Wesker

The fourth degree of freedom in the fingers is the “side-to-side” movement of the proximal phalanges about the metacarpophalangeal joint. Where the distal and proximal interphalangeal joints can be modelled as simple hinges, the metacarpophalangeal joint is a more complex condyloid style joint as shown in Figure 2.5. A condyloid joint is similar to a ball and socket joint except the ball and cavity is elongated in a single axis to resemble an ellipsoid. This means that most of the motion is flexion and extension but a there is also small amount of lateral motion. Several muscles located in the palm including the palmar and dorsal interossei and the lumbricals control this motion, shown in Figure 2.4. In the palmar plane, the proximal phalanx rotates 15° either side of the neutral position about the MCP, for a total of 30° range of motion on average according to Hirt et al (2017) (although this can be higher in some individuals). As it does this, it also twists inwards towards the pivot at its most extended in either direction by a very small amount (roughly 6 degrees either direction).

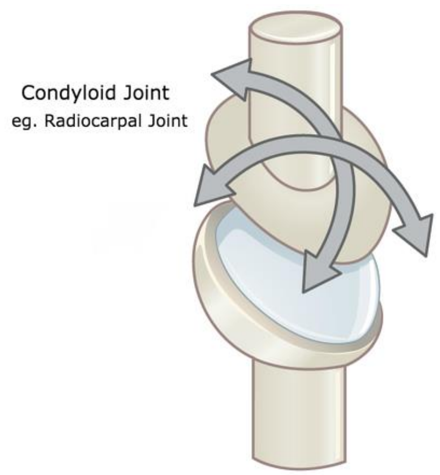


Figure 2.5 - Condyloid Joint: OpenStax College (2013)

The lateral motion of the proximal phalanges and the accompanying roll is a very important feature which greatly enhances the precision grip capabilities of the hand. It can be noted in one's own hand that the little finger and sometimes the ring finger is capable of directly opposing the thumb at a 180° angle, a maneuverer made possible by the lateral movement of the proximal phalanges. Note that there are virtually zero bionic hands capable of this movement because the fourth degree of motion in the fingers is almost never considered.

2.2 Thumb

Although the thumb has one less joint than the fingers, it has an extra degree of freedom making it the most mobile of the digits. The carpometacarpal (CMC) joint in the thumb connects the base of the thumb (which is blended into the palm) to the carpals above the wrist and is an extremely complex joint with 9 muscles controlling its movement. According to Hirt et al (2017) numerous studies have addressed the structure and function of the thumb CMC joint, and it has been described as a double hinge, ball-socket but most commonly a saddle joint (the only one of its kind in the human body) as shown in Figure 2.6. A saddle joint is defined as allowing two degrees of freedom the same as a condyloid joint, but unlike ball-socket joints they do not allow axial rotation. Therefore, the CMC joint of the thumb gives it a roughly semi-circle shaped range of motion about the palm.

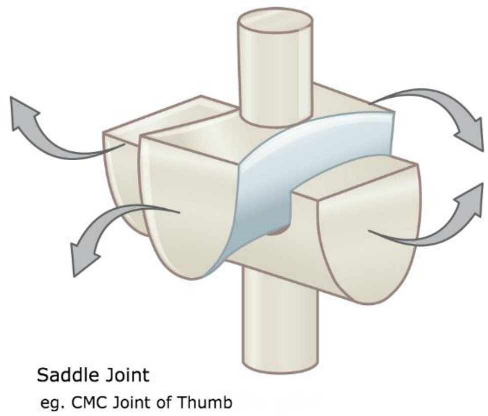


Figure 2.6 - Saddle Joint: OpenStax College (2013)

Although the CMC joint of the thumb does not allow axial rotation, the thumb can be thought of as axially rotating about its origin at the CMC joint as it swings through its range of motion. This definition of the CMC joint as not allowing axial rotation could be interpreted as being slightly misleading because it implies that the thumb would oppose the fingers at the same angle no matter the position of the first metacarpal. However, one can clearly see this not to be true by touching the thumb to the index finger and moving the thumb's metacarpal around – the angle between the tip of the index finger and the tip of the thumb will clearly change. This is the stage at which joints in the human body become difficult to quantify and represent as simple mechanical joints. As stated previously, the CMC joint has 9 muscles controlling its movement, but it also has 16 ligaments that dictate and stabilise how the joint moves. Because of this it will surely be necessary to design some joints by observing hand motion empirically, as some joints are simply too complex and poorly understood to consider trying to emulate directly.

The next joint in the thumb is the metacarpophalangeal joint, which is an ovoid joint like the MCP joints in the fingers. It is capable of flexion of the proximal phalange from parallel (to the metacarpal) to roughly 70° according to a study by Yoshida et al (2003), as well as lateral motion through a similar range of motion as the fingers (30°). Finally, the interphalangeal joint of the thumb is a pure hinge joint with around 90° of flexion and up to 80° of hyperextension in some people.

2.3 Palm

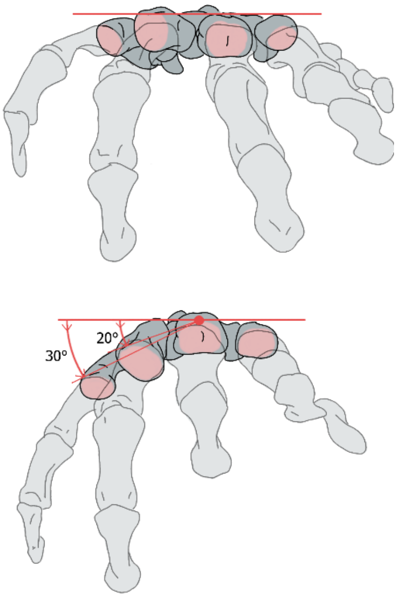


Figure 2.7 - Movement of the metacarpals as viewed from the front of the hand

The palm contains many muscles and supports many tendons which pass through it, but its motion is very limited. The top of the palm appears to move as the proximal phalanges flex, but this is actually loose skin on the other side of the knuckles. The fourth and fifth metacarpals (ring and little fingers) however do flex and extend very slightly about the carpometacarpal joint as controlled by the bundle of muscles around the base of the little finger, as can be seen in Figure 2.7. This movement allows these last two fingers to more severely oppose the other fingers and thumb, and also allows the palm to more intimately grip round objects. The displacement of the metacarpals varies considerably, but as a rough estimate the fifth metacarpal moves 30° about an axis in the centre of the third metacarpal, and the fourth metacarpal moves 20°. The shape of the palm is also influenced by movement of the thumb

2.4 Wrist

At first glance the wrist may appear to act as a simple ball-socket joint, but up close it is apparent that it is much more complex. There are 8 carpal bones which make up the wrist joint as shown in Figure 2.8 but

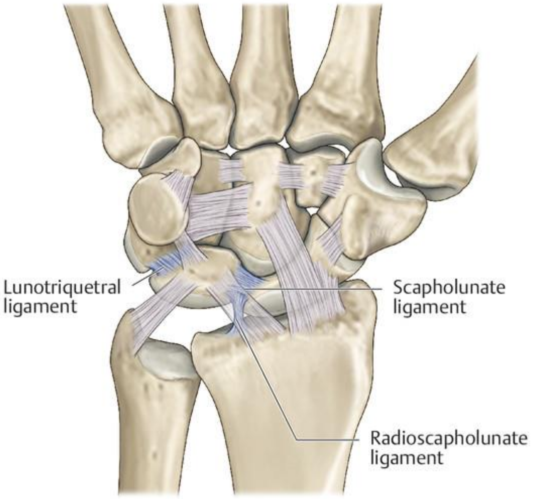
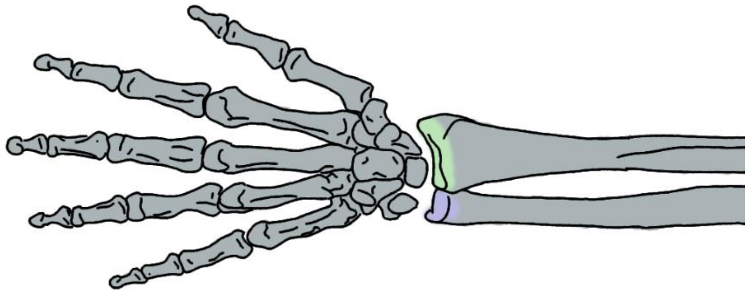


Figure 2.8 - Ligaments and bone structure of the wrist. Gilroy et al (2016) Illustration by Karl Wesker



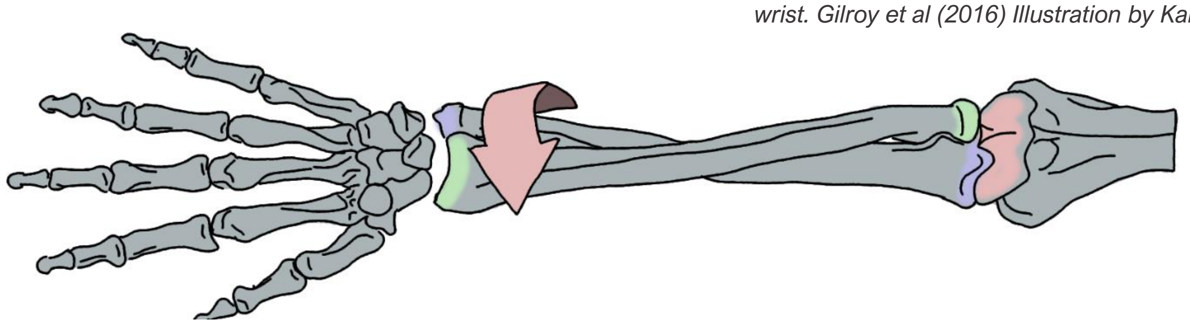


Figure 2.9 - Axial rotation of wrist via radius and ulnar bones of the forearm

Hirt et al (2017) state that, morphologically, it can be divided into 2 separate joints – proximal and distal. The proximal wrist joint connects the hand to the radius and ulna in an extremely complex interaction permitting flexion/extension and lateral deviation. For the purposes of this project it is simplest to think of the wrist as a condyloid joint like the MCP joints of the fingers and thumb. Axial rotation of the wrist is achieved via the radius and ulnar bones of the forearm as can be seen in Figure 2.9 – the ulna bone remains stationary while the radius moves around it, and both bones are fixed relative to each other by ligaments in the forearm.

2.5 Considerations for Mechatronic Emulation

Ranges of motion and movement paths are easy to define, if not through examination of joint anatomy then through empirical examination. What remains unclear is to what extent certain movement paths and endpoints should be mechanically or electronically linked. For example, most bionic hands have one actuator which controls the flexion of all of the fingers into the palm, even though in the human body this requires flexion of least 12 major tendons. In order to optimise weight, complexity and limited control options, designers generally find the most useful motion patterns and design the mechanisms to enact the motion with as few actuators as possible. This project aims to create a bionic hand with as diverse and biomimetic kinaesthetic function as possible, but the human body has many physical and neural movement chains “built in” which cannot be avoided. One such example is the flexor digitorum profundus tendon which flexes the distal phalanges of the fingers – however, it will also flex every one of the phalanges and the wrist, and some people are unable to flex only the distal phalanges of their fingers.

The interaction of all the hand's muscles is extraordinarily complex and varies widely from person to person, meaning that trying to design a bionic hand with every muscle, stabilising ligament and interlinked motion pattern in real hands is in no way feasible within the scope of this project. If myoelectric technology were to increase massively to the point where every nerve signal controlling the hand could be isolated and identified, then it would make sense to try and design a hand which directly emulates a real hand. Since this project aims to use a real hand as a physical controller, physical/electronic endpoints in joints and interlinked motion paths are not actually necessary for the movement of the hand to be as biomimetic as possible, but some thought should be given to optimising the number of actuators in the hand. An example of a movement which should be locked to the movement of other components is the slight flexion of the metacarpal bones which occurs to allow the little finger to oppose the thumb further than its MCP joint would allow by itself, and also to more intimately grip round objects. As the fifth metacarpal flexes, the fourth also follows it slightly, and there is no way that the fourth metacarpal could ever move independently of the fifth without interference from an outside force. Since analysing the effects of outside forces on the bionic hand are not a part of this project, the metacarpals of the ring and little finger should be mechanically linked, requiring one less actuator than if they were electronically linked or not linked at all.

Another example of a movement that could be optimised is the lateral movement of the proximal phalanges on their MCP joints. Normally there are several muscles intrinsic to the hand which orchestrate this motion, but a useful simplification would be to have just one actuator to enact this movement. In some cases however, the range of motion and function of the bionic hand may have to exceed that of the real hand in order to avoid trying to replicate very complex biological joints. For example, the extremely complex saddle joint of the CMC joint in the base of the thumb consists of two opposing surfaces which are reciprocally concave-convex. However, by modelling the joint as a simple ball-socket joint a component could just be purchased, at the expense of not having physical endpoints built-in to the joint's design.

One other parameter of the hand's motion that has not yet been explored is the speed of motion. Chappell, P, H (2016) states that a prosthetic hand should be able to contract within one second or it will not be satisfactory to the user. A biomimetic mechatronic hand, by contrast, should be faster and more responsive than this. In humans, movement speed of any limb or appendage varies wildly due to numerous factors making acceptable limits difficult to obtain. At such an early stage in development it would be very difficult to set an upper acceptable speed, but as a very rough target the biomimetic mechatronic hand should aim to be around twice the speed as Chappell specifies, meaning it should be able to contract in under half a second.

Compilation of Motion Range Parameters

Using anatomical data, information from "Hand and Wrist Anatomy and Biomechanics" Hirt et al (2017), and empirical observations of the primary operator's own hand where data was lacking or gave a range of values, diagrams were created to visually show the range of motion for each joint.

2.6 The motion of all phalanges up to the MCP joint, including lateral motion and hinging at each inter-phalangeal joint is shown in the appendix in Figure 21.1 and Figure 21.5. Ranges of motion relating to the metacarpals are shown in Figure 21.6. The thumb's motion is illustrated in Figure 21.2, Figure 21.3, Figure 21.4 and Figure 21.7. Finally, the wrist's motion including the interaction between radial and ulnar bones is shown in Figure 21.8, Figure 21.9 and Figure 21.10.

Testing

Since the main aim of this project is to replicate the fine motor skills and control of a
2.7 real human hand, a vital component of the project must be to test the final prototype using a robust and quantifiable method. The only standardised test that has been developed with bionic hands in mind and is "clinically validated" is the Southampton Hand Assessment Procedure (SHAP) which Chappell, P, H (2016) claims is used internationally to assess both natural and artificial hands.

In his book Mechatronic Hands, Chappell, P, H (2016) describes a standardised procedure consisting of 12 abstract tests and 14 "activities of daily living" tests. The procedure was designed to be cheap, fast, easy to manufacture and easy to use. Critically, it is suitable for a wide range of natural and artificial hands according to Chappell, and as such is often used internationally to assess the quality of bionic hands in relation to natural hands. Also, the result is quantifiable as an overall score can be calculated out of 100 based on the time taken to complete each task.

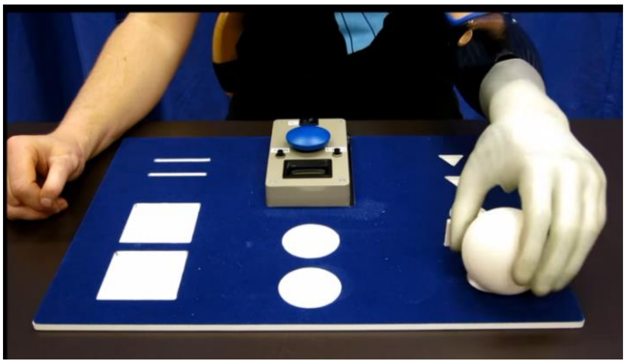
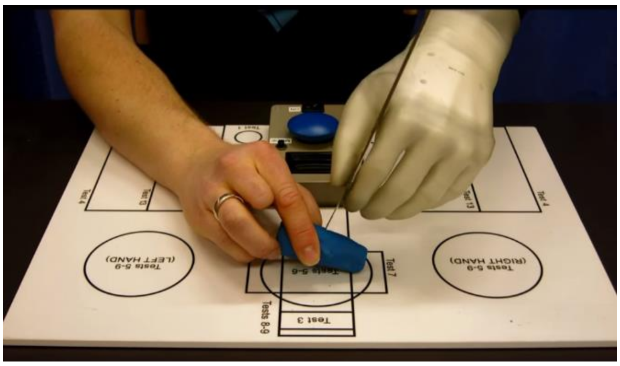


Figure 2.10 - The "Michelangelo" prosthetic hand (Developed by Ottobock) being used to perform the abstract section of the SHAP. Alina Varer (2015)

The abstract section of the procedure shown in Figure 2.10 uses 6 different shapes demonstrating different grip types, each having a light version made of balsa wood and a heavy version made of steel or aluminium. The user must press a button in the centre of the testing platform to start the timer, pick up and move the object to a new position as indicated on the platform, and press the timer again to complete that test.



The "activities of daily living" (ADL) section of the procedure shown in Figure 2.11 consists of 14 simple activities that represent activities that would be encountered in everyday life. Examples of these include picking up coins and placing them in a jar, using a door handle, and cutting food with a knife (simulated with plasticine). It should be noted that in the ADL section, the offhand is used for some tests, where the hand being assessed performs the primary action (e.g. using a knife to cut plasticine) and the offhand stabilises the object. Clearly this can be used to the user's advantage, as the test is self-administered and the rules are limited. The SHAP can be purchased for £2000.00 or hired.

Figure 2.11 - The "Michealangelo" prosthetic hand (Developed by Ottobock) being used to perform the abstract section of the SHAP. Alina Varer (2015)

Unfortunately, there is no standardised test which evaluates the function of bionic hands in isolation, as the SHAP as well as clinical tests used in rehabilitation of natural hands only evaluate the hand's functionality assuming that it is attached to a healthy arm. For this reason, it should be decided if the hand being developed in this project will have a wrist or elbow joint (if only for the sake of effective testing). As this project does not include myoelectric or EEG control of the bionic hand, it cannot be tested using a volunteer amputee, and must be tested using the control glove which means it cannot be picked up during testing. Because of these unique requirements, an entirely new test will likely need to be devised taking inspiration from the SHAP (such as activities of daily living). Also, since this project will prioritise biomimetic motion over strength and maximum speeds, the test devised could isolate different factors to determine functionality independently of time taken, whereas the SHAP only uses speed as the factor of quality.

2.8 Physical Constraints

Because of the natural variation in human hands due to genetics, age and even climate, the dimensional and physical measurements of the hand vary substantially. In this project, a control glove will be designed specifically to fit the primary user's hand, so while efforts will be made to make the final prototype adaptable to different users, the standard measurements that will serve as a baseline will be taken directly from the primary user's hand in order to ensure that the glove will fit correctly and the bionic hand will replicate motion as closely as possible.

3 Review of Previous Works

Bionic hands are already widely available as prosthetics, and highly biomimetic hands have also been developed but have not yet been made available commercially. Prosthetic hands generally have a very limited number of degrees of freedom, largely due to the limitations of myoelectric technology (detecting signals from the nerves and using these to control bionics), but some designs are much closer to human hands than others.

Some works have also attempted to design a control glove alongside a bionic hand (as this project will), while other projects have looked at designing a control glove independently of a bionic hand, to be used in PC simulations. Only a very small number of projects have specifically tried to create a *biomimetic* hand alongside a control glove as a single project, so it will be useful to examine other projects as well as these specific ones.

3.1 Design of a Highly Biomimetic Anthropomorphic Robotic Hand towards Artificial Limb Regeneration

In their biomimetic bionic hand project, Todorov and Xu (2016) designed and built a hand “that closely mimics its human counterpart with artificial joint capsules, crocheted ligaments and tendons, laser-cut extensor hood, and elastic pulley mechanisms”. The aim of the project was to explore methods of actuation directly taken from the human body and even biomimetic linking of the hand structures through artificial ligaments. The final prototype is shown in Figure 3.1

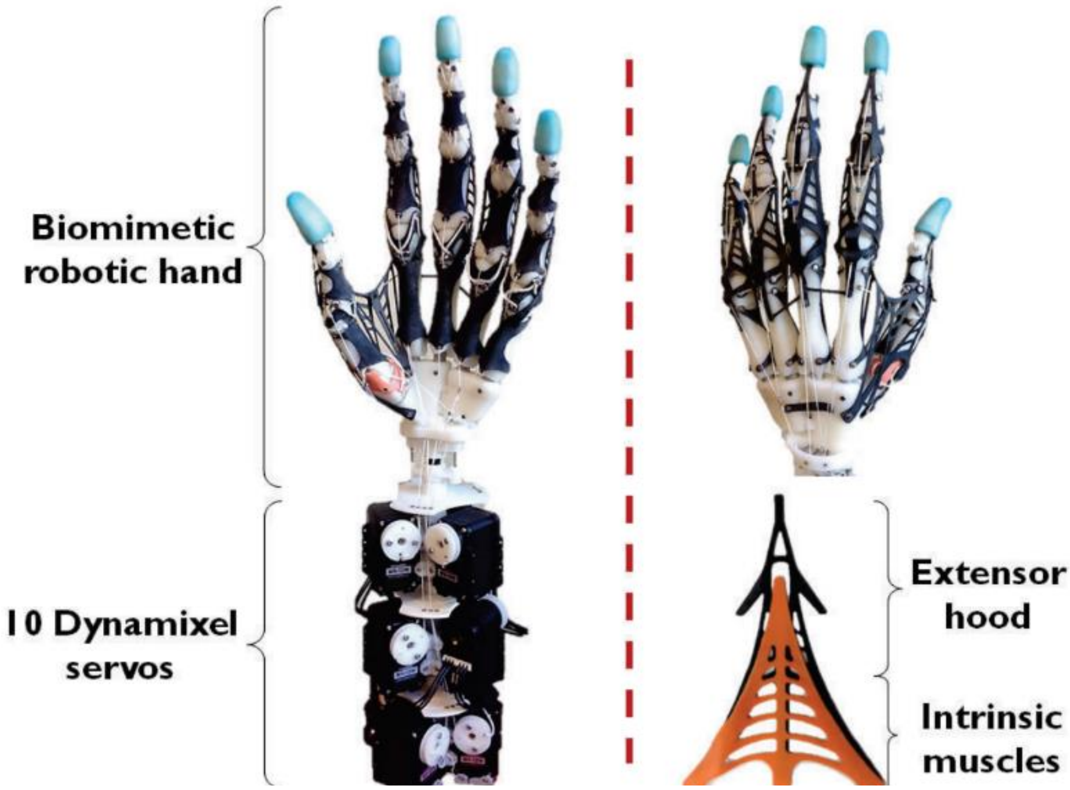


Figure 3.1 - The fully assembled biomimetic robotic hand. Todorov and Xu (2016)

Although the title of the paper suggests that the development of such technology is aimed towards artificial limb regeneration, Todorov and Xu also write that it could be useful in a wide range of research areas "from telemanipulation in robotics to limb regeneration in tissue engineering". The project used a laser/MRI scanner to examine in close detail the bone structures of the hand, which were 3D printed in such fine detail so as to include detailed surface features such as tendon insertion sites. These were used as points of reference to build crocheted tendons and ligaments, shown in Figure 3.2. The joint surfaces were examined in close detail and 3D printed in full, meaning that the complex joint surface interactions as covered in the biomechanics section of this research were not mechanically simplified, but directly replicated.

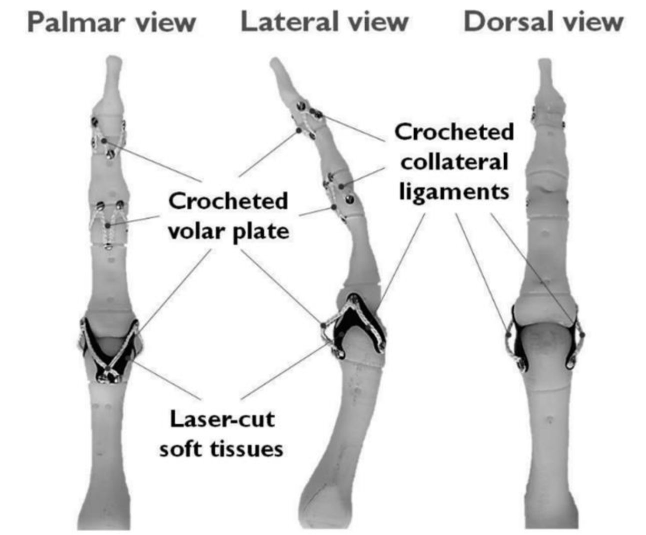


Figure 3.2 - The skeleton of the 3D printed hand with soft tissues. Todorov and Xu (2016)

The hand was actuated by 10 Dynamixel servos located in the "forearm", which moved the hand via Spectra® string tendons, and controlled by a "data glove" shown in Figure 3.3 and not covered in this paper, but mentioned in "Design and Control of an Anthropomorphic Robotic Hand: Learning Advantages from the Human Body & Brain" by Xu (2015). In it, Xu describes how string potentiometers were used to measure movement of the fingers in a similar tendon-like arrangement to the bionic hand itself. The hand was tested by analysing the trajectories of motion at the fingertips as compared with the data glove, then with a series of object grasping and manipulation tasks demonstrating the ability to manipulate a wide variety of low-mass objects.

The project far exceeded this one in terms of budget and timescale, so much of the work from the project cannot be directly built upon. With an extremely in-depth analysis of the human hand and in particular the soft-tissue interactions of tendons, ligaments etc, the project replicated human motion by being as mechanically close to it as possible. In this project however, advanced medical scanning capabilities may not be available, so

Figure 3.3 - Data glove used to control the hand. Xu (2015)

the engineering of the hand may use software or different actuation methods to achieve similar results. For example, Todorov and Xu's project involves complex tendon and ligament interactions that make joints move in synchronisation with each other in the same way that a human's would, but an alternative way to replicate this motion would be to use more smaller servos and actuate each joint independently as measured directly from the control glove. Use of artificial ligaments to create joint capsules would be possible within this project, but for greater robustness it may be preferable to build mechanical simplifications of the joint surfaces – one of the primary limiting factors being the very accurate 3D printer necessary to make a good joint surface, and the fact that this could probably never be as robust as a simple bearing joint.

3.2 DLR-HIT Hand I and II

The DLR-HIT hand was developed jointly between the Harbin Institute of Technology and the German Aerospace Centre, shown in Figure 3.4. Visually it is not biomimetic, with three identical fingers and one thumb, but each finger is highly mobile with four joints and three actuators discreetly integrated into the fingers themselves. It's successor, the DLR-HIT hand II (shown in Figure 3.5) has much a much more lifelike appearance, with all four fingers and realistic structure. It still has the same degrees of freedom but is smaller and lighter than its predecessor. The hands are commercially available, one of the main advertised applications being telemanipulation.

Figure 3.4 - DLR-HIT Hand I, with plastic shell. DLR (2007)

The first DLR-HIT hand weighs around 2.2kg (note that this hand does not include a forearm like some of the others) and is constructed with a lightweight metal skeleton and aesthetically minimalistic exterior plastic shell. It is actuated with commercial brushless DC motors integrated into the fingers and palm and controlled with a PC software platform. It also uses hall effect sensors to detect its joint angles, providing a feedback loop to the controller for accurate positioning. Even with such accurate positioning features it is able to move all its joints at a maximum speed of 180 degrees per second. The second iteration is simply a refinement of the first without any major design changes other than an additional finger and sleeker form factor. It can move with twice the speed and fingertip force as the first and is 75% of the total weight of the first.

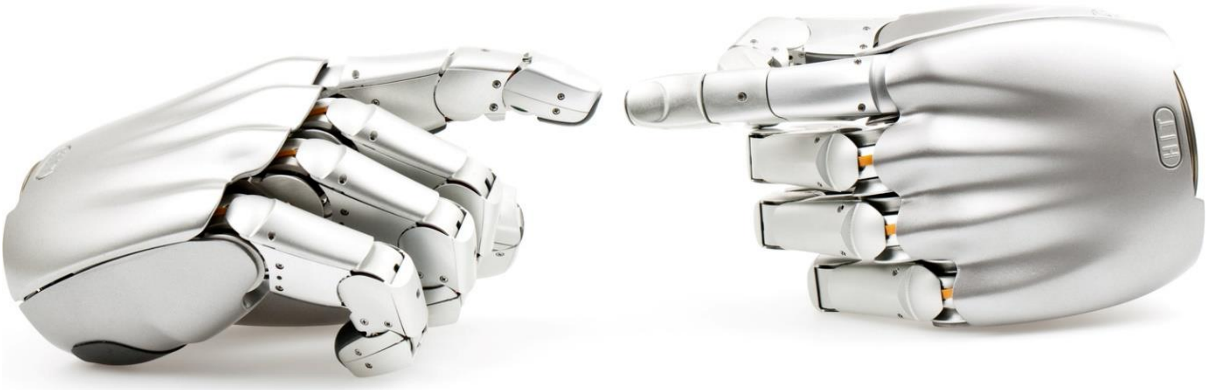


Figure 3.5 - DLR-HIT Hand II. DLR (2008)

Being such highly engineered, expensive and cutting-edge robot hands, much of the design is not useful to this project. However, examining the projects in detail brings up several important considerations, such as accuracy and how a closed loop control system can be used to provide joint angle information back to the control software.

3.3 Sensor Controlled Robotic Hand with Haptic Feedback

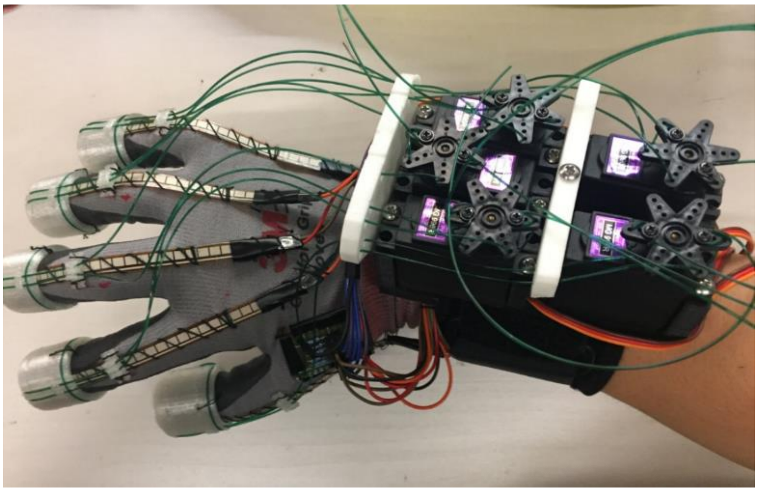


Figure 3.6 - Haphand Control Glove, Hon (2017)

The goal of Hon (2017) in his project was to design a sensor glove that not only controlled a bionic hand but also provided haptic feedback to allow the user to effectively feel through the artificial hand (shown in Figure 3.6). The main application of this was said to be for people to control robots remotely in hazardous environments. The actual bionic hand used in the project was the InMoov, an open source, 3D printable hand design which again uses servos located in the forearm to control the fingers via tendons. The InMoov is a very affordable option as it can be entirely 3D printed including bolts, which also makes it somewhat un-robust. An example of a printed prototype is shown in Figure 3.7.

The design part of the project only involved the control glove, which was built around a fabric glove and used flex sensors to detect motion. Flex sensors vary linearly in resistance based on their bend radius, so they can be used to acutely detect the position of the fingers. However, being long and expensive they could only be used one on each finger. It can be noted that without the other components being used for haptic feedback, the design of this control glove is minimalistic and does not impede motion.

A modified Arduino microcontroller was used to translate the sensor values into instructions for the bionic hand.

As the main focus of the project was more to do with haptic feedback, the most important points for consideration are the use of bend sensors and their interpretation via Arduino for control of the servos.

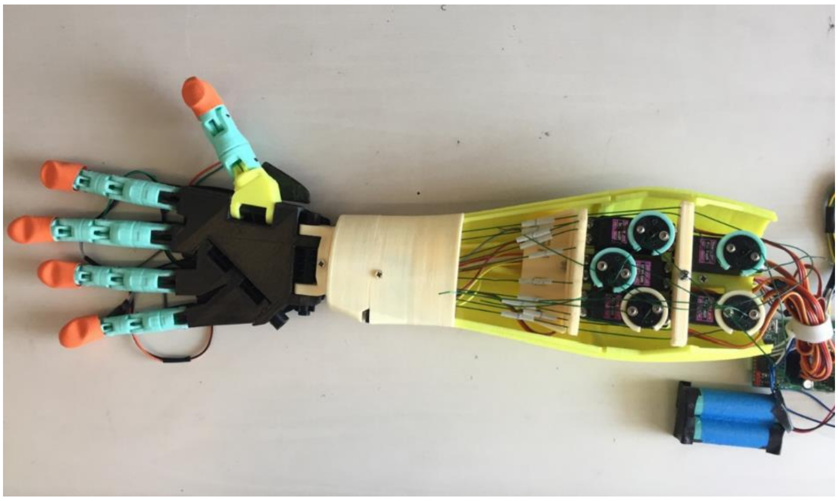


Figure 3.7 - Assembled InMoov Open Source 3D printed bionic hand, Hon (2017)

3.4 Fooma "Sushi Robot"

Japanese food technology company Fooma developed a robot in 2009 designed to showcase newly developed pneumatic actuators by demonstrating how they could be used to delicately manipulate sushi with the precision of a human hand. The fine details of the robot's construction were not made public but Fooma demonstrated their use of pneumatic actuators at the international food machinery and technology exhibition. Compressed air was used to inflate small "muscles" that contract as the pressure inside them increases as shown in Figure 3.8. These muscles were implemented inside the exoskeleton of the hand and the bionic hand as a whole was given a silicone skin which closely resembled a real hand.

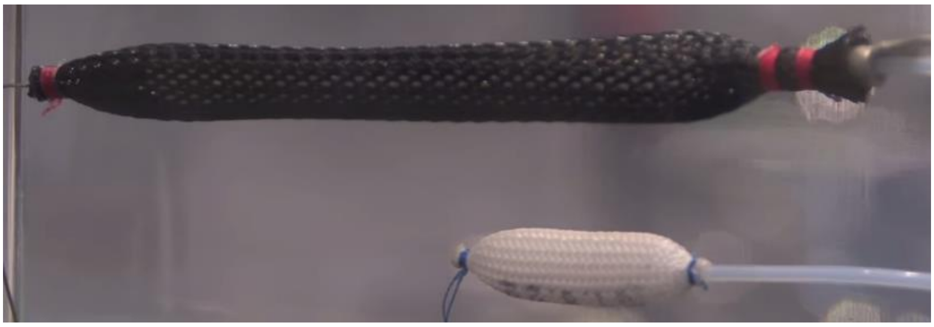


Figure 3.8 - Pnuematic muscles, ikinamo (2009)

4 Actuation

There is a wealth of different actuators used in modern robotics, ranging from electric motors to hydraulics. Parameters which are important in this project are:

- Torque
  - The actuators must be strong enough to move the hand quickly, with strength left over to interact with surroundings. Strength of the hand is less important than the biomimicry of its motion in this project, yet it is still an important consideration.
- Speed
  - Despite torque requirements the actuator must still have a reasonable speed to mimic human movement well, so the balance between torque and speed must be considered.
- Holding Strength
  - The human hand can be strong and rigid in more positions than just the end-points of its motion, so the holding strength of an actuator at any given position is important for how the hand will be able to interact with its environment.
- Control
  - Some actuators, such as servos, come with intuitive built-in controllers that also contain feedback sensors for maximum ease of use. Other actuators however are much more complex and will require several sub-systems to get them working.

Because of their availability, cost, and ease of use, it is largely already decided that the hand will use electric motors as the primary actuators. Alternative systems such as hydraulics will not be considered, due to the scope of this project. It should be noted that all the bionic hands researched used electric motors (mostly servos) apart from the Fooma sushi robot.

4.1 Types of Electric Motors

One of the simplest types of actuator to integrate into the bionic hand would be an electric motor. Generally, the direction and speed of electric motors can be easily controlled using a variable voltage or pulse-width modulation (PWM) in the case of servos and other digitally controlled motors. With the rising popularity of microcontrollers such as Arduino, high demand for electric motors means that they tend to be very affordable and user-friendly.

4.2 DC Motors

Figure 4.1 - "Micro metal gearmotor" Small DC motor with gearbox PIMORONI (2017)

Perhaps the cheapest and most adaptable type of motor to use would be a DC motor with a gearbox to increase the torque output. An input such as a potentiometer would take readings from the user's hand, and this signal could be used to control the speed and direction of the DC motor, likely requiring another sensor at the moving component to verify the joint angle and feed back to the controller. Aside from the control components and power supply, using a DC motor would require a gearbox (unless the motor is already supplied with one), a transistor to control the voltage and an additional sensor such as a potentiometer for feedback.

The main advantage using a DC motor is that it can be adapted to suit any speed or torque requirement provided the motor is powerful enough, and the gearbox can be designed for transmission at unusual angles or it can be a specific shape to fit inside a small space. With proper design, it could be the most space-efficient option for actuation as DC motors can be purchased extremely small. For example, DC motors can be purchased as small as (10*10*20)mm (shown in Figure 4.1), obviously such a small motor would have meagre torque but with a well-designed gear train the motor could be ideal for parts of the hand with low torque requirements. Very high torque can also be achieved with larger, more expensive motors.

The main disadvantage of using a DC motor is that control would be much less simple than a servo for example, as the speed and direction would need to be fine-tuned via an electronic control system, requiring feedback from a sensor. If using a microcontroller, a program would need to be written to interpret the input signal, and convert it into a set of instructions the motor could use to move into position. A PID controller could be used to control the motor, but with a large number of actuators, processing speed may be severely limited by overly complex code. Another drawback is simply that gearboxes may need to be designed and built, as well as housing to fit the motors into position, adding to the complexity of the assembly.

DC motors may be the most versatile option for actuating the hand, but they also may be the most time consuming and complex electric motor to design and assemble.

4.3 Stepper Motors

A stepper motor can be used to precisely rotate through a specified angle in "steps" (divisions of a full rotation), with reasonable torque and speed, and can remain at a specified angle with a very high holding torque, all without a feedback sensor. The step size of the motor depends on the specification of the motor but can be under 1°, so by using gearing it is possible to control an angle or position very precisely. Stepper motors tend to be large and heavy, but it is entirely possible to buy them extremely small at the cost of torque and accuracy. Some variants are shown in Figure 4.2)

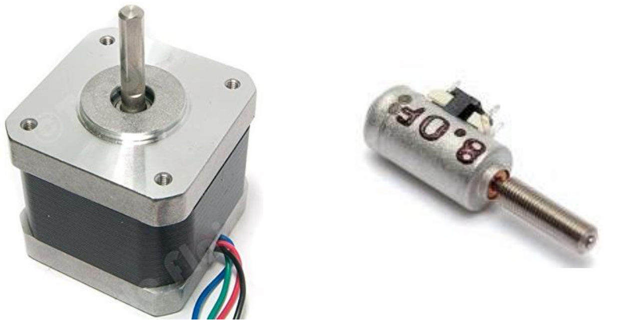


Figure 4.2 - A "traditional" stepper motor (left, Make Nation (2017)) and a micro stepper motor (right, Banggood.com (2017))

Stepper motors are easier to control than DC motors when trying to move a component to a specified position, because it is designed to move by a specified amount as per the input, whereas a DC motor simply runs at a speed proportional to the voltage provided. However, a controller board is also needed, adding to the expense and complexity. Their main advantage is their very high accuracy, which is why they are often used in 3D printers to control the position of the extruder, allowing for accuracies under 0.02mm.

Unfortunately, stepper motors tend to be expensive, heavy and bulky. Their torque also tends to be lower than DC motors for around the same price, and their control is not as simple as with servos. Despite these drawbacks, stepper motors are unrivalled when it comes to accuracy and holding torque.

4.4 Servo Motors

Servo motors are commonly used in robotics, and they have become very popular with hobbyists leading to them becoming one of the best value for money options. A servo generally consists of a DC motor with a built-in control board and gearing system (an example is shown in Figure 4.3) such that all the user needs to do is provide a position for the servo to move to via PWM and it will do so. Servos also feature a built-in potentiometer to feed back to its own controller and verify its position. They also generally come with levers called "horns" with many holes pre-drilled, and feature mounting holes for ease of operation.

Figure 4.3 - Micro servo with horns and bolts, shown closed and open: ValueHobby (2017)

Servos are by far the easiest and most intuitive form of electric motor to use with a microcontroller, and in general they are very well balanced between speed, torque, size and weight, and are increasingly affordable due to their high demand. Multiple servos being controlled from one microcontroller can easily be powered using a servo driver board.

Servo motors are either continuous rotation types or are locked to only rotate through a certain angle, generally 180° - 360° (positional servos), the difference being that continuous rotation servos are controlled by their speed whereas positional rotation servos are controlled by angle. Linear servos can also be bought but these tend to be more of a specialist item. Servos are designed to be very user-friendly when it comes to robotics, so they stand out as a good choice and well balanced between all parameters.

5 Sensors

Sensors are an important aspect of both the bionic hand and the control glove. The control glove obviously needs a way to detect changes in motion in the user's hand, while the bionic hand may also need sensors for accuracy.

5.1 Potentiometers

Potentiometers are a very simple kind of sensor that is powered through two of its pins while a single output can provide information about its angle, an example is shown in Figure 5.1. As a potentiometer's knob is turned, the resistance increases or decreases linearly, and this information can be fed directly to a microcontroller or even used as a variable resistor. They are available in a huge range of sizes, resistance ranges and accuracies so they are adaptable to fit a variety of different applications.

Figure 5.1 - Alps RK163 Series Carbon Film Potentiometer, RS (2017)

Potentiometers can be used to directly measure an angle so it would be possible to directly integrate them at joints in the control glove, but due to their versatility they could be implemented in any number of other ways also. It should be noted that many servos have potentiometers integrated into their design so that their angle can be measured and fed back all within the servos housing, but more potentiometers could still be integrated into the design of the bionic hand for more accurate feedback.

5.2 String Potentiometers

In the review of previous works it was seen that Xu (2015) used string potentiometers to measure the position of the user's fingers in his control glove. The potentiometers were mounted on the forearm area and the string ran up to the finger tips, similar to how tendons run through the arm. These sensors made it possible to obtain very fine positional data about the user's hand, but the sensors were extremely bulky and their large size severely limited the amount of sensors that could be used. String potentiometers are also a fairly specialist item that are generally expensive.

Using a string potentiometer to measure displacement at a joint would return data about the length of string that was displaced, meaning that the readings would need to be mapped on to a separate range of values corresponding to the joint angle before being used to control the servos unlike if, for example, a potentiometer directly read rotation from the joint itself. Some accuracy would certainly be lost by having the tendons as a buffer between the sensors and the joint being measured. If used in the bionic hand they would be implemented in the exact same way to measure joint angle for feedback.

5.3 Slide Potentiometers

Figure 5.2 - Alps RS45 Series Slide Potentiometer, RS (2017)

Potentiometers can also take the form of linear tracks that have varying resistance as a slider glides along a straight path as shown in Figure 5.2. Like regular rotational potentiometers they are available in a wide range of shapes and sizes, and can be implemented in a number of ways. They could be used to measure distance between two finger segments and therefore estimate the joint angle, but like the string potentiometer this data would need to be mapped onto another range of values.

Alternatively, slide potentiometers could be used in the place of string potentiometers to measure joint angles through the use of tendons, perhaps using springs to return the slider to a starting position as the user's hand moves. Feedback sensors would be applied in the same way.

5.4 Flex Sensors

Another popular way to measure joint angles in a control glove is through the use of flex sensors, as seen in the "Sensor Controlled Robotic Hand with Haptic Feedback" by Hon (2017). Flex sensors measure the deflection caused by bending the strip. Bi-polar flexion sensors can measure the deflection either side of their neutral position, and this may be suitable for measuring flexion and extension of the hand. The main drawback of flex sensors is that they are often very expensive and bulky (Although very flat). If every joint on the control glove was to be measured with flex sensors, the cost would be well over budget and the glove itself may be so bulky so as to restrict motion.

5.5 Switches

A final type of sensor to consider would be simple push-to-make switches. Very small switches could be implemented around the bionic hand to cut power to certain servos to prevent it from damaging itself, but ideally the hand would be designed and coded to eliminate these possibilities. Alternatively they could simply be used as on/off switches.

6 Control

The final electronic section to be explored in the bionic hand is the control system which will interpret the signals from the sensors and use them to drive the actuators. There are a very large number of ways to achieve control of a mechatronic system, and this section will briefly go over some simple examples. The primary objective of the project is efficient mechanical design, so the specifics of control will not be explored in great detail at this early stage.

Using a Microcontroller

Using simple code, all of the actuators could be controlled via a microcontroller board such as an Arduino or raspberry pi. An example of an Arduino is shown in Figure 6.1.
6.1 The analogue signal from the sensors could easily be detected by the microcontroller and used to create a digital signal that drives an actuator. This method would likely be much simpler than using integrated circuits and would surely require far less components. The main advantage would be being able to easily make adjustments to the code rather than having to alter physical components. However, having all the actuators controlled via one component would make troubleshooting more problematic and the responsiveness of the system would be limited by the processor.

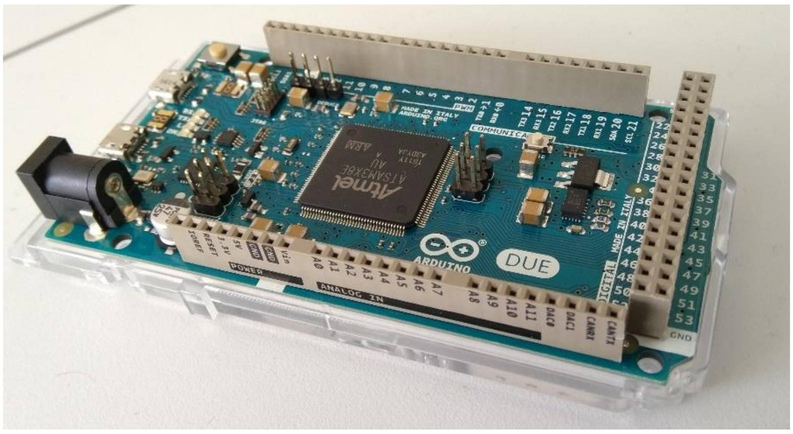


Figure 6.1 - Arduino Due Microcontroller

If using servos, a digital on/off signal tells the servo what position it should move to, based on the time between pulses in the signal wave. Using a microcontroller board, it would be very simple to generate such a signal, with many IDEs (integrated development environment) for such controllers already having servo libraries included in the software package. Stepper motors use a more complicated digital signalling system, and often it is simpler to use the microcontroller to control a separate stepper motor board but the same principles apply. DC motor speed control could also be achieved using a microcontroller, with a transistor used to deliver power to the motor independently of the microcontroller itself.

It should also be noted that consumer microcontroller boards such as Arduino and raspberry pi are open source and could be used as a base for a new circuit board specifically for the project. The processors used in the microcontroller boards as well as the circuit board layout can be observed and built upon, in a mass-manufacture scenario it would even be possible to order printed circuit boards with the program pre-loaded on to the board.

Using Integrated Circuits

If using potentiometers as a control method, the varying resistance of the sensor could be used to directly influence the position of a servo motor. Servos are controlled by pulse-width modulation, meaning that their position is dependent on the parameters of an on/off wave that is supplied to it. The potentiometer could be incorporated into an
6.2 astable multivibrator circuit using an IC such as the 555 timer, the output of which would have a varying pulse width according to the potentiometer and could be calibrated to be more accurate. Servos have a potentiometer built-in for position feedback, but if feedback was required from a separate potentiometer at the joint itself then a system of logic gates and possibly other ICs could create this feedback loop. A similar method could also be used to control other motors like simple DC motors or stepper motors.

This method could be tuned to be fast and accurate, and each actuator could be isolated from the others, however the circuit would likely be complicated, and many components would be required.

7 Biomimetic Mechatronic Hand PDS

Based on the research compiled in previous sections, a product design specification was created to guide the conceptualisation and development of the bionic hand.

1.0 Weight

- **1.1** Chappell (2016) states that the weight of a prosthetic hand should be limited to less than 500g based on feedback from patients, this agrees with data gathered by Plagenhoef et al (1983) on mean body segment weight wherein the average hand (male and female) was found to be 580g. Chappell's 500g limit will be used for this project since the data is based on patient feedback on actual prosthetics.
- **1.2** Based on mean body segment weight data from Plagenhoef et al (1983), the mean forearm weight is around 3x mean hand weight. Therefore, using Chappell's limit of 500g as an ideal guideline for a prosthetic weight limit, the forearm should weigh under 1.5kg (if it is incorporated into the design at all).
- **1.3** The base which the assembly will be attached to is regarded as a testing platform therefore its weight will not be considered.

2.0 Size and Dimensions

- **2.1** The hand's dimensions should fit roughly within the primary operators own hand (a standard sized male hand), i.e. it should be no larger in any dimension than the primary operator's hand.
- **2.2** The forearm section may be slightly larger than the primary operator's arm but must physically resemble it and appear in proportion with the size of the hand.

3.0 Performance

- **3.1** Chappell, P, H (2016) states that a prosthetic hand should be able to contract within one second or it will not be satisfactory to the user. As the objective of this project is accurate emulation of real human motion, the limit of the biomimetic mechatronic hand should be a full contraction within 0.5 seconds.
- **3.2** The hand should be able to move through the full ranges of motion quantified in the biomechanics research section of the project.
- **3.3** The motion of the hand should be biomimetic, meaning that any motion it makes should visually appear human and realistic.
- **3.4** The hand must be capable of grasping a variety of unique objects with different gripping techniques.
- **3.5** The hand will be subject to testing of its function based on elements from various standardised tests, as described in "2.7 - Testing".
- **3.6** The hand should be operable for up to 30 minutes of continuous use with mains power.

4.0 Operating Environment

- **4.1** The hand should be operable in a standard university room environment with standard pressure, humidity, temperature.
- **4.2** The hand must be resistant to small amounts of dust and debris resulting from storage conditions.
- **4.3** The hand must be resistant to minor vibration and shock loading for when it is moved.

Aesthetics

- **4.4** The product must proportionately resemble a human hand as closely as possible.
- **4.5** The actual hand may not look like a real hand because of its construction but its outer casing should be a similar shape to the outer structures of the human hand.

5.0 Cost

- **5.1** The project (bionic hand and control glove) should be under £200 total cost to the university.

6.0 Maintenance

- **6.1** Components likely to need service should be easily accessible.
- **6.2** Construction of the hand should allow for easy disassembly to replace parts or make repairs independently of other components.
- **6.3** Fasteners should be used in preference of more permanent fixing solutions such as glue.
- **6.4** Overall number of fasteners should be kept low, provided this does not interfere with the build quality.

7.0 Manufacturing

- **7.1** FDM 3D printers will be used primarily to manufacture components of the bionic hand, including finishing techniques such as sanding and drilling.
- **7.2** Construction of the hand will include simple bench-based activities such as screwing in bolts, soldering etc.

8.0 Time Scale

- **8.1** Design of the hand should be completed before the end of the first semester.
- **8.2** Construction of the hand should begin in the second semester or earlier and be completed by March.
- **8.3** Testing should be completed within one month.

9.0 Product Life Span

- **9.1** The hand should remain fully functional until at least the end of the academic year.

9.2 During this time, it should be able to endure 10 hours of cumulative testing and demonstrations.

10.0 Materials

10.1 Plastic filaments for use with FDM printers will be used for the majority of the construction.

10.2 Fasteners, bearings and other components may be used, and must fit within the budget and weight restrictions.

11.0 Installation

11.1 The hand should be desktop based and mains powered.

11.2 The structure should be easy to move to different locations for testing and demonstrations.

12.0 Disposal

12.1 Upon disassembly the 3D printed plastic parts should be recyclable.

12.2 Components such as bearings bolts and motors should not be substantially damaged under normal operation circumstances meaning they could be reused in other projects.

13.0 Safety

13.1 The design and manufacture process should adhere to the risk management strategies described in the risk identification form submitted early in the project.

13.2 The hand should be powered from mains electricity with a safe transformer which limits voltage to under 15V.

13.3 The hand itself should pose no major threat to observers and should be able to interact with humans in simple ways (for example shaking hands) without posing a safety threat.

13.4 Sections of the design which pose a hazard by being sharp or an area which could cause entrapment should be covered appropriately.

13.5 Electronics should be sensibly enclosed with a venting method in case of pressure build-up.

14.0 Quantity

14.1 Only one functional prototype required.

15.0 Testing

15.1 After construction the hand will be subject to several tests of its functionality and compared with functional human hands.

15.2 The test will take elements from the Southampton Hand Assessment Procedure as described by Chappell (2016) but will be individualised depending on how mobile the final prototype is.

8 Control Glove PDS

Based on the research compiled in previous sections, a product design specification was created to guide the conceptualisation and development of the control glove.

1.0 Weight

- **1.1** The HSE Manual Handling Operations Regulation (1992) States that a load at shoulder height and forearm-hand distance from the body should not exceed 3kg for a female, and 5kg for a male. For maximum comfort and ease of use the weight of the glove should not exceed 2kg.

2.0 Size and Dimensions

- **2.1** The glove should fit closely to the user's hand and arm but can be as large as necessary within the weight requirements and only if it does not impede motion.
- **2.2** The most important factor is that all joints of the hand should be able to move as freely as possible whilst wearing the glove, so the size and dimensions should reflect this.

3.0 Performance

- **3.1** The control glove will use integrated sensors to accurately measure the angle of each joint in the hand of the user.
- **3.2** The glove must not impede motion either by colliding with itself or by being too stiff.
- **3.3** The glove must be easy to put on and take off within around 1 minute each, for ease of demonstrations and testing.
- **3.4** The user should be able to move their hand through the full ranges of motion quantified in the biomechanics research section of the project.
- **3.5** The glove should be operable indefinitely with mains power, or 10 minutes if using a battery.

4.0 Operating Environment

- **4.1** The glove should be operable in a standard university room environment with standard pressure, humidity, temperature.
- **4.2** The glove must be resistant to small amounts of dust and debris resulting from storage conditions.
- **4.3** The glove must be resistant to minor vibration and shock loading for when it is moved.
- **4.4** The glove must be resistant to small amounts of moisture from the skin of the user.

5.0 Aesthetics

5.1 Being simply a testing tool, there are no aesthetic requirements for the glove.

6.0 Cost

6.1 The project (bionic hand and control glove) should be under £200 total cost to the university.

7.0 Maintenance

7.1 Components likely to need service should be easily accessible.

7.2 Construction of the glove should allow for easy disassembly to replace parts or make repairs independently of other components.

7.3 Fasteners should be used in preference of more permanent fixing solutions such as glue.

7.4 Overall number of fasteners should be kept low, provided this does not interfere with the build quality.

8.0 Manufacturing

8.1 FDM 3D printers will be used primarily to manufacture components of the glove, including finishing techniques such as sanding and drilling.

8.2 Construction of the glove will include simple bench-based activities such as screwing in bolts, soldering etc.

8.3 The unique requirements of the glove may also benefit from alternative manufacturing techniques such as sewing, leatherworking etc.

9.0 Time Scale

9.1 Design of the glove should be completed before the end of the first semester.

9.2 Construction of the glove should begin in the second semester or earlier and be completed by March.

9.3 Testing should be completed within one month.

10.0 Product Life Span

10.1 The glove should remain fully functional until at least the end of the academic year.

10.2 During this time, it should be able to endure 10 hours of cumulative testing and demonstrations.

11.0 Materials

11.1 Plastic filaments for use with FDM printers will be used for the majority of the construction.

11.2 Fasteners, bearings and other components may be used, and must fit within the budget and weight restrictions.

11.3 Depending on the final design, fabric or leather may also be used in the final prototype.

12.0 Installation

12.1 The glove should be very easy to transport as a wearable prototype.

12.2 The glove should be powered through the bionic hand platform and transformer with a very low voltage of 9V or under, or if a wireless solution is possible it should use a battery of 9V or under.

Disposal

12.3 Upon disassembly the 3D printed plastic parts could be recycled.

12.4 Components such as bearings, bolts and motors should not be substantially damaged under normal operation circumstances meaning they could be reused in other projects.

13.0 Safety

13.1 The design and manufacture process should adhere to the risk management strategies described in the risk identification form submitted early in the project.

13.2 The HSE's Electricity at Work Safe Working Practices (2013) states that uninsulated and exposed live parts are considered hazardous if the voltage exceeds 50V AC or 120V DC in dry conditions. It also states that some voltages are so low they cannot cause a harmful electric shock but may present other hazards such as burns or sparks. With this in mind, the glove should use a very conservative voltage of under 12V since it is actually in contact with the skin, and conditions should be dry.

13.3 The glove should be powered with low voltage power source, if this is a battery it should be located externally relative to the user and shielded, with an appropriate venting mechanism in case of pressure build-up.

13.4 The glove itself should pose no major threat to observers and should be able to interact with humans in simple ways (for example shaking hands) without posing a safety threat.

13.5 The glove should pose absolutely no threat to the user, and every measure should be taken to ensure there are no internal hazardous features.

13.6 External sections of the design which pose a hazard by being sharp or an area which could cause entrapment should be covered appropriately.

13.7 Electronics should be sensibly enclosed with a venting method in case of pressure build-up.

14.0 Quantity

14.1 Only one functional prototype required.

15.0 Testing

15.1 After construction the glove will be subject to several tests of its functionality.

15.2 The test will take elements from the Southampton Hand Assessment Procedure but will be individualised depending on the bionic hand's design.

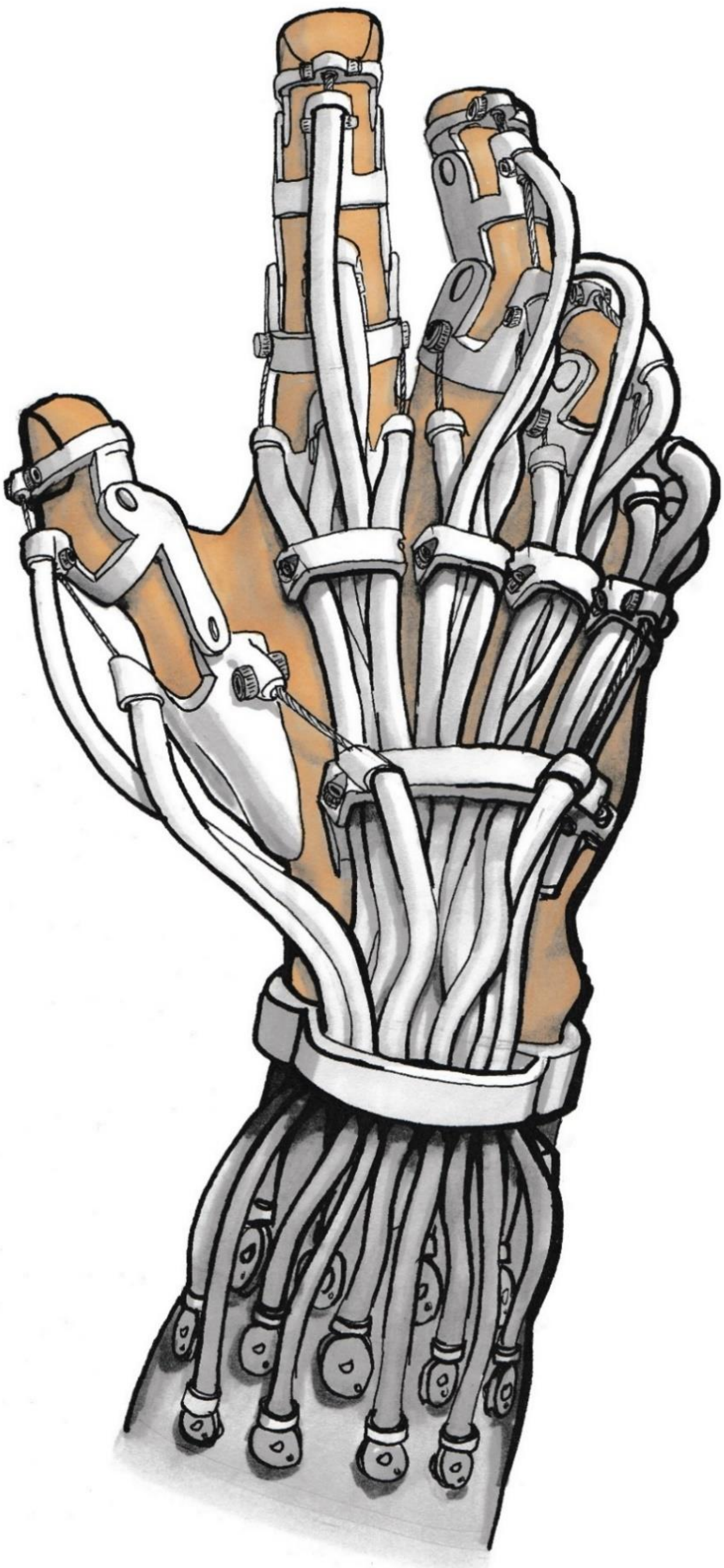


Figure 9.1 - Displaced sensor concept overall design

9 Overall Concept Designs

Displaced Sensor Control Glove Concept

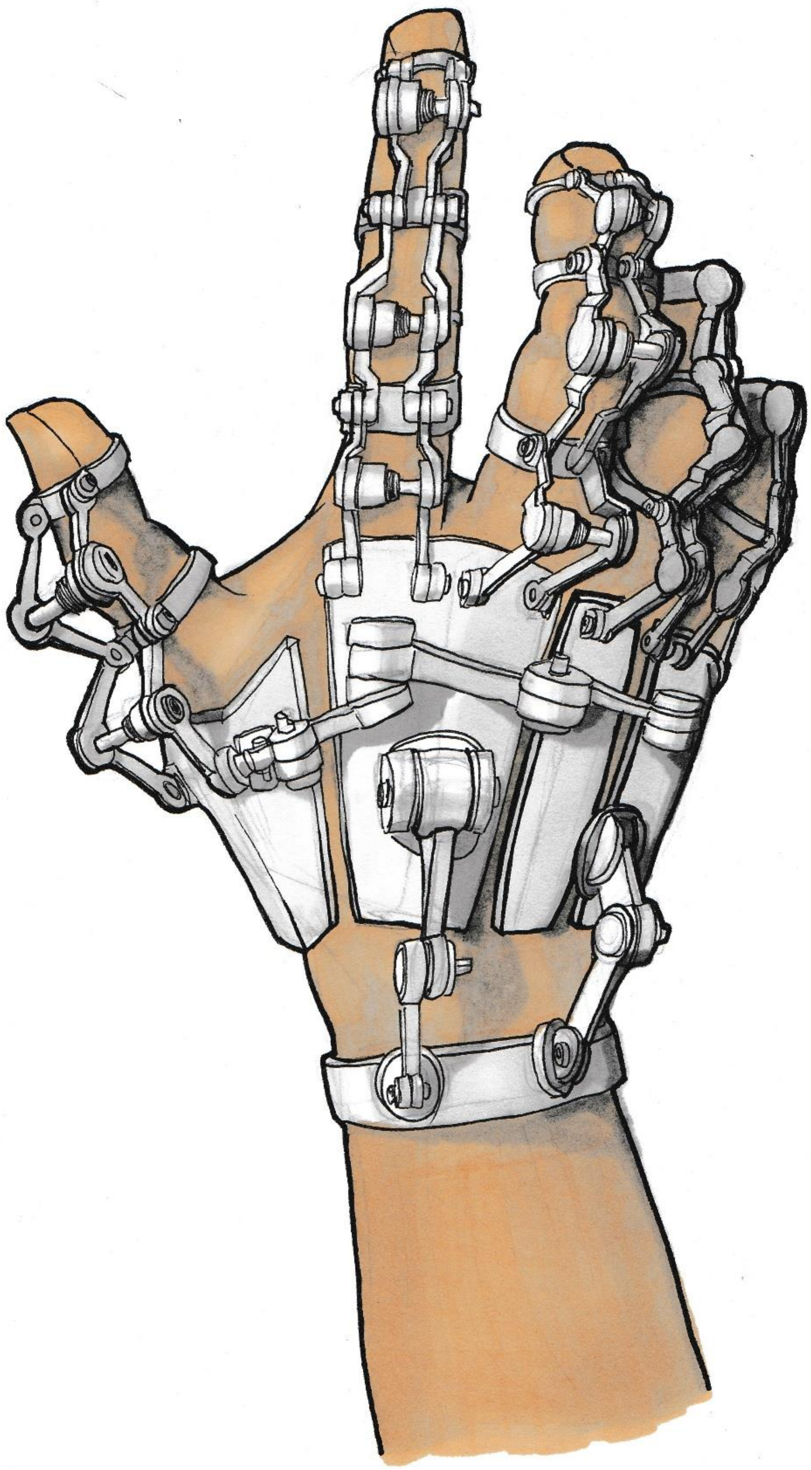
Due to the very large amount of different joint angles that could be measured in a human hand, it may be difficult to physically fit all of the sensors into a dextrous glove. One solution to this problem would be to have all the sensors (potentiometers in this design) located in a forearm mounted block. Using a system of inextensible cables in flexible sheathes, each joint angle could be measured remotely. An overall rendering of this concept is shown in Figure 9.1.

When the user's hand moves from a neutral position to a flexed position, the cable is pulled through the sheath to allow the various joints of the hand to move. This in turn rotates a potentiometer via a pulley, registering a value proportional to the change in joint angle. The design uses a discreet torsional spring system integrated into the potentiometer, which provides resistance to any change in position, and returns the potentiometer and cable to their neutral positions when the hand relaxes.

In order to guide each cable to its joint, each finger segment has a guide ring containing a threaded section to clamp one cable through, and a larger hole to brace the cable sheath and allow the inner cable to pass through. The segments also have a simple snap-fit hinge that maintains a constant distance between segments, but this hinge should be as unobtrusive as possible to allow free motion.

More complex joints such as parts of the thumb may use the same cable system although a different arrangement will need to be devised in the final design.

Local Sensor Control Glove Concept



As an alternative to the displaced sensor design, sensors could be located more locally to the joints themselves, reducing inaccuracies. Since one of the primary design considerations for the control glove is discreet construction allowing for maximum dexterity, it would not be possible to use sensors directly at the pivot point of the joints. In this design, the potentiometer is suspended above the joint in each segment. Certain areas could have more than one sensor for joints that move in more than one axis. An overall rendering of this concept is shown in Figure 9.2.

Unfortunately, this design would only have a minimal amount of rotation in each servo, whereas the displaced sensor concept can take advantage of the full 360° of rotation. This means that the sensitivity of the controller would not be ideal but at the benefit of a much smaller and more compact glove.

Figure 9.2 - Local sensor concept overall design

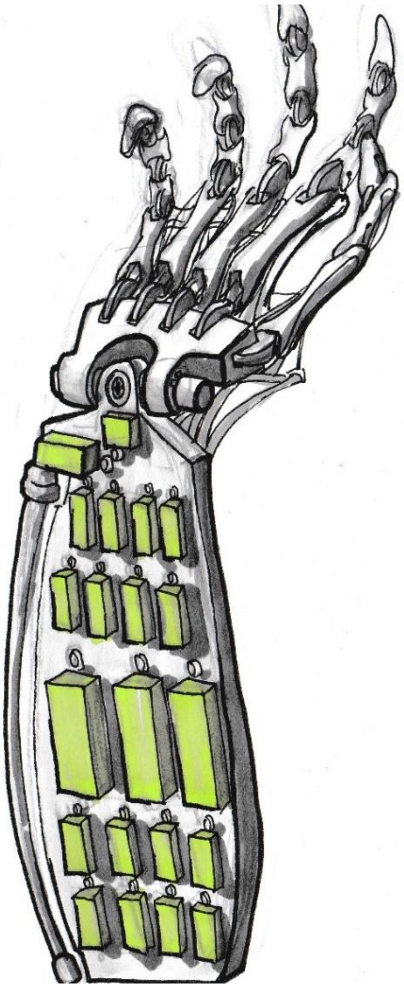
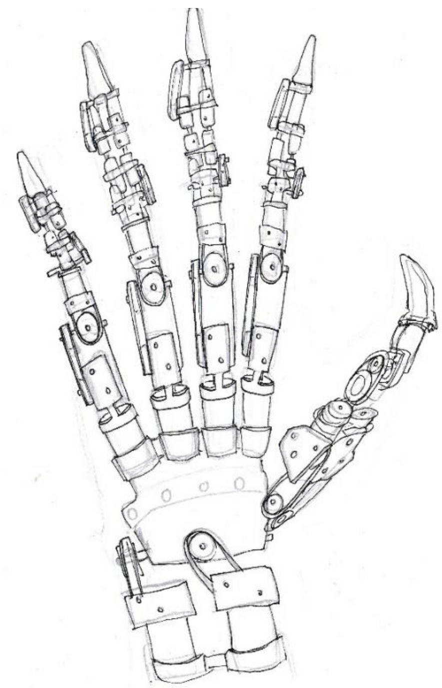


Figure 9.3 - Cable servo operated hand concept overall design



9.3 Cable Servo Operated Bionic Hand Concept

Using the real structures of the human hand as a point of inspiration – tendons and tendon sheaths, this concept uses servos located in the forearm to drive the joints via inextensible cable. This allows for a very high build quality at the hand itself and at the same time more powerful motors can be used.

The fingers have a core made of a flexible material such as nylon or spring steel to return the fingers to their neutral position when the force from the cable is relaxed. The overall design is shown in Figure 9.3 and more detailed, annotated designs are shown in the appendix in Figure 21.11.

Integrated Motor Hand Design

A somewhat "brute force" approach to fitting the large number of actuators into the design of the bionic hand would be to simply integrate DC motors and their gearboxes into the structures of the hand itself. The theory behind this design is simple but the engineering would be quite complex.

Within the first and second phalanges of the hand there may enough room to integrate all the motors needed to emulate full biomimetic motion (4 degrees of freedom), this design would substantially reduce the overall size of the hand assembly (compared with the displaced servo concept) but it would come at the cost of potentially lower robustness and strength. The overall design is shown in Figure 9.4 and a more detailed, annotated design is shown in the appendix in Figure 21.12.

Figure 9.4 - Integrated motor hand concept overall design

Figure 4.3.3 - Cable servo operated hand concept overall design (right)

Figure 9.5Figure 4.3.3 - Cable servo operated hand concept overall design (right)

10 Specific Concept Designs: Bionic Hand

At the start of the specific design stage, a diagram of a human skeleton was created to summarise the range of different joint types that needed to be designed. These are summarised in the diagram Figure 10.1.

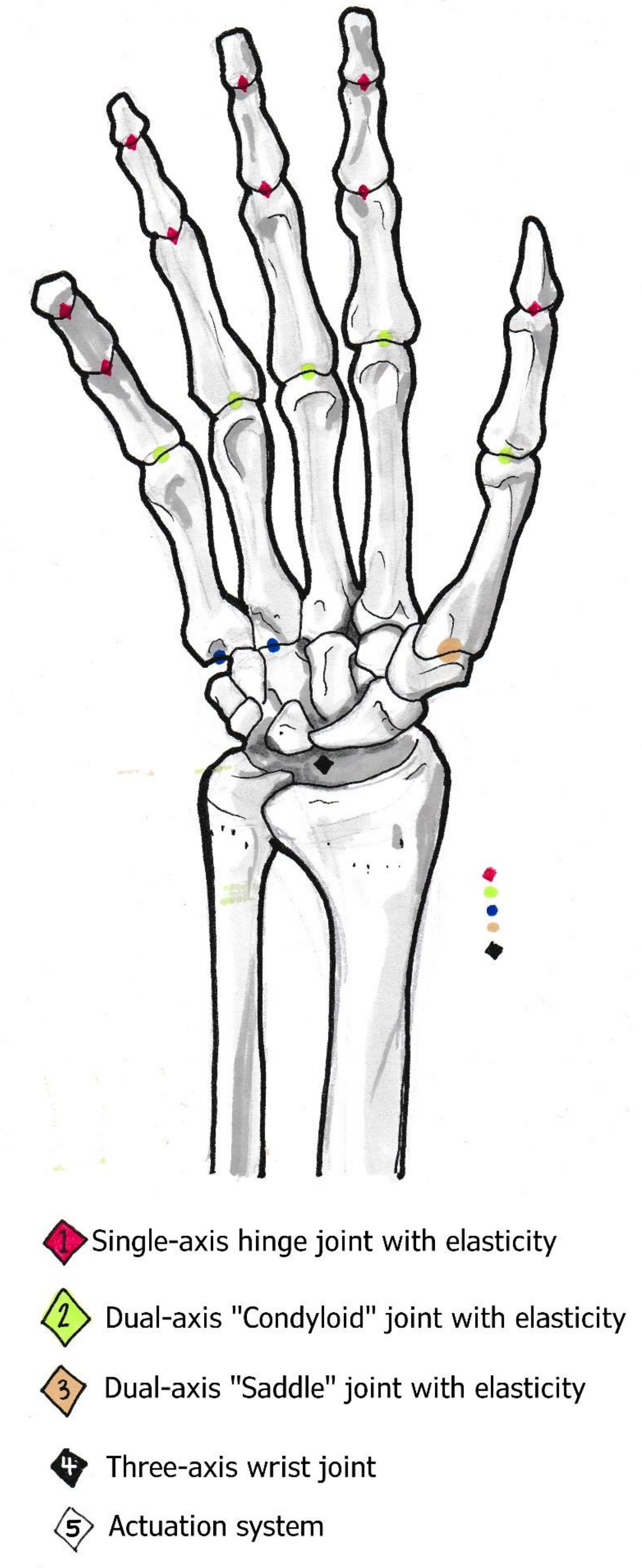


Figure 10.1 – Joint type summary

The first and most common type of joint (type **BHA**) that will be present throughout the bionic hand is a simple single axis hinge joint, with elasticity that will return the joint to its neutral position when the servo relaxes.

The second joint type (type **BHB**) that may be used in up to five instances is a dual-axis “condyloid” style joint. This joint type presents unique difficulties because it must perform the same function as the simple hinge, while also moving in a separate axis *and* rotating slightly as it does so.

The third type of joint (type **BHC**), only found in the base of the thumb (much like the human skeleton itself) is the saddle joint which moves in a very unique way as defined early in the project in the biomechanics section.

Additionally, a 3-axis wrist joint (type **BHD**) was to be designed as well as the overall actuation system.

10.1 BHA Single Axis Hinge

Early designs and ideas included bearings at the pivot point for low-friction rotation and robustness, but it quickly became apparent that bearings would add unnecessary bulk to the fingers. In the early stages, ideas about how having a single, central pivot or two parallel ones allowing the control cables to pass through the centre were considered, as well as more complex linkage systems as described by Chappell, P, H (2016). An example of some of these designs are shown in the appendix in Figure 21.13.

Later designs did not include bearings, and the assumption was made that 3D printed PLA against a smooth steel surface would be an adequate pivoting surface interaction for the kind of low loads expected in the prototype. Most designs used a simple pivot consisting of a partially threaded bolt and a “nyloc” nut.

10.1.1 Concept Design BHA01

The first design **BHA01** used a dual pivot, allowing the passage of two flexible wires (such as nylon or a spring material) and the control wire. It used a modular block system so that the mechanism could be designed only once and implemented in areas with different shapes, for example in fingers with different lengths. It was considered how the design might be generated on a 3D printer, and in areas where a weak, vertical hole needed to be, it was decided that a threaded insert could be used to negate the stresses on the weak plane of the 3D printed block.

The overall design for **BHA01** is shown in Figure 10.2, and an annotated design is shown in the appendix is Figure 21.14.

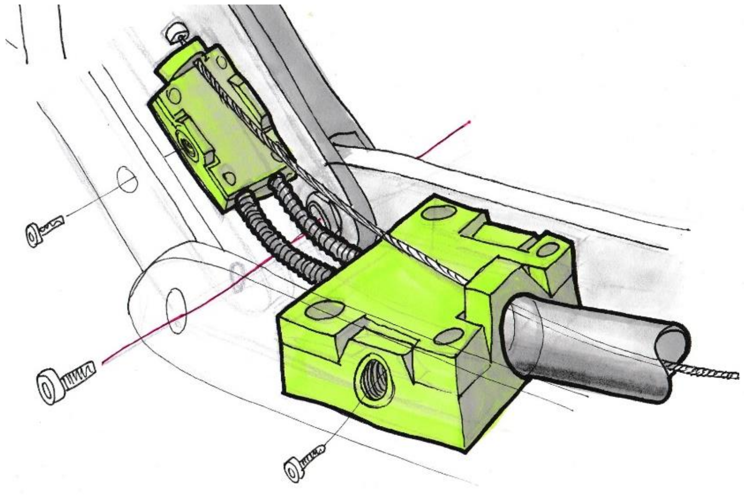


*Figure 10.2 - Concept Design **BHA01***

10.1.2 Concept Design BHA02

The second design **BHA02** (shown in Figure 10.3) was essentially a simplification of the first. Rather than a complex block system, this design had only one central pivot and the flexible wires ran along the outside of the joint. The design does not have the advantage of being modular and easy to reuse, but it is more compact and may be more suited to shorter fingers. Full annotated designs are shown in the appendix in Figure 21.15.

10.1.3 Concept Design BHA03.1

The third design **BHA03.1** (shown in Figure 10.3) featured an integrated elasticity and actuation component, resembling a piston. It was designed to be square since, if it must be printed on a 3D printer, a square shape can be printed much more accurately than a cylinder. This design seemed to be very compact and simple to implement in several different areas, but it would need to be redesigned for each joint with a different ROM. Full annotated designs are shown in the appendix in Figure 21.16. A detailed diagram of the cylinder design was also created (Concept **BHA03.2**, shown in the appendix in Figure 21.17).

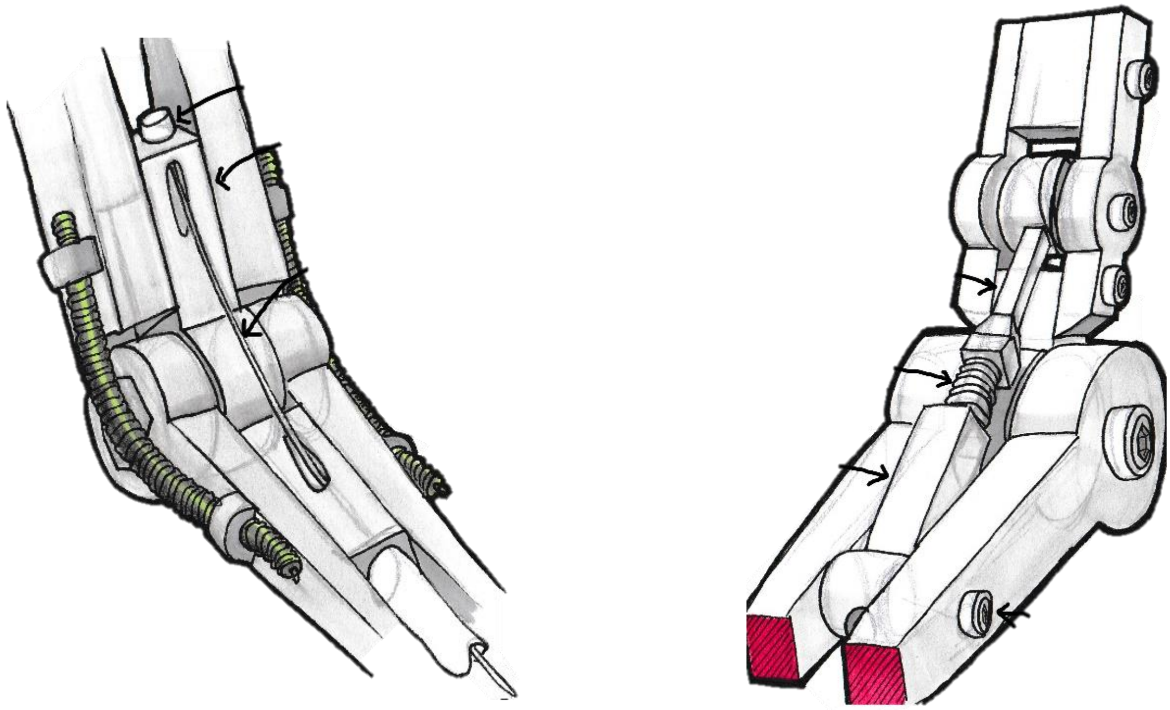


*Figure 10.3 – Concept design **BHA02** and **BHA03.1** respectively*

10.2 BHB Condyloid Joint

Two main designs were conceptualised for the condyloid joint. It was decided that if both of the two designs were deemed infeasible, a simplified joint would be used that consists of one hinge on top of another on a separate axis, and the third axis twisting motion would not be considered (as is the case in virtually all other bionic hand designs).

10.2.1 Concept Design BHB01

The first concept **BHB01** (shown in Figure 10.4) used an encapsulated brass ball in a ball-socket type arrangement, with a rear protrusion that fixes its motion to a guide rail, and a protrusion through the front that forms the hinge for the other axis of rotation. The concept would be actuated remotely like the other hinge joints designed before it.

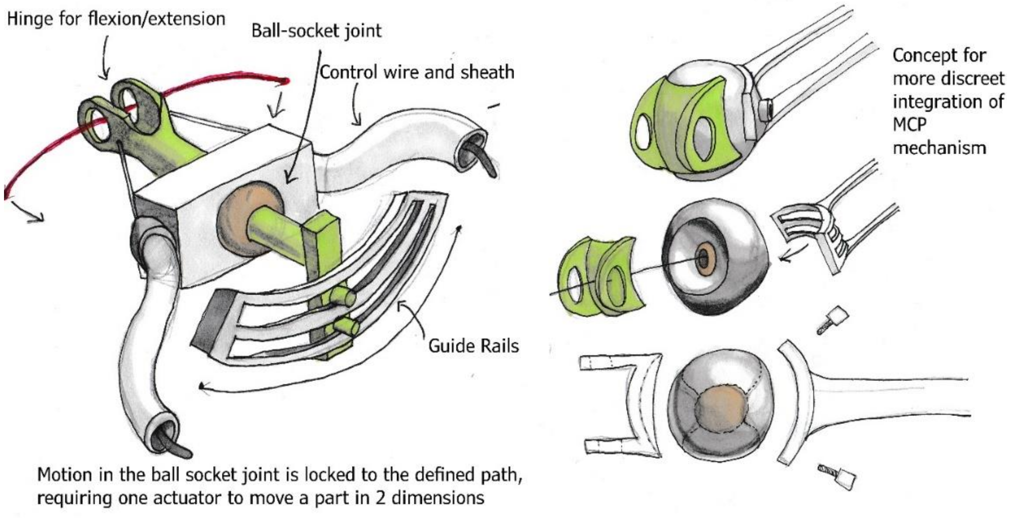


*Figure 10.4 – Concept design **BHB01***

10.2.2 Concept Design BHB02

The second design **BHB02** (Figure 10.5) used an integrated servo actuating a separate component, effectively dragging a ball socket joint through a fixed range of motion at each side, removing the need for elasticity. This design would be very compact and more robust than its predecessor, but it does rely on a few assumptions that the deviation upon rotation will be small enough at the hinges so as to be negligible. Various annotated views are shown in the appendix in Figure 21.18.

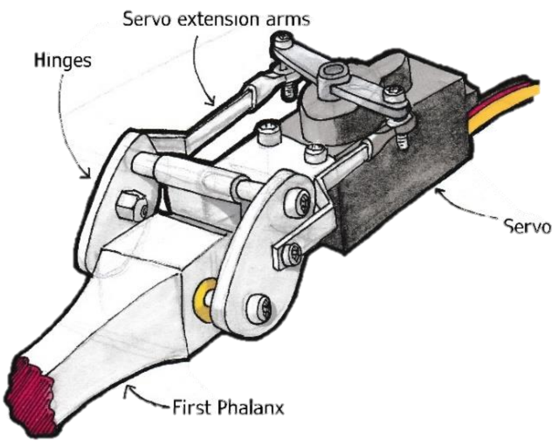


*Figure 10.5 – Concept Design **BHB02***

10.3 BHC Saddle Joint

The saddle joint of the thumb will function very similarly to the condyloid joint of the MCP joints of the fingers. For this reason, it was decided that the saddle joint would be designed after a suitable MCP condyloid joint has been designed and tested, particularly because the range of motion in this joint may need to be simplified if the current designs are found to be infeasible.

10.3.1 Concept Design BHC01

Concept design **BHC01** (Figure 10.6) is a mock-up of what the saddle joint may look like translated from concept design **BHB02**. Because of the limited space in the carpal area, the joint would likely need to be actuated remotely using control wire as with most of the other joints in the hand, meaning that it would also require a return spring. This would also be advantageous in that a larger, more powerful servo could be used to give the thumb the required strength. More views and annotated designs are shown in the

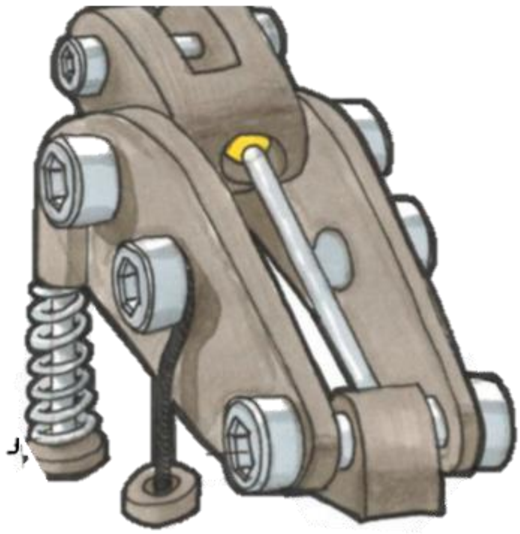


*Figure 10.6 – Concept design **BHC01***

appendix in Figure 21.19.

10.4 BHD Wrist Joint

Because of the large size of the wrist joint in comparison to some of the other joint types in the bionic hand, designing a mechanism for its 3 axes of motion was simpler than the other sub-sections.

10.4.1 Concept Design BHD01

The first design **BHD01** (Figure 10.7) was a very compact system using two actuators and belts to control all aspects of the wrist's motion. Although compact, it does require careful coordination of the two motors, and would need additional feedback since very small errors in calibration would throw the system off.

10.4.2 Concept Design BHD02

The second design **BHD02.1** (Figure 10.7 and Figure 21.20) was much more straightforward and used servos integrated into the forearm/wrist's construction. Because the wrist may need to move a greater load than any other joint, it was considered what sizes of servo may need to be used. As such, a slightly modified mechanism **BHD02.2** was designed that included displaced servos to allow room to move should the servos needed be especially large. This design is shown in the appendix in Figure 21.21.

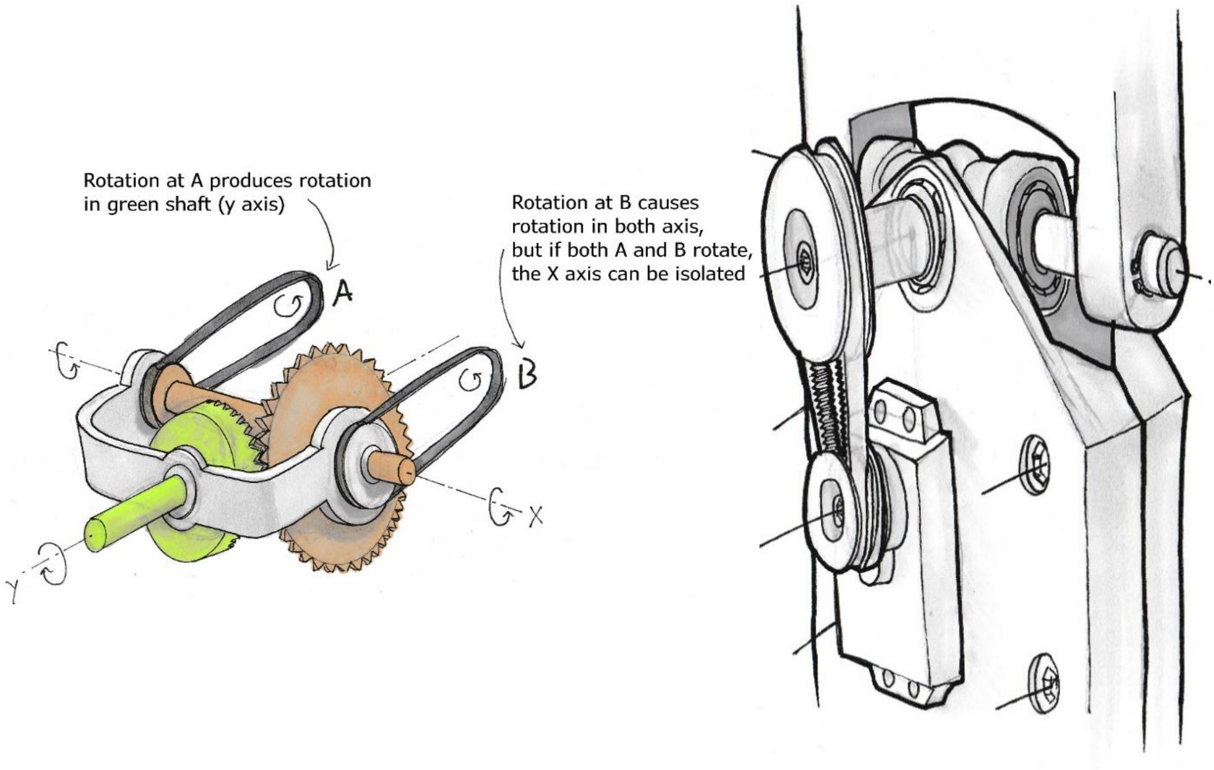


*Figure 10.7 – Concept design **BHD01** and **BHD02.1** respectively*

11 Specific Concept Designs: Control Glove

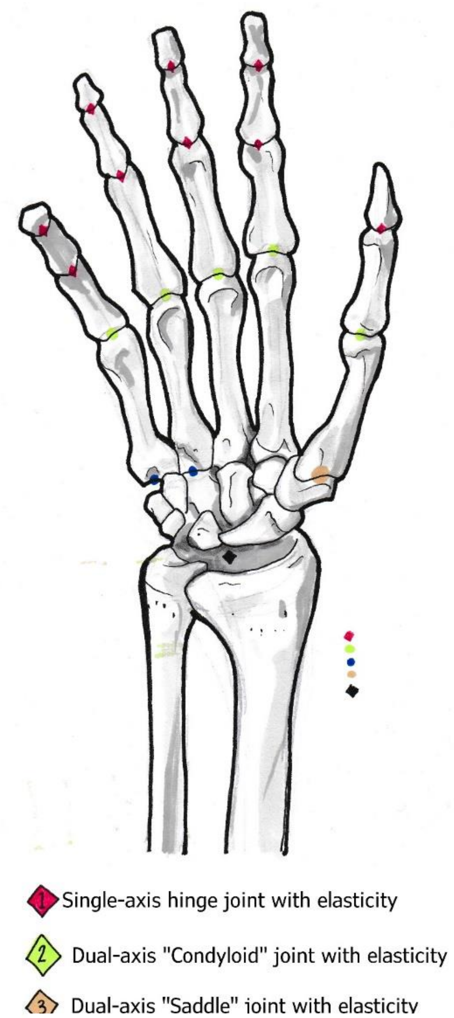


Figure 11.1 – Joint type summary

The control glove required a similar variation of different joint types to the bionic hand, primarily consisting of simple single-axis hinges and employing more complex structures elsewhere. The same diagram (Figure 11.1)can be used to illustrate the range of joint types in the glove. In some areas however, motion was known to be locked to motion in another axis so less complex measurements methods were needed as compared to the bionic hand. For example, the “condyloid” style joint of the MCP joints does not need its inward rotation to be measured, only the two axis of movement of the first phalanges about the metacarpals.

Each finger segment required a single axis hinge which ideally could be constructed as a parameterised model in SOLIDWORKS, such that one could quickly be made for all 9 parts. This joint type is referred to as type **CGA**. The main consideration for their design was that they must be as unobtrusive as possible, not restricting motion in any way. Because of this constraint, many of the designs for this joint type feature a displaced sensor, greatly increasing dexterity at the cost of some accuracy.

Type **CGB** joints are simpler than their counterparts in the bionic hand itself, because, as discussed previously, the inward rotation of the phalanges about the metacarpals does not need to be measured. The key movements to be measured are the flexion/extension of the first phalanges and the lateral motion.

The third joint type **CGC** cannot simply be derived from joint type **CGB** as with the bionic hand due to the physical restraints, but it may bear some similarities. Again, this sensor type will only measure two axis of motion and the third type (rotation about the neutral position) will be inferred from the other two sensors.

The wrist will also need to be measured in all three dimensions, this will be joint type **CGC**. Since potentiometers are the simplest and most accessible type of sensor researched in this project, it is assumed that all joints will use them for measurement. Where possible, every joint type should be measured with the full 360° of rotation of the potentiometer, to increase precision.

11.1 CGA Single Axis Hinge

The main problem in the design of joint type **CGA** was how to connect each segment in a way which would not limit the range of motion in the fingers and also be robust enough. Most of the ideas presented are different ways of tackling this issue – **CGA01** uses a thin snap-fit joint design and **CGA03** uses a leather glove as a way to retain dexterity and the distance between points. **CGA02** uses a slider centred around the joint in order to be completely unobtrusive and also provides a surface which control wire can be fed through.

11.1.1 Concept Design CGA01

Concept design **CGA01** shown in Figure 11.2 uses a small snap-fit hinge system to maintain distance between finger segments and to remain as unobtrusive as possible, but this design could easily be adapted to be riveted on to a glove like **CGA03**. An annotated design as well as a visualisation of a final prototype design is shown in the appendix in Figure 21.22 and Figure 21.23, respectively.

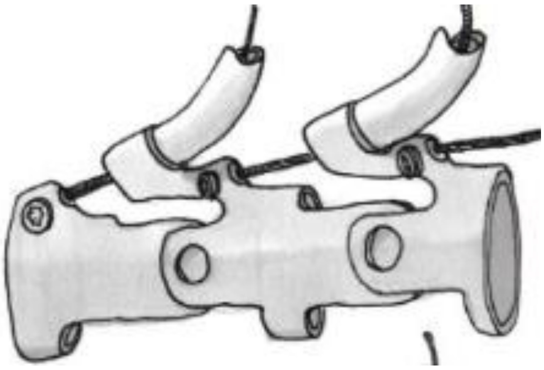


*Figure 11.2 - Concept design **CGA01***

11.1.2 Concept Design CGA02

The second concept design was conceptualised as a way to have a link acting in the same area as the skeletal joint but to have the joint effectively spread out over an arc. The arc slider can also be used as a way to mount the control wire within the structure. An example of one slider mechanism is shown in Figure 11.3, and a visualisation of an ideal final prototype is shown in the appendix in Figure 21.24.

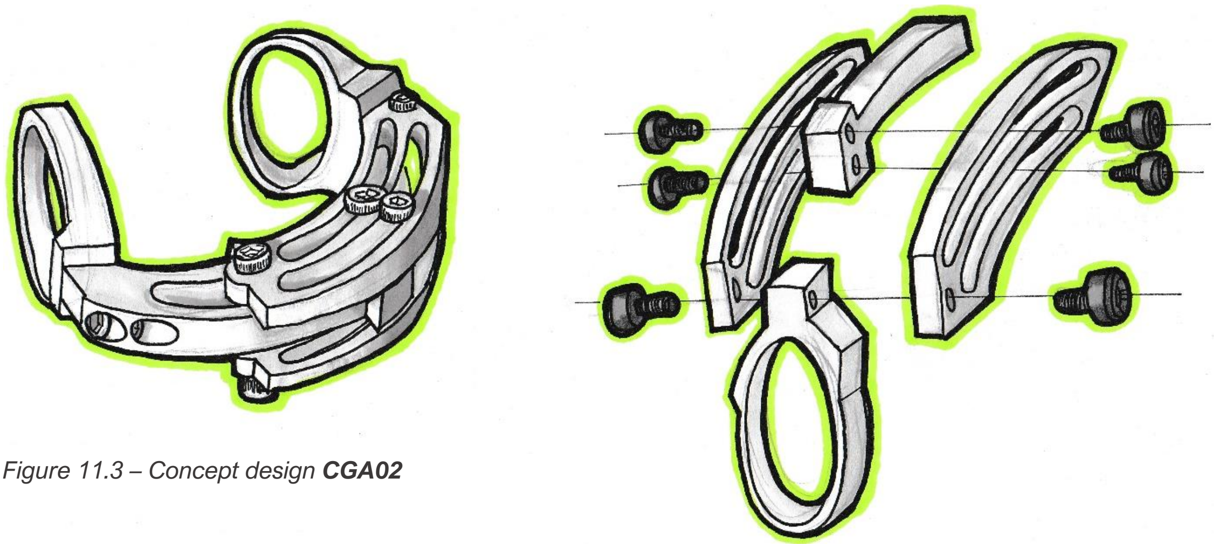


*Figure 11.3 – Concept design **CGA02***

11.1.3 Concept Design CGA03

CGA03 uses a segmented design, secured to a leather glove using rivets. The potentiometers are held above the joints to be measured meaning that the design is extremely unobtrusive to the dexterity of the user. The cost of this design however is a substantially lowered precision because the rotation produced in the potentiometers will be very small. A summary of the design is shown in Figure 11.4.

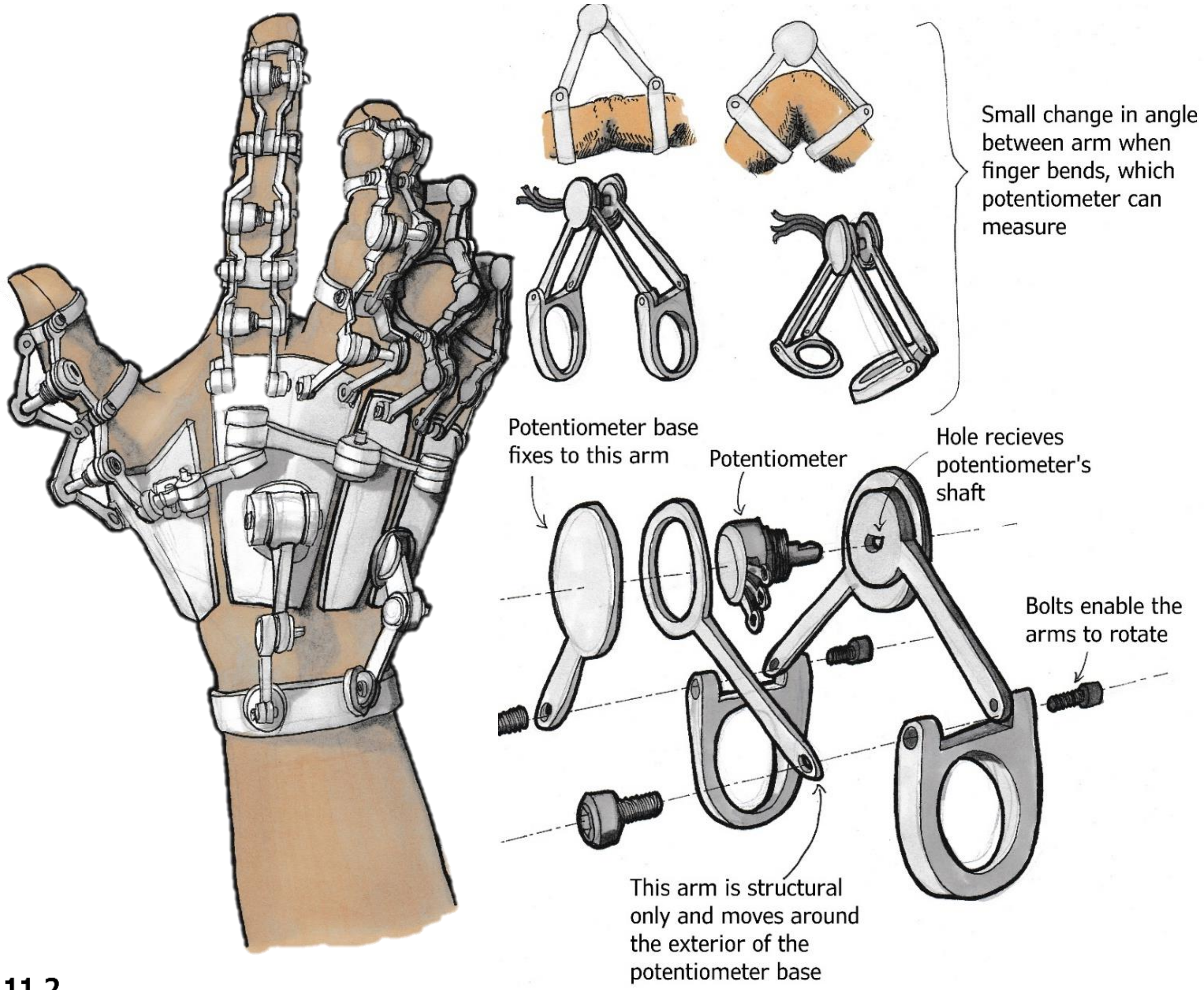


*Figure 11.4 – Concept design **CGA03***

11.2 Joint Types CGB, CGC and CGD

Because of the high degree of uncertainty regarding the general structure of the control glove at this stage in the project, it was decided that prototyping of concept designs CGA01 through CGA03 would take priority over conceptualisation of joint types CGB through CGD. This is because most other types of sensor can be derived in some capacity from the simple hinge type, and once fundamental questions about how the glove should be constructed can be answered (e.g. Will the glove be based around a leather glove? Can the potentiometers be reliably displaced using cables and tubing?), it will be easier to conceptualise designs in this tighter margin. Whereas the bionic hand sub-assemblies are easy to design in isolation, the sensors of the control glove necessarily "flow into" one another, so a successive design strategy must be employed.

12 CAD Concept Development: Bionic Hand

12.1 Joint Type BHA

For each of the three main concept designs **BHA01, BHA02 and BHA03,** a CAD model was created using standard fittings where possible and aiming to keep within the size constraints of the PDS. These designs are shown in Figure 12.1, and comparisons to original sketches is shown in the appendix in Figure 21.25

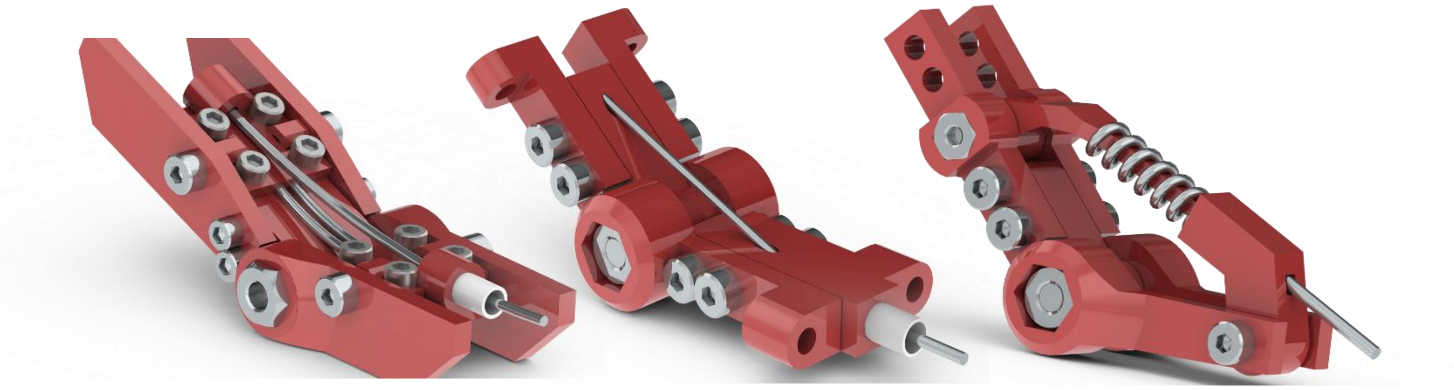


*Figure 12.1 – Concept designs **BHA01**, **02** and **03** respectively*

12.1.1 CAD Model BHA01

The first concept design translated reasonably well into a CAD design. Using standard components, the final width of the assembly at the joint (the largest part of the assembly) was 18mm which is perfectly acceptable for most of the IP joints in the hand. Of the 3 concepts **BHA01** seemed to be the most viable however the very small-scale details of the structure present a cause for concern if actually printed in PLA, as the 3D printer may struggle to create such small parts. An advantage of this design was that both the top and bottom sections use the same block, reducing the number of unique components that need to be made. Additional views are shown in Figure 21.26.

12.1.2 CAD Model BHA02

The second design also translated well, but the width was found to be well over 18mm, subject to the type of elastic material used. Concept **BHA02** was designed primarily as a simplification of **BHA01**, allowing it to feature bulkier and easier to print components than its predecessor. However, once the CAD model was constructed it began to appear as though this design may be an oversimplification with its lack of support for the elastic tubing. Additional views are shown in Figure 21.27.

12.1.3 CAD Model BHA03

The final design unfortunately was clearly flawed, only becoming apparent once the design had been converted into CAD. On such a small scale it was very difficult to fit the mechanisms discreetly into place without having the large protrusion as is clearly visible in Figure 12.1. This design would, however, be very well suited to applications where only a small ROM is required, such as the metacarpals' small movements on the carpal bones. One feature that was added to this design was a slight offset of the "piston" relative to its pivot points, this was to allow the finger joint to lay flat. Alternative views are shown in Figure 21.28.

12.1.4 CAD Model BHA02II

Using the previous models as guidelines, a new concept was generated based on the design of **BHA02** that used a torsional spring centred around the joint's pivot point as the return mechanism. Immediately this design seemed to be the best option at 15mm at its widest, a very densely packed mechanism and even space left over that could be used to mount additional components such as shielding. This design is shown in Figure 12.2

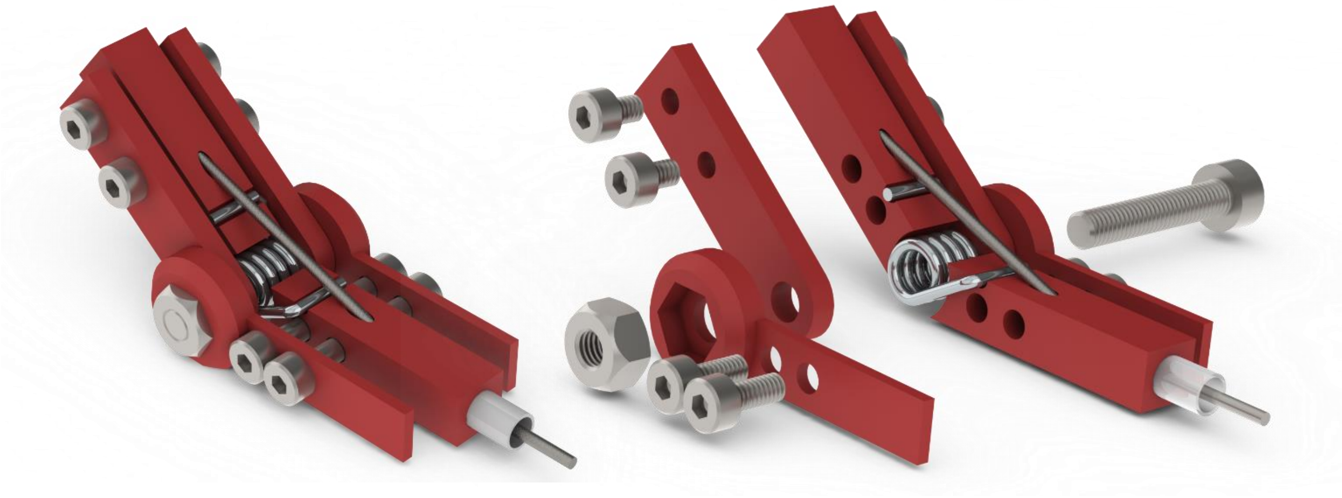


*Figure 12.2 – Derivative concept design **BHA02II***

12.2 Joint Type BHB

Only 2 initial concept designs were generated for joint type BHB, as it was decided that if neither joint was appropriate, a simplification would be made to the motion of the joint. The designs are shown in Figure 12.3, and the comparison to original sketches are shown in the appendix in Figure 21.29.

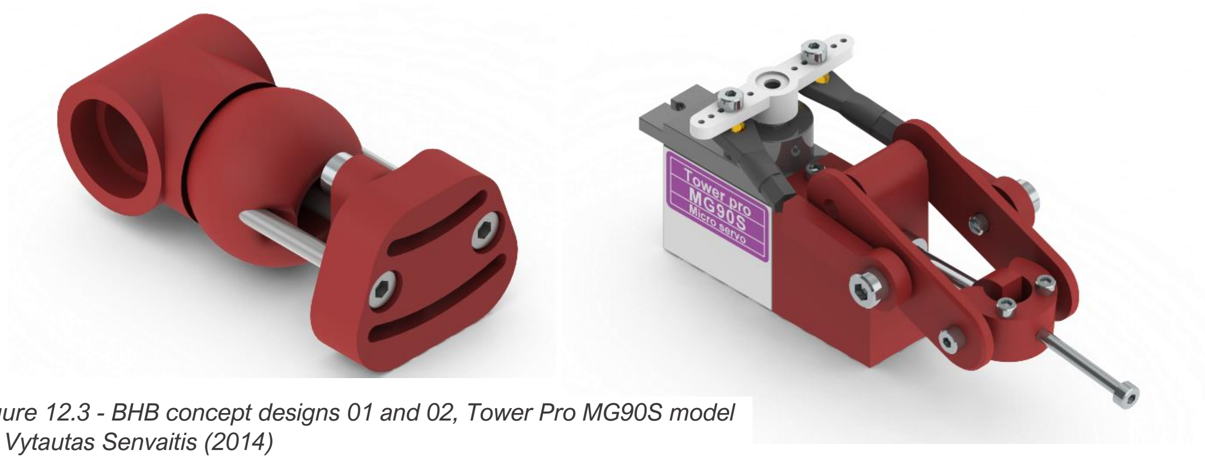


Figure 12.3 - BHB concept designs 01 and 02, Tower Pro MG90S model By Vytautas Senvaitis (2014)

12.2.1 CAD Model BHB01

The first CAD model went through several design iterations before arriving at a suitable design prototype. The final iteration does not feature mounting holes for the control wire because it will be necessary to see if the joint type actually functions well before committing to further design, as there is a high probability for its failure. If the design does work, it will no doubt be an extremely compact solution to the joint type. Additional views are shown in Figure 21.30.

12.2.2 CAD Model BHB02

The second design was much more simple to convert into a CAD model, however there are a few design inefficiencies. For instance, the full range of motion in the servo cannot be taken advantage of meaning that the motion will not be as fine as it could be. Also, an effective solution was not found during this design phase of how to connect the servo horn to the actuating arms but this should not pose a major issue. Additional views are shown in Figure 21.31. Servo CAD model by Vytautas Senvaitis (2014).

12.3 Joint Type BHD

For the wrist, it was decided that the interaction between concept design **BHD01** was too complex for the scope of this project and so only concept design **BHD02.2** was carried forward for further development.

12.3.1 CAD Model BHD02.2

The Tower Pro MG996 was chosen as a good servo for reference design due to its very high availability with a stall torque of up to 15kg/cm it appeared to be a good choice for the wrist, and a CAD model by Alfonso Cruz Collacca (2015).Due mainly to the unforeseen size limitations for the chosen servo however, it quickly became apparent that the concept design would turn out much bulkier than intended. Because of this, the design was quickly abandoned in favour of a new design – **BHD02.3**. **BHD02.2** is shown in the appendix in Figure 21.32 and Figure 21.33.

12.3.2 CAD Model BHD02.3

As discussed in section 11, **BHD02.3** was created as a more compact redesign of **BHD02.2**, which was itself a redesign of **BHD02.1**. The result was a much more appropriate design which would fit easily within the defined constraints. The design is shown in Figure 12.4, additional views are shown in the appendix in Figure 21.34 (exploded views) and Figure 21.35 (comparison to scale model by Joerg Schmit (2012)).

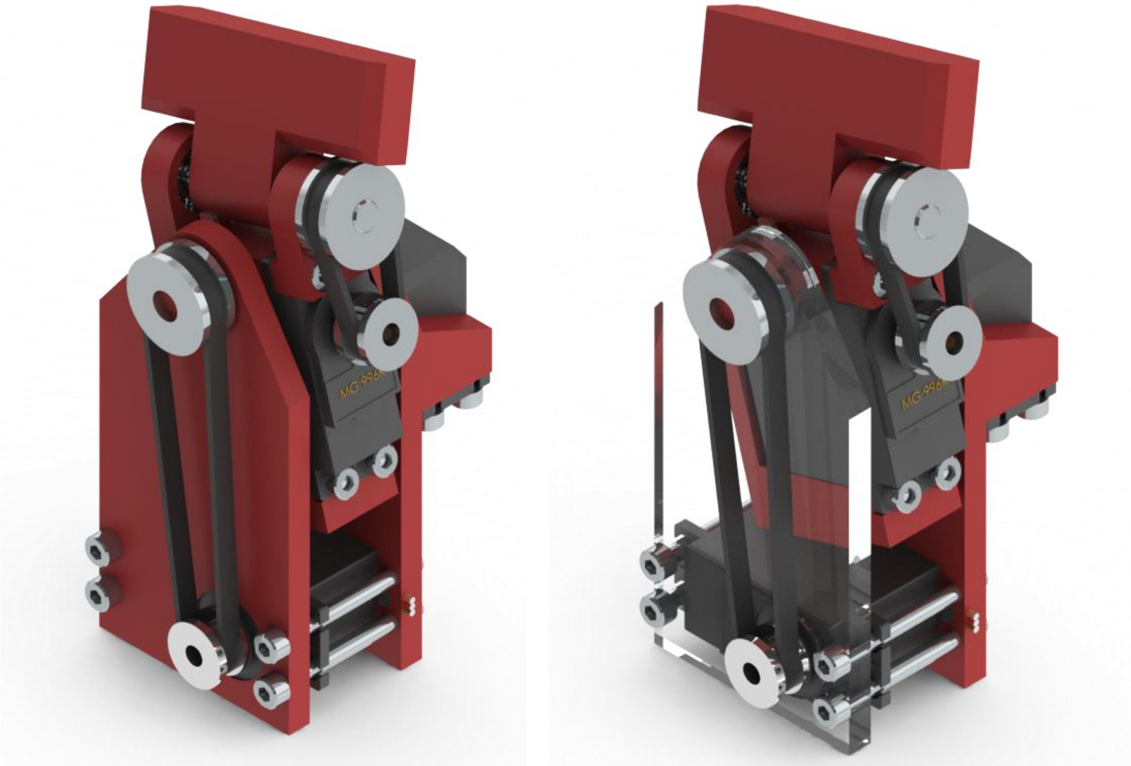


*Figure 12.4 - CAD design **BHD02.3** exploded view and closeup, using servo model by Alfonso Cruz Collacca (2015)*

12.4 Actuation System

Because of the large reliance on cable-actuated joints in the bionic hand, a robust pulley system had to be designed. Initially, a model was designed to examine the viability of the main design with a large servo (MG996, Figure 12.5). The design was found to be very effective and so a parameterised model was made for the Tower Pro MG90S (a much smaller servo suitable for most joints in the model). Using SOLIDWORKS' equation system, a value for the range of motion in the joint that the control cable would move though could be input and a model would be generated based on this value. The equation was based on the fact that, for a 180° rotation servo, one half of the circumference of the pulley should be equal to the range of motion. This design is shown in Figure 21.36.

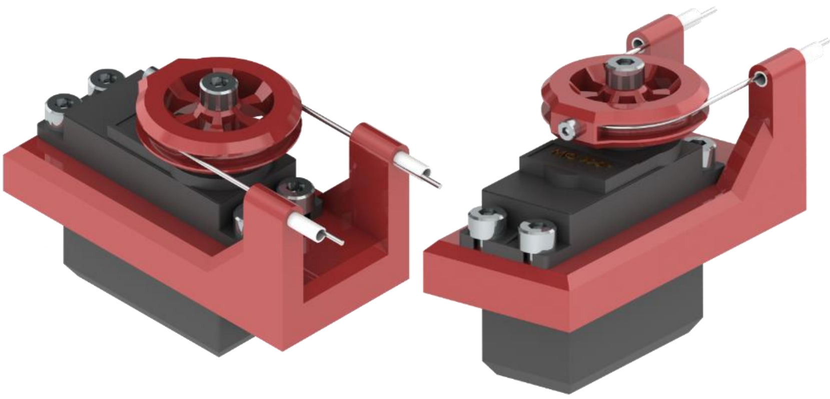


Figure 12.5 - Actuation system initial design with CAD model by Alfonso Cruz Collacca (2015)

13 CAD Concept Development: Control Glove

13.1 CAD Model CGA01

Concept design **CGA01** went through a few design iterations before it was decided that the snap fit hinge system would not be an effective design. It became apparent while using standard sized components that such a thin structure when printed in PLA would be very weak, and making them any larger would substantially affect dexterity. Therefore, the design was switched over to a leather glove and rivet system as with concept design **CGA03**. Also, it became obvious that the structure could not be moved properly without any leverage, so the ring was extended to make more contact with the fingers. The CAD model is shown in Figure 13.1, and additional views are shown in Figure 21.38. Comparison to initial sketches are shown in Figure 21.37.

13.2 CAD Model CGA02

Once again CAD Model **CGA02** went through a few design iterations, including giving a proper leverage surface to the joint. It was found to have a much lower range of motion than originally thought, but did function roughly as expected in simulation. The CAD model is shown in Figure 13.1, and additional views are shown in Figure 21.39.

13.3 CAD Model CGA03

The third CAD model used **CGA01** as a starting point, giving the structure some additional leverage as previously discussed. One major change that was made was that the potentiometer was moved from being above the finger to being mounted on one of the rings, because this made it easier to devise a fixing solution and there was a greater amount of rotation in this area that could be measured. A medium/small wire-wound potentiometer was chosen (using a CAD model by Dodong Smith (2017))as a model to base the design from, although in the final design a much smaller potentiometer could be used. The CAD model is shown in Figure 13.1 and Figure 21.40.

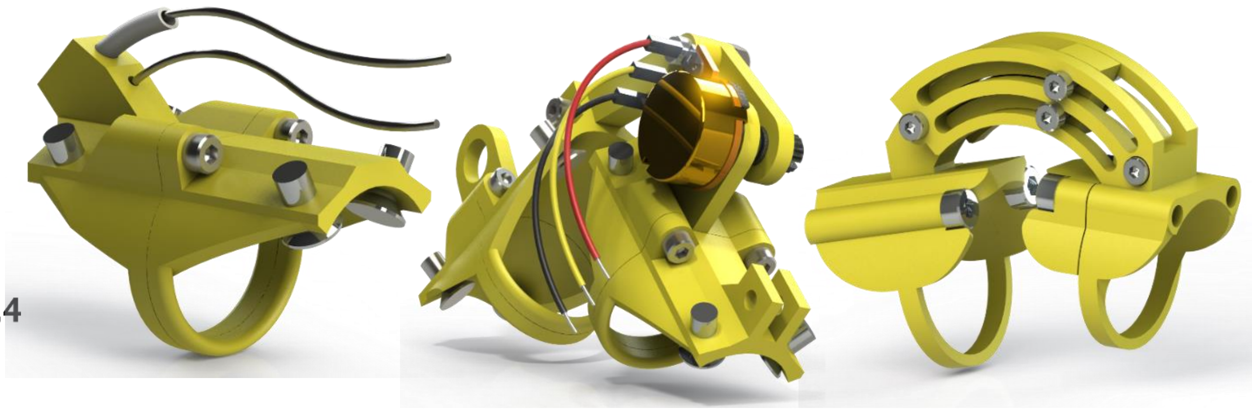


*Figure 13.1 - **CGA** Designs 01, 02 and 03, with potentiometer CAD model by Dodong Smith (2017)*

13.4 Joint Types CGB, CGC, CGD

As discussed in the specific design conceptualisation section of the project, some of the less common joint type sensors used in the control glove were to be designed based on the outcomes of the prototyping stage. Therefore, the design processes of these elements were left out of this section.

14 CAD Development: First Full CAD Assembly

Biomimetic Bionic Hand

Following from the development of the specific concept designs, a large-scale assembly was constructed in SOLIDWORKS, suitable for an initial prototype and base for testing.

As the most uncertain sub-assembly of the design, CAD model **BHB02** (3-axis MCP
14.1 "condyloid" joint with local servo) was redesigned using simple trigonometry to be mathematically suited for its ROM parameters, shown in Figure 21.41. Despite further iterations on the design, it became apparent that a suitably robust joint could not be made to fit within the roughly $20mm^3$ space with the components available for the project. No structural components in the designs were thick enough due to the large amount of moving parts and complex kinetic requirements, and the best design still required 5 ball-socket joints to work (a very temperamental joint type to use at such a small scale). Because of this, it was decided that a simple dual-hinge design would be far more robust, at the sacrifice of the 6° of internal rotation that the finger would normally move through about the MCP joint.

After making this critical decision about the design of the hand, a simple phalanx assembly (including the metacarpal and all phalanges) was built based primarily on **BHA02II** (torsion spring hinge), but it quickly became clear that a better option would be to use a parameterised model such that all phalanges could be quickly generated from a master. The master component did not differ substantially from the initial **BHA02II** design, the key element of its construction being that as many parts as possible were only extruded in a single axis, making them very easy to print. In the component settings, the length of the phalanx from the centre of its rotation could be entered and

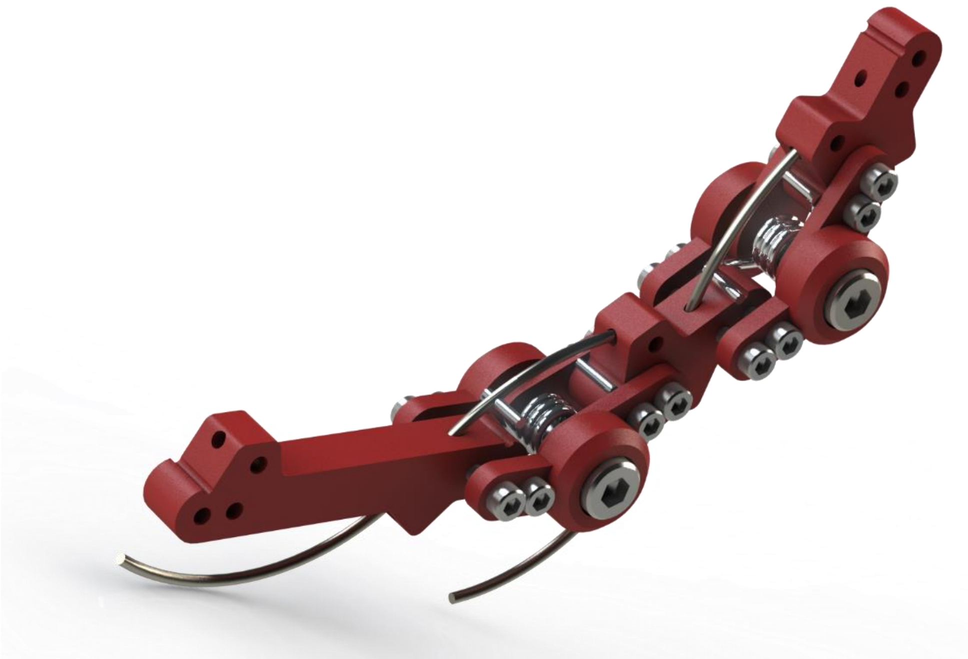


Figure 14.1 – Phalanx base using parameterized connectors

a connector would be generated to link the pivoting components at the specified length. This model is shown in Figure 14.1, and additional views are shown in Figure 21.42.

After all lengths needed for the connector component were verified to construct correctly, a thumb assembly was built. Due to the simplification of the MCP joints in the fingers, the thumb also was simplified to use a dual axis-hinge, but with the additional space available and larger strength requirements of the thumb as compared with the MCP joints, a more robust assembly could be created. A very compact deep groove bearing (623) was selected to support the thumb through lateral rotation (the sweeping of the thumb across the palm). The role of the bearing was to support both the vertical loading that the thumb will be subjected to as well as the radial forces generated by gripping. Ideally a tapered bearing would be used, but since they are not manufactured as small as would be needed, a deep-groove ball bearing was chosen as they can at least withstand some radial force.

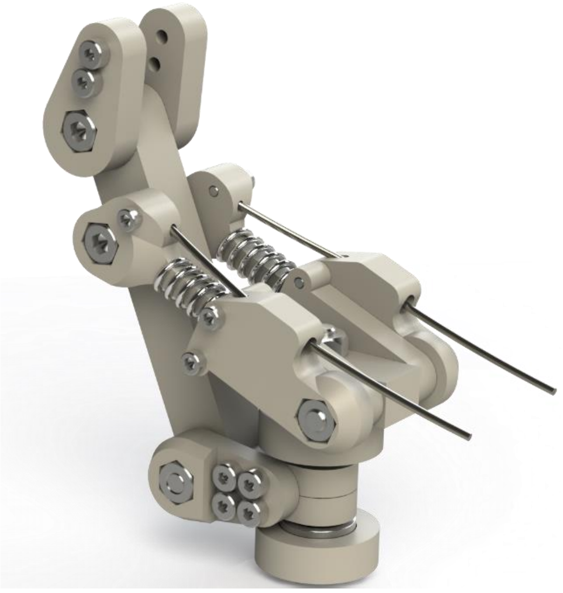


Figure 14.2 – Thumb assembly

Concept design **BHA03** (compression spring "piston-esque" design) was also used in the design of the thumb to facilitate flexion/extension. Two pistons were used in the design to evenly apply force the thumb's metacarpal, requiring a servo with a dual pulley attached. The rest of the thumb was then built using the parameterised phalanx components, making minor adjustments where necessary. The thumb designs are shown in Figure 14.2, Figure 21.43, and Figure 21.44.

Using generated models of each finger with accurate lengths as measured with Vernier callipers, a mock-up assembly was made in order to link each finger and the thumb at the correct orientation/position (shown in Figure 21.45). A component was designed to hold the index and middle finger's metacarpal in a fixed position, while the ring and little finger's metacarpals were hinged, this component is referred to as the carpal block. The carpal block was also required to hold the thumb at a specific inclination so that it

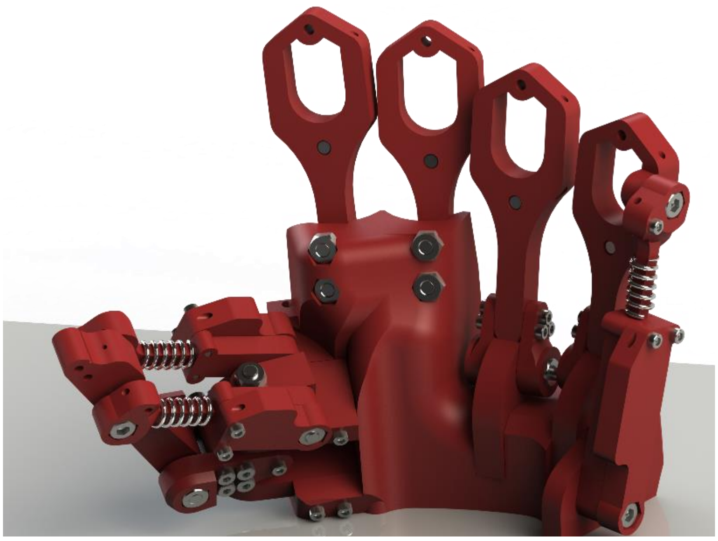


Figure 14.3 – Carpal block with thumb assembly and metacarpal bases

could directly oppose any finger. This positioning was calculated empirically and by trial and error, due to the abstract nature of the saddle joint being emulated. Using concept design **BHA03** (compression spring "piston-esque" design) once again in the carpal block at the outer edge, a longer piston was created to allow the final metacarpal to be flexed slightly, and the ring finger metacarpal would follow it via a flexible material attached across all metacarpals. The carpal block needed to join several different components at unusual angles, so the final outcome was a fairly abstract and organic-looking shape, but fortunately it did not contain any significant overhangs that would complicate the 3D printing process. The carpal block is shown in Figure 14.3 and Figure 21.44.

After the "skeleton" had been designed and tested in SOLIDWORKS (Figure 21.46), a segmented shell structure was designed to add rigidity and protection to the fingers but crucially to bring the dimensions of the hand to roughly human proportions so that later it could be tested as fairly as possible. For example, having a palm structure enables the hand to be tested holding larger objects that rest in the palm, whereas if the object was sitting on the moving components of the bionic hand its function may be impaired. As the shell components are comprised of complex organic surfaces, they were unsuitable for printing on an FDM printer without a large amount of support material and extensive print-times, although an SLS printer may be very well suited to such structures.

At this milestone in the project, several renderings were made of the bionic hand, these are shown in Figure 14.4, Figure 21.47, Figure 21.48 and Figure 21.49.

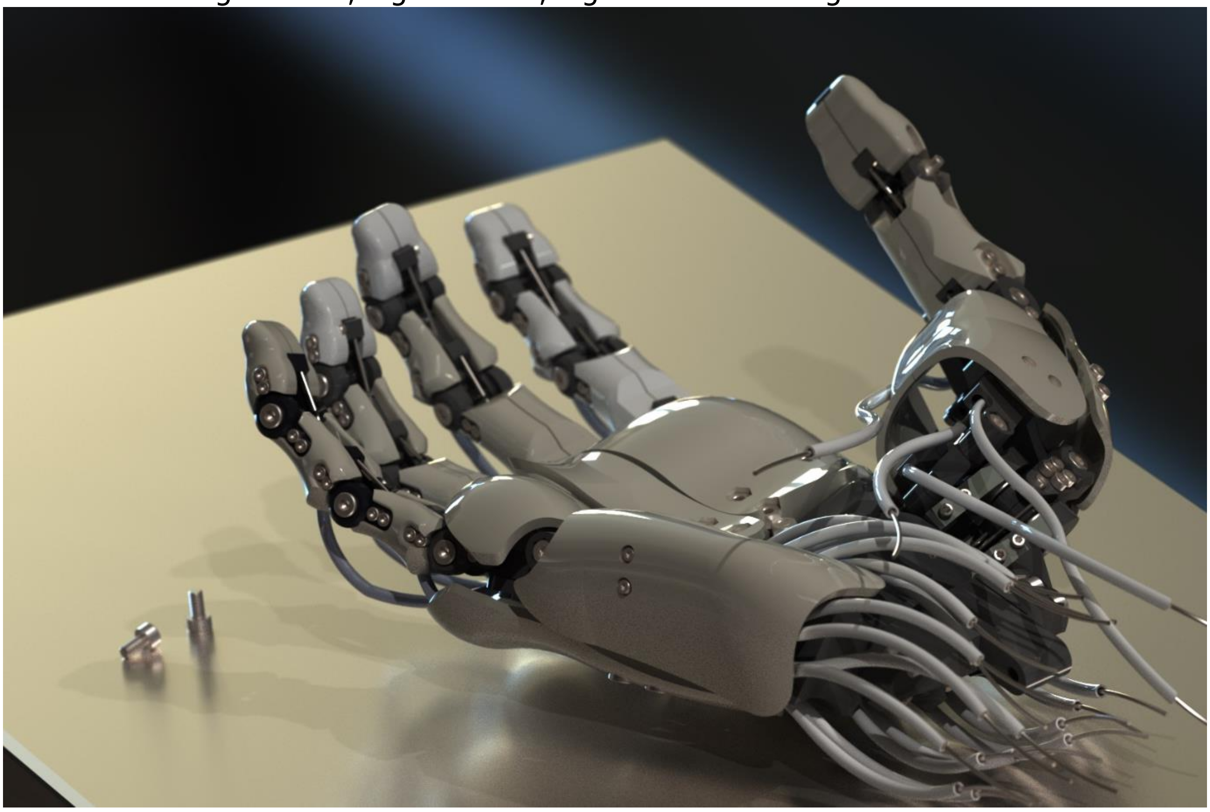


Figure 14.4 – Rendering of the first prototype design

14.2 Control Glove

Due to the uncertainty regarding the functionality of the control glove concepts, it was decided that test structures would be created for both the **CGA01** (displaced, spring-loaded sensors) and **02** (Local, lever-operated sensors) designs. The **CGA03** (arc-slider design) was also considered for implementation into the final design, but since its functionality hinged on **CGA01** working as planned, a prototype was not designed until the spring-loaded sensor concept could be verified to work as planned.

The local sensor concept was designed first, using a parameterised model to generate finger segments for each phalanx. Initially, the main concern with this concept design had been that the minimal rotation produced at the potentiometer would not give a high enough degree of accuracy for satisfactory biomimetic motion. However, it was proven in SOLIDWORKS that if a lever system was designed mathematically, a full 180° of rotation could be produced in the potentiometer, which should produce a high degree of accuracy if the potentiometer is good enough quality.

When measuring the lateral rotation of the MCP joint, there was some uncertainty about how both axes of rotation could be measured independently using local sensors. The final design used a ball-socket joint to connect the MCP potentiometer to the proximal phalanx segment, but testing was necessary to ensure this design was viable. This structure was necessary because, unless the potentiometer was placed directly above the knuckle, moving the fingers side-to-side would misalign the lever measuring flexion/extension. The lever design was very successful in producing constant linear rotation in the potentiometers in response to the bending of the fingers when simulated in SOLIDWORKS, but there were still concerns about certain parts of the model being too thin or weak.

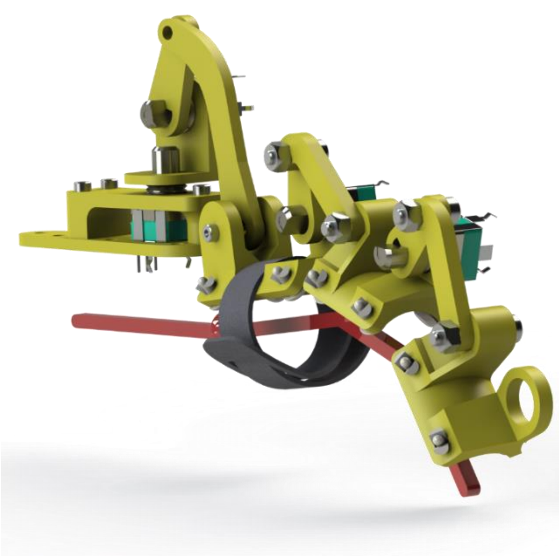


Figure 14.5 - Local sensor lever design for control glove

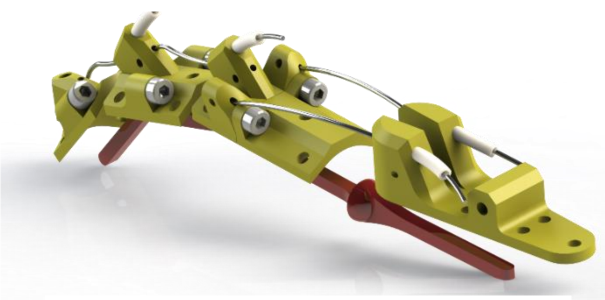


Figure 14.6 - Displaced sensor design for control glove

The displaced sensor concept was ideal for complex joints such as the MCP joint, because, whereas the local sensor concept was very bulky in these areas, the displaced servo concept would be very compact and would not impact the hand's dexterity. In order to measure flexion, extension and lateral rotation in the MCP joint, 2 wires measured the displacement of the first finger segment on either side. If both wires were extended/retracted equally, then only flexion or extension occurred in the user's hand, but if the wires became different lengths then the finger was moving side-to-side. At this stage in the project the displaced sensor concept seemed like a much more elegant solution if it could be proven to work effectively.

15 Prototyping

15.1 Bionic Hand Joint Types Testing

Four separate testing platforms were developed to test the various joint types within the bionic hand. Two of these were simple motor housings and the other two were larger sections of final design including the “carpal block”, such as the palm testing platform shown in Figure 15.6, an important structural component in the bionic hand. A separate, simplified testing platform was also made to test the BHB02 MCP joint design, and another was made to test the validity of the pulley mechanism itself.

Components were 3D printed using a GEEETech Prusa i3 3D printer, and most mechanisms used an Arduino Uno microcontroller, an Adafruit PWM servo driver board (to deliver more power to the servos), with simple code that moved the servos using a potentiometer. This section covers the mechanical function of the prototypes, while the code and electronics used is discussed in full in in section 15.4: Electronics and Programming. In this section testing procedures are touched upon but tests which are critical to the success of the project are not detailed until section 17**:** Bionic Hand Evaluation.

15.1.1 Actuation System

The first prototype for the actuation system was a direct 3D print of the parameterised pulley system described in Section 13.4. The prototype shown in Figure 15.1 consisted of a Tower Pro MG90s Servo selected simply for its availability and low price, 1mm steel cable and an M3 threaded insert and bolt. The prototype was attached to an Arduino with very simple code and a potentiometer for control, and the system was found to work as expected for such a simplified scenario. Having found no major issues with the concept, no large-scale changes were made to the bionic hand at this point.

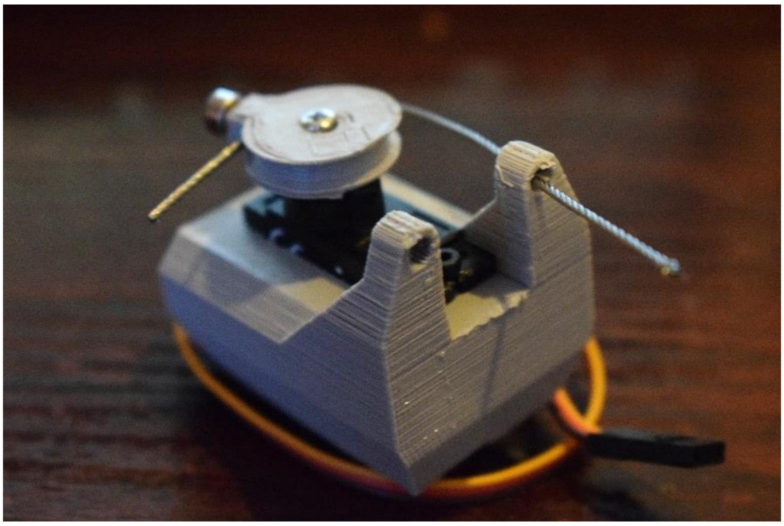


Figure 15.1 - Initial actuation system test

15.1.2 First Finger Testing Prototype

After the actuation system had been verified to work as intended, the master phalanx design, derived from the BHA02II torsion spring hinge was tested in the context of a full finger as shown in Figure 15.4. The testing platform held three Parallax Inc Standard Servos in a compact block, designed to be similar to how the motors would be mounted in the forearm in the final model. The block also held a copy of the index finger at an inclined position so that it could be evaluated more easily.

In order to set up the model, a simple Arduino program was used that allowed the model to be controlled by a potentiometer simply by mapping the readings on to a range of pulse widths used to control the position of the bionic finger. The pulse widths were also printed to the Arduino IDE's serial monitor so that the range of values corresponding to a full range of motion in each joint could be noted and used later. Once the pulse width endpoints had been found, a new code was uploaded to take the values detected by a prototype control glove and use them to drive the bionic finger.

Testing of the prototype could then commence, but tests were not performed in depth because a number of issues were already apparent, therefore most testing was left until the next design iteration. Speed was tested however, and through analysis of video testing footage the prototype was found to exceed targets (this test is discussed in detail in section 17.3: Speed). Although the design succeeded in this regard, its movement was still very weak and sometimes sluggish, and the build quality was clearly very unreliable as parts continually fell off or came loose during testing. Problems were found with the actuation mechanism, most notably was that the steel cable was hard to clamp securely at both the pulley and the fingers, as the 3D printed material was too weak for the kinds of forces necessary to actuate the fingers. In general, testing revealed the system to be very stiff yet delicate, with the servos having to generate a lot of force to overcome the friction in the tubes and joints to actuate the model.

15.1.3 Second Finger Testing Prototype

A new testing prototype was developed based on the results of the first, which proved to be a substantial improvement. The design used Tower Pro MG90s servos which are substantially smaller and weaker than the Parallax Inc Standard Servos but despite this it was found to be markedly faster, stronger and more responsive.

Figure 15.2 - Original pulley design (left) and optimised pulley design (right)

To rectify the issues with clamping, all clamping systems were altered such that the M3 bolt would clamp the cable directly on to the threaded insert at the pulleys and moving components alike. A comparison of the designs is shown in Figure 15.2. In this way, no major forces were imparted on to the 3D printed material, as all clamping tension resided between the insert and the bolt. The new pulley design also incorporated space for two cables to be clamped simultaneously. Originally, 3mm PTFE tubing had been selected to guide the cable because of its self-lubricating properties, but this was found to be very stiff and impeded motion. The steel cable was substantially stronger than required, so it was replaced for 0.32mm diameter ultra-high-molecular-weight polyethylene braided fishing line. The material is very low friction, bendable and inextensible, as well as still being far stronger than necessary. The PTFE tubing was replaced for flexible PVC tubing which may have slightly more friction, but the smaller diameter of only 1mm, increased flexibility and drastically reduced price made it a much more attractive option at this stage. Later in the project however major issues were found with this tubing.

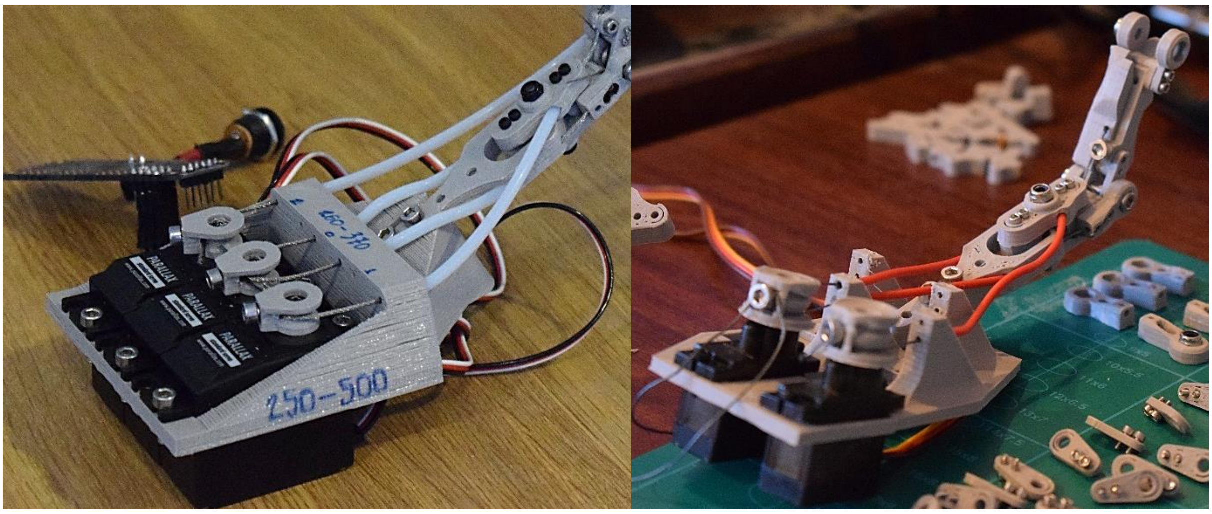


Figure 15.3 - First actuation testing platform (left) and optimised platform (right)

At the MCP joint of the finger, the clamping components were redesigned to be more compact and to have a better grip on the cable. All phalanx components were switched from a system which clamped the cable against the 3D printed material to one in which the only clamping forces were between the threaded insert and the bolt, this can be seen in Figure 15.4. Finally, the torsional springs being used were changed from roughly 20*N/mm* to around 5*N/mm*, made possible by the switch to more flexible tubing and cable. This meant that smaller servos could be used, but since the springs only serve to return the fingers back to a neutral position, this would not necessarily impact grip strength. Later, all components could be made slightly smaller due to the guide cable being 1mm rather than 3mm.

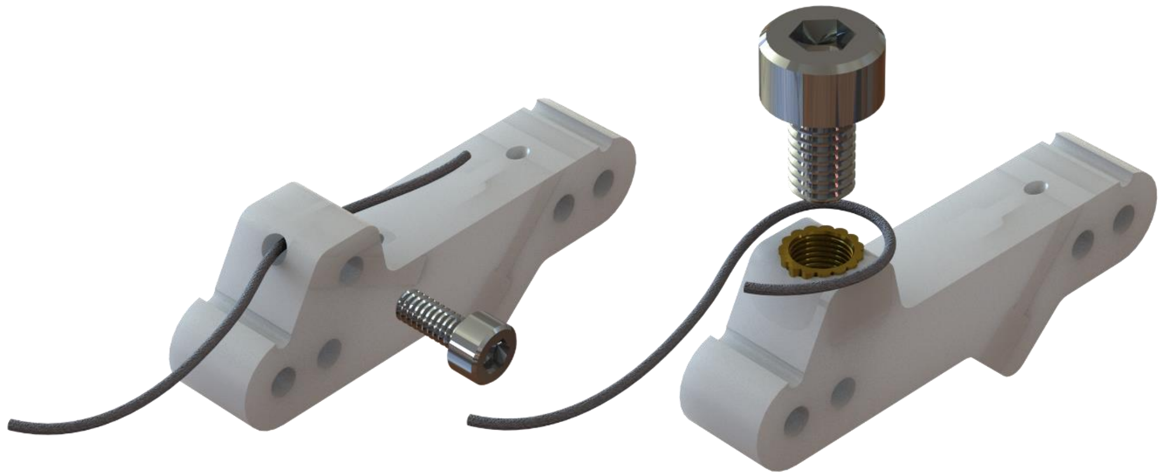


Figure 15.4 - Old master phalanx clamping system (left) and new system (right)

15.1.4 Thumb and Palm Assembly

In order to test the functions of the thumb and palm, another testing platform was developed which was based on the one used to test the finger, shown in Figure 15.6. The base of the thumb was built on to the carpal block and a makeshift servo housing was used to mount three Parallax Inc Standard Servos and pulleys. The assembly was tested using very simple code to adjust the position of each motor based on input from three potentiometers.

The lateral rotation of the thumb on the "CMC" joint was found to work excellently (although the clamping system was later redesigned in the same way as described for the master phalanx), however the piston system was not able to actuate the thumb. This is because the force imparted on the piston by the cable occurred around 15mm away from the centre of the piston, producing a moment in the piston. Because of the flexibility of the 3D printed PLA, this meant that the piston would simply flex to accommodate the pull of the cable rather than slide into the guide as intended. The fix for this was to redesign the component so that the cable would pull directly through the centre of the piston, imparting no moment on the piston itself. The design changes and a diagram of forces is shown in Figure 15.5. This design was tested and found to work as intended.

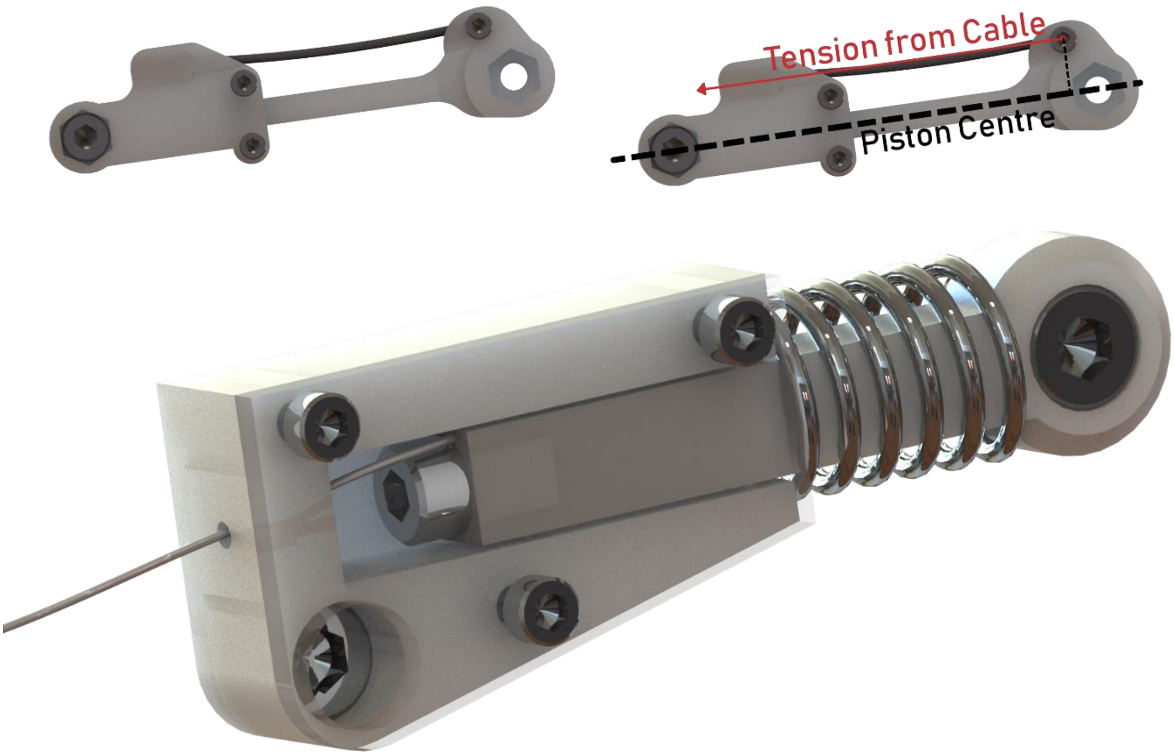


Figure 15.5 - Original piston (top left), diagram of forces (top right) and optimised piston design (bottom)

The palm movement, i.e. the deviation of the ring and little finger metacarpals from the palm's neutral position was tested using a spring and a narrow section of bicycle inner tube to return the parts to a neutral position. For the same reasons as with the thumb CMC flexion, the component did not actuate. Using the new piston design however the design was shown to work as intended.

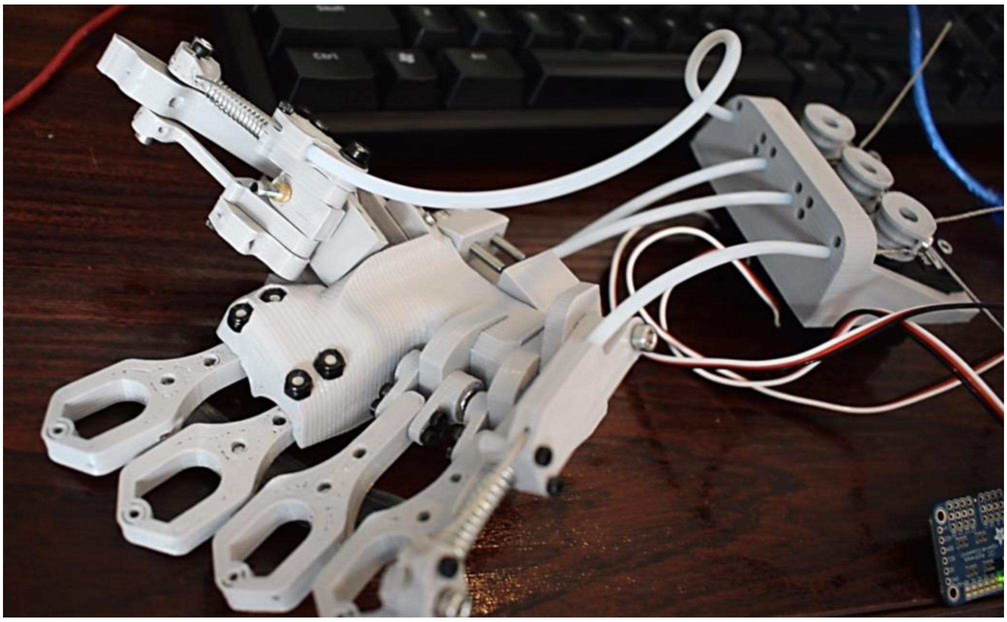


Figure 15.6 - Palm testing platform using carpal block component

15.1.5 MCP Concept Designs

Both the BHB01 and BHB02 concept designs were printed, constructed and evaluated without motor actuation. As described in section 15.1 Biomimetic Bionic Hand, both designs unfortunately were not robust enough for the types of materials available in this project. Both of these components shared the same issues in that they were simply too complex and small, and even if they did work they would be very weak. BHB01 can be seen in Figure 15.7 whereas the prototype for BHB03 was not completed due to its obvious flaws.

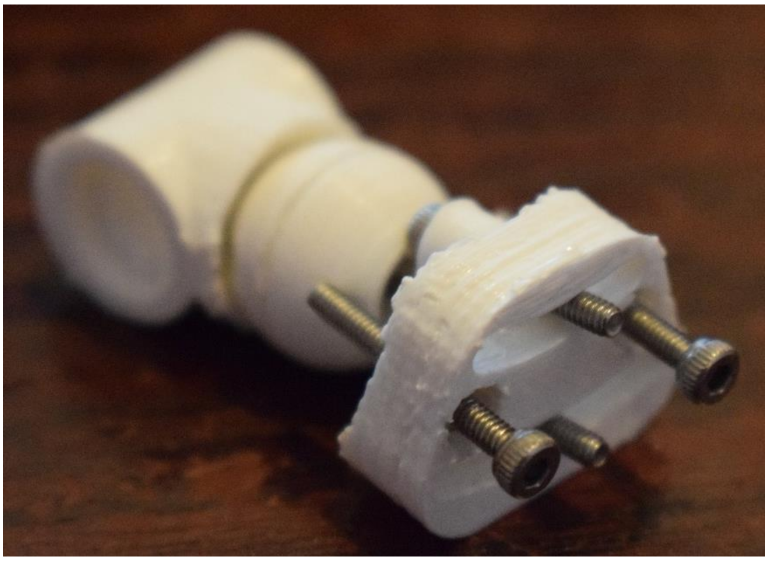


Figure 15.7 - BHB01 Prototype deemed unsuitable

15.2 Bionic Hand Master Prototyping Platform

Once the majority of issues with the various sub-assemblies had been resolved, a "forearm" structure was developed which would house all of the motors for the hand. Because of time and budget concerns, the initial forearm assembly did not feature a mechanism to rotate the arm about its base, and the structure served only to house the motors and provide a solid base for the whole assembly to rest on.

15.2.1 Wrist Mechanism

Because of concerns about the functionality and size of the **BHD02.3** wrist mechanism, the entire structure was redesigned to be more compact, this new design is shown in Figure 21.53. No major changes were made to how the mechanism would work conceptually, but many components were redesigned. One issue was that the design required two custom load-bearing rods to connect the pulleys, and 3D printed materials were not likely to be a sensible choice of material. For this reason, the components were machined from aluminium using a micro-lathe. Testing revealed this new system to work as intended.

15.2.2 Motor Housing

In order to actuate each finger, a total of 21 motors needed to be housed in the forearm, not including the 2 used in the wrist mechanism. Based solely on availability, Tower Pro MG90S servos were selected for the smaller motors and MG996R for the larger, simply because these motors were already available having no cost to the university. In a more functional prototype or final product, better quality servos may be selected. The structure consisted of two plates, one of which had guide posts for the control wires and the other was simply for support for the motors. The general outline of the plates was designed to resemble a forearm, and the motors were fitted to accommodate this shape but also to fit as closely as possible while keeping the structure strong. Because of the large size of the plates, the models had to be separated into a total of four plates to fit in the 3D printer, using small components to hold them together.

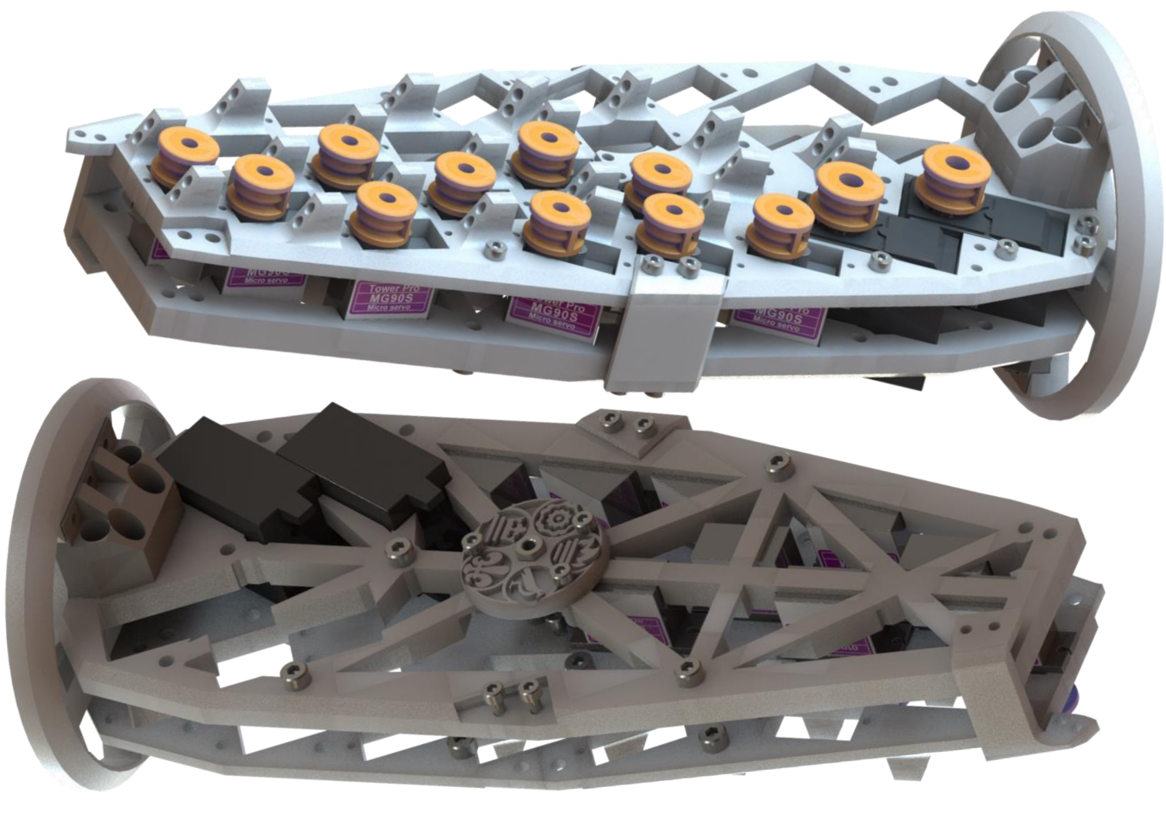


Figure 15.8 – Forearm motor housing render

The actuation mechanism consisting of a pulley and wire guide post was developed during the prototyping phase, so as a simple flat plate the forearm was not tested extensively. By inspection and simply assembling the pieces, it was very clear that the design was strong enough and suitable. The design featured a simple base which would be inadequate without a clamp holding it to the work surface, but for simple testing without the use of some of the wrist motors, the design worked well as a free-standing structure.

15.3 Control Glove

15.3.1 Prototype Construction

A prototype of the control glove was created with only one finger as can be seen in Figure 15.9 (with additional views shown in Figure 21.54), allowing some of the bionic hand prototypes to be tested with a controller. Unlike the bionic hand, prototyping of the control glove proceeded without the need for any new design iterations or sub-assembly prototypes.

Components were 3D printed using a GEEETech Prusa i3 3D printer, and a leather glove was used as the base to mount the components on. As specified in the design section, the parts were secured using nylon pop-rivets and hook and loop cable ties. Four "10kΩ Alps RK09L Series Potentiometers" were used, selected for their small size and resistance range being ideal for use with the Arduino Uno microcontroller. Jumper cables were used primarily for wiring although some contacts did require soldering.

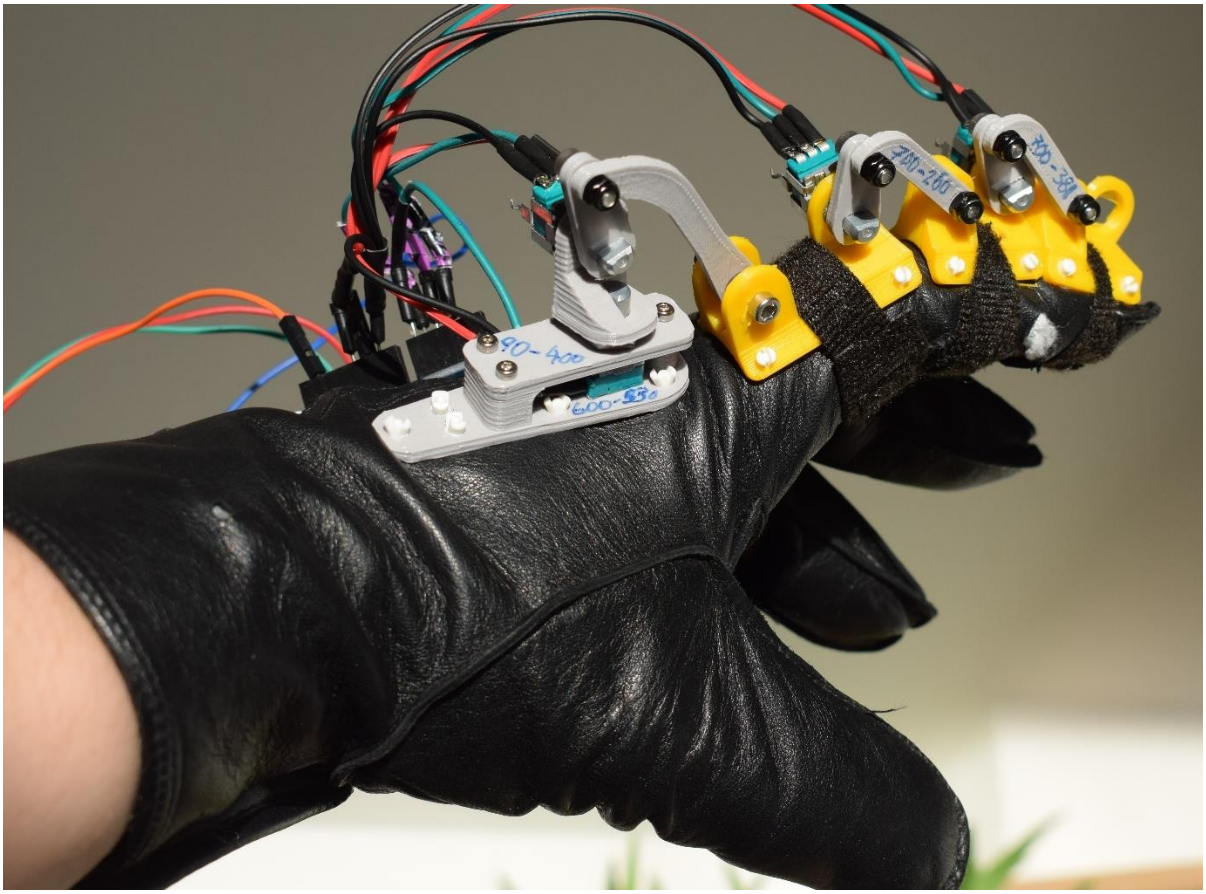


Figure 15.9 – Control glove prototype

15.3.2 Setup

When the glove was complete, a simple code was uploaded to the Arduino which measured the analogue output of the servos from 0-1023, and output this to the serial monitor in the Arduino IDE (programming is discussed in greater detail in section 15.4: Electronics and Programming). This gave important data about the range of values detected as the glove was moved through a full range of motion, which was used as the minimum and maximum values that would be used to drive the servos. The greater the range of values in each sensor, the more precise the measurement at each joint could be. Most of the sensors had a total range of around 300-400 which, while it doesn't make use of the entire range of motion in the potentiometer, does give a very large number of possible readings. Assuming an average range of motion in the finger joints of 90°, this gives a precision of 0.25°- this value does seem small enough at first but when taking into account the mechanical resistance of the potentiometers, as well as resistance in the glove itself then the true precision and accuracy would be much poorer. The lateral motion at the MCP joint only had a range of around 70 however, which ideally would need to be increased in future iterations. Across a range of motion of 30° this range would indicate a precision of around 0.4°, just over half the precision of the other joints.

15.4 Electronics and Programming

The first section of code in the prototyping section was simply to read values from the control glove and output these to the Arduino IDE serial monitor and plotter. This code simply used the "analogRead" function to read the sensors as a value between 0 and 1023, then used "Serial.print" to output this value to the Arduino IDE's built in display windows. Finally, a short delay was added to reduce the chance of errors. This code can be seen in Figure 21.55.

The other test involved using the glove as a controller for the prototype finger, with 3 active servos mimicking the position of the potentiometers. An Adafruit 16-channel 12-bit PWM driver was used to supply power to the servos, connected to the Arduino using the I^2C protocol. The program firstly defined the limits for the servos in terms of pulse length. Different values had to be tested in order to calibrate the servos, otherwise the motor could move past the physical end-stop and damage the mechanism. Some other setup was required including the frequency of servo updates and other lines of code for the driver board, although much of this was copied from the examples provided with the board.

The actual looping section of the code took analogue readings of the servos in the same way as previously, then used the "map" function to map the values from a range as calculated in the previous section for each sensor, on to a range specifically for the ROM needed in each servo. In some cases, it was necessary to invert the range, because of differences in the direction of rotation of the servo or potentiometer – for example the potentiometer at one joint may rotate clockwise while the servo counterpart may need to rotate counter-clockwise.

Finally, the "set.PWM" command was used to actuate the servos. The looping section of the code can be seen in Figure 21.56.

16 Bionic Hand Full Prototype Construction

At this stage in the project, most issues with the design had been rectified, and the next step was to build a full-scale model, Figure 21.57 shows a mock-up of the final model rendered in SOLIDWORKS. The structure was printed using PLA filament on a GEEETech Prusa i3 3D printer, mainly due to budget and time constraints. In order to isolate issues within the prototype and to reduce the amount of compressible guide cable that would be used the wrist mechanism was disabled, such that the hand was permanantely in an extended position. Also, some panels on the palm were removed to facilitate quick modifications. One angle of the prototype can be seen in Figure 16.1, and many more views can be seen in Figure 21.58 to Figure 21.63.

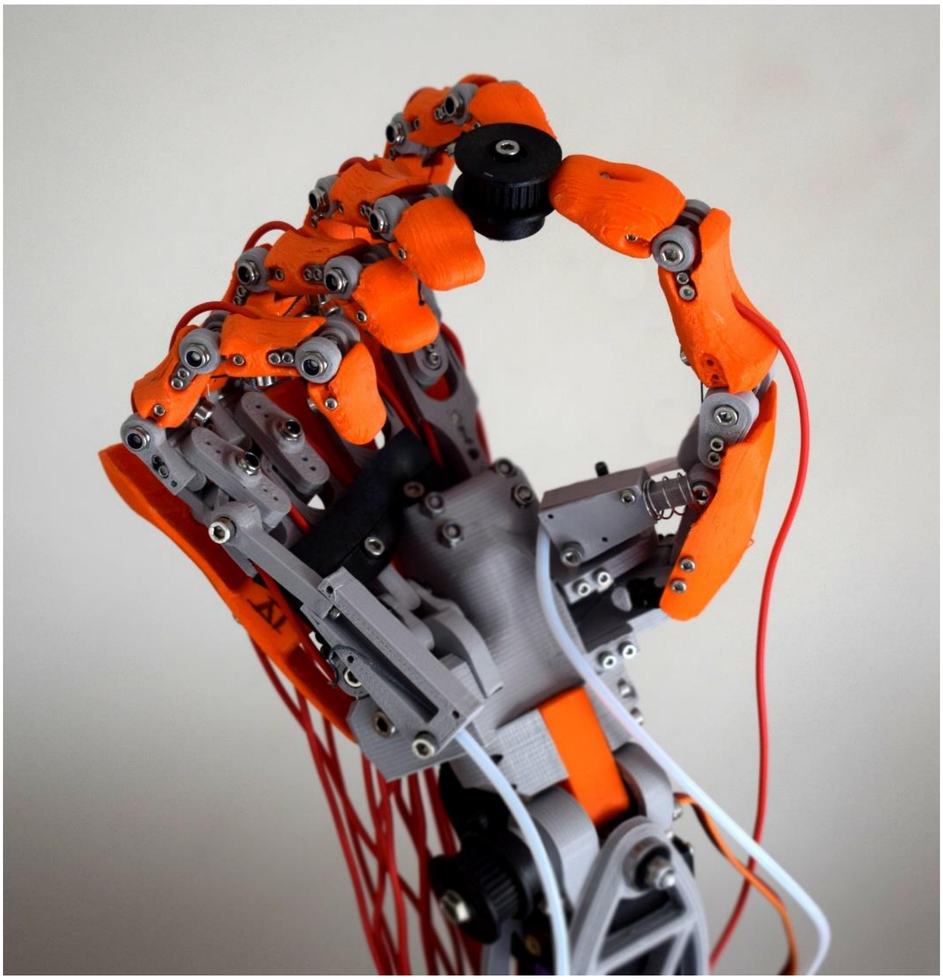


Figure 16.1 - Full prototype using "tripod" grip type photograph

Most of the construction was straight-forward, although the majority of the components required a large amount of post-processing after printing. The "brim" used to adhere components to the print bed during printing had to be carefully removed for every component to allow smooth motion, and since the assembly contained over 200 printed parts this process was extremely time consuming. This high component count was chosen so that simpler, single plane extruded shapes could be printed greatly reducing the need for support structures on moving parts (grey in Figure 16.1) thereby reducing friction. Support structures used for abstract shapes such as the shell components were plentiful however in areas that required a close-tolerance fit and these had to be carefully removed.

One component not accounted for in the CAD design was the elastic material connecting the third and fourth metacarpals. In the prototype a section of a bicycle inner-tube was used as a cheap and available elastic section, but a better alternative may have been a very thin piece of spring steel or nylon, since these materials could be used to more effectively apply a force pushing the last metacarpals back to a neutral position, removing the need for a spring on the palm flexion piston.

During the construction of the prototype, a few issues were found that were not apparent with the smaller-scale prototypes. The first was that the PVC guide tubing used (red tubes in Figure 16.1) was found to be too compressible at longer lengths. Because of the small scale of the early prototypes this did not appear to be an issue early on. Ideally, incompressible PTFE tubing would be used (at a smaller diameter than the 3mm tubing used earlier in the project for greater flexibility), as it was found that its stiffness was less restrictive to movement at longer lengths. Another alternative would be spring guide wire, but both of these materials are expensive and difficult to source.

Another major issue with the prototype was that some torsion springs, particularly those in the MCP joints were not strong enough to return the phalanges to a neutral position. This is because, although the springs appeared adequate during testing, other forces were not accounted for such as the interaction with other fingers and the guide wire as well as the wrist angle changing. Unfortunately, the small torsional springs needed were not available to buy in quantities under 30 from any supplier, meaning that buying different springs would have quickly exceeded the budget of the project. It also may have been necessary to use stronger servos to account for the increased resistance of the springs. For these reasons some of the joints on the prototype were sluggish in extension.

A final overlooked feature of the assembly was how the pulleys would attach to the servos. In standard nylon servo horns, a complex star shape with around 25 points holds the horn with a pressure fit (and sometimes a bolt) and facilitates the transfer of torque. This star shape would have been difficult for the printer to make because it was so small, so instead a form was made from part of a broken servo, and the star shape was made by pressing this form into an undersized hole printed in the pulley by using pliers. The result was a tight pressure fit that did not require a bolt, meaning its angle could be quickly changed on the servo.

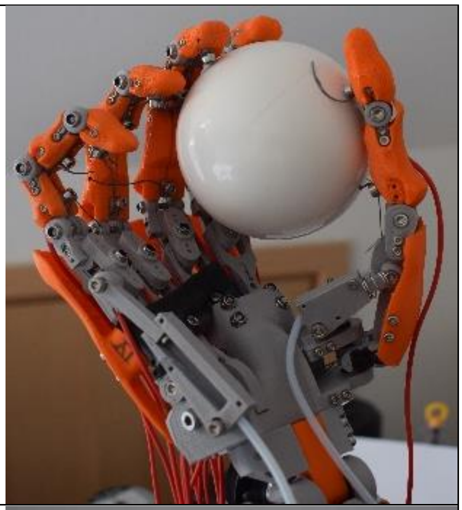
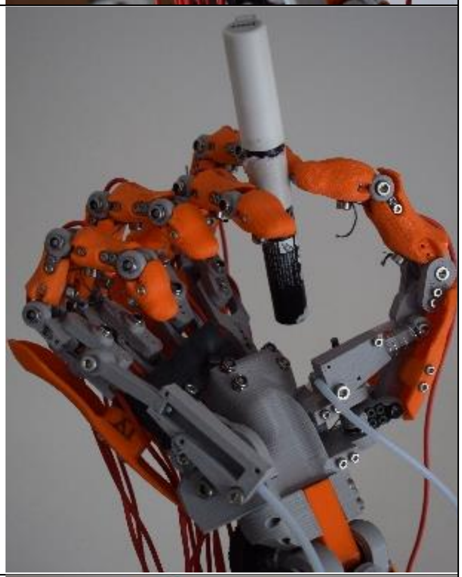
17 Bionic Hand Evaluation

17.1 Basic Grip Types

Without the use of the control glove, the bionic hand could be mechanically evaluated in terms of the kinds of grip types it could perform by manually positioning each joint, either by hand or using a simple Arduino circuit with a potentiometer. According to the abstract objects section of the SHAP (Southampton Hand Assessment Procedure), and as described by Chappell (2016), grip types necessary for a functional hand are:

- Sphere – fingers clasped around a large sphere held in the palm
- Tripod – using the thumb, index and middle finger to hold an object such as a pen
- Power – holding a bar with all fingers against the palm, thumb on top of fingers
- Lateral – using the thumb to support a small object such as a key against the first finger
- Tip – holding an object between the tips of the thumb and first finger
- Extension – holding a flat object such as a book with all fingers straight.

The hand was manually placed into each of these positions as described above, a table of the results is shown in Figure 17.1, while several alternative views can be seen in Figure 21.64 to Figure 21.70. It is important to note that this test evaluated mechanical range of motion only, not strength or speed, therefore the objects used should be viewed only as a visual aid to evaluate the ability of the hand.

Sphere		
Tripod		
Power		

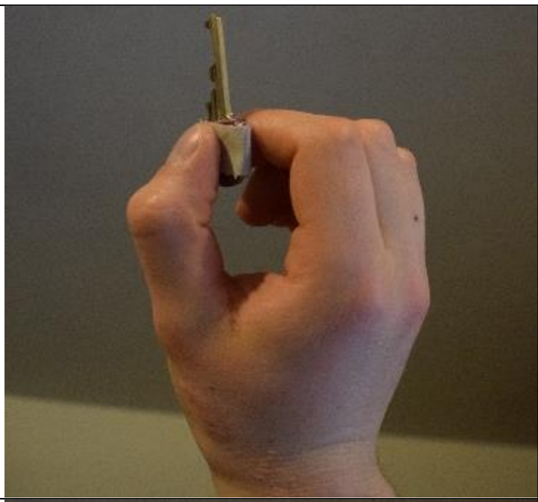
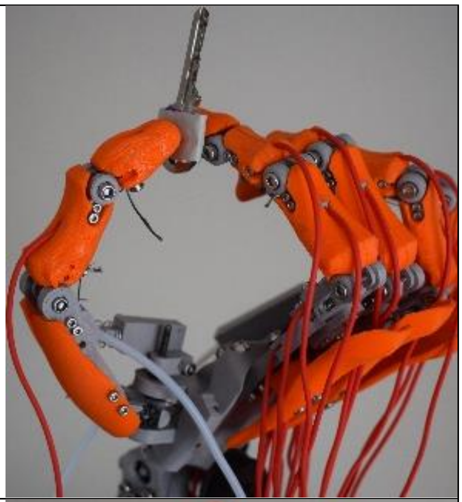
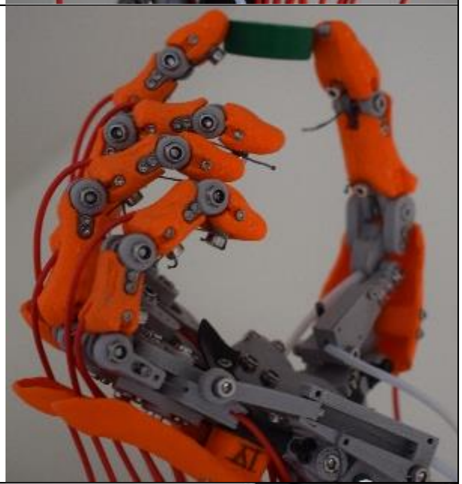
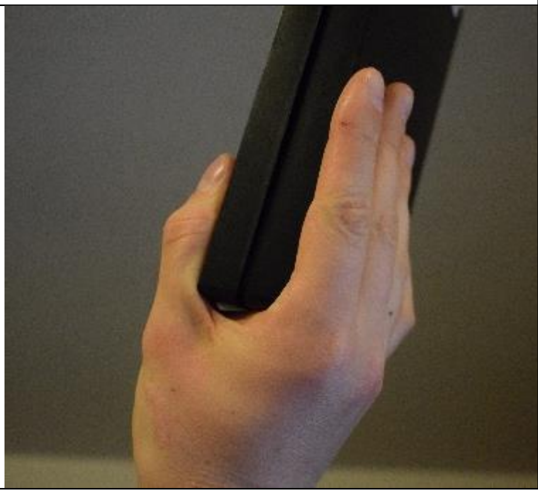
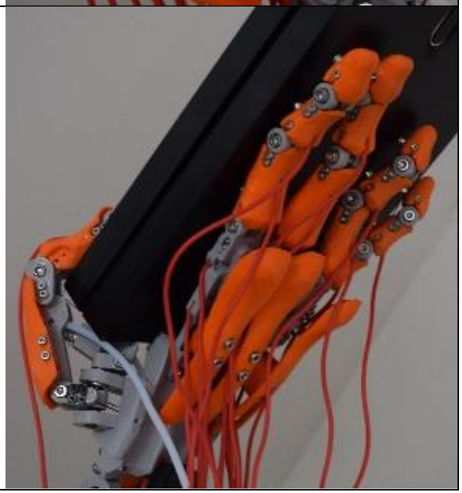
Lateral		
Tip		
Extension		

Figure 17.1 - Grip types test results

17.1.1 Sphere

The sphere grip type was relatively easy for the prototype to perform. Due to the omission of palm shell components, the hand did not have as much as a secure base for the sphere to rest on as a person would, but this did not hinder it substantially. The palm flexion of the final model should have been a very important factor in making the hand grip the sphere as intimately as possible, but unfortunately the mechanism had a lot of resistance meaning the servo could not hold its position. As discussed previously, one major factor was likely the use of bicycle inner tube which appeared to produce more direct resistance to the motor than was actually useful in returning the joint to a neutral position. In future design iterations this mechanism should use a different material such as nylon or spring steel, and the piston mechanism should be made stronger to cope with the high stress needed to actuate the section.

One other concern highlighted by this test is the size of the hand. In Figure 17.1 it can clearly be seen that the bionic hand appears much larger than the reference hand using the sphere as a point of reference. During the hand's design, each phalanx was made to be the exact same size as a real reference hand, but the design of the carpal section appears to be larger than necessary. Another factor contributing to the size difference is the omission of shell components around the base of the thumb, which do reduce the apparent scale of the hand in the rendered images.

17.1.2 Tripod

The tripod grip was more difficult for the hand to perform, one major issue being the total lack of friction between the pen and fingertips. This problem was anticipated previously, with the best course of action being to print fingertip shell components in a flexible filament such as TPU, but since the first prototype had to perform within a tight budget and timeframe double sided tape was used to increase the friction between surfaces. Care was taken to ensure the fingers weren't simply stuck to the tape, but since this test did not evaluate strength but simply mechanical range of motion, the important factor is the position of the fingers and the pen is simply a prop to illustrate this.

The fingers did have some trouble moving close enough together, this is in large part due to the simplification made earlier in the project to make the MCP joint a simple double-axis hinge rather than the complex 3-axis condyloid joint it aims to emulate. In a real hand, the structure of the joint means that fingers can more easily twist to oppose one another, whereas the bionic hand struggled with this task. Using a pen of around 15mm diameter worked fine, but smaller objects could not be held in this position.

17.1.3 Power

The power grip was relatively easy for the hand to perform, but one major issue was that the lack of shell components around the base of the thumb did not provide a solid base for the bar. In a human hand, the thumb's metacarpal is "buried" under a layer of muscle, with skin connecting the MCP joint of the thumb to the MCP of the first finger. The bionic hand was missing the shell component which would emulate this skin/muscle structure, due to a last-minute redesign of the thumb piston, so the bar was resting too far down on the thumb. This issue could be fixed simply by redesigning the shell section and including it in the test.

17.1.4 Lateral

The lateral grip type was difficult for the hand to perform, but it still succeeded. As with the tripod grip, the simplification of the MCP joint of the thumb from a complex saddle joint to a simple double-axis hinge meant that the range of motion was greatly decreased. Especially with the thumb, this additional range of motion is very important in a human hand to perform a variety of grip types. The thumb was able to brace the key against the first finger, but it could only do so on the distal phalanx of the finger, not on the middle phalanx as would be most comfortable for a person. Changing the angle of the thumb CMC joint on the carpal block could fix this problem, or even converting it into a second hinge (although this solution would seriously increase the complexity of the model).

17.1.5 Tip

The tip grip type was very easy for the hand to perform, and although no double-sided tape was necessary in this test the only improvement would be to use a grippier material for the fingertips as discussed previously.

17.1.6 Extension

The hand performed this test well using a 35mm thick box, but had the shape been much smaller than this it would have been more difficult for the hand to hold. The only limiting factor for this test was the flexion limit of the thumb's CMC joint, i.e., the thumb couldn't get any closer to the palm because of the mechanical limits of the piston. This problem could be fixed simply by extending the range of motion in the thumb's piston, although care would need to be taken to ensure this did not interfere with the carpal block on which the thumb was mounted.

17.2 Range of Motion

Using the research compiled in section 2: Functional Anatomy and Biomechanics of the Human Hand, and in particular the range of motion diagrams in Figure 21.2 to Figure 21.10, the bionic hand's range of motion was evaluated for each joint type and compared to real human values. This was performed by examination of photos and use of the photo editing software "GIMP 2" to find an angle for each joint. This method gave fairly rough results but the data was enough to critically evaluate the hand's ROM. As with the compilation of motion range parameters, information from "Hand and Wrist Anatomy and Biomechanics" Hirt et al (2017), and empirical observations of the primary operator's own hand were used where data was lacking or gave a range of values.

Joint Type/Function	ROM in Real Hand (°)	ROM in Bionic Hand (°)
Thumb MCP, (lateral)	30	0
Thumb MCP (flexion, extension)	80, 0	90, 10
Thumb IP (flexion, extension)	90, 80	90, 0
Thumb CMC (flexion)	20	20
Thumb CMC (lateral)	80	70
Finger MCP (flexion, extension)	90, 40	90, 0
Finger PIP (flexion, extension)	130, 0	90, 10
Finger DIP (flexion, extension)	90, 30	90, 10
Finger MCP, (lateral)	30	30

Palm metacarpal (flexion)	30	40
Wrist (lateral)	65	80
Wrist (flexion, extension)	80, 70	50, 50

Figure 17.2 – ROM data for real hands and the full prototype bionic hand

The results show that, in general, the bionic hand is capable of similar ranges of motion as real hands. In flexion, the bionic hand hit almost every target, and is actually hyper-mobile in extension in some joints. Joints which had more mobility than real hands were not of great concern because limits could be defined in the software that would prevent this. Some joints did fall short on extension however, which is not particularly important since almost all actions performed with the hands are in flexion relative to the neutral position. Joints in extension couldn't be more than a few degrees past the neutral position because the control wire would have a poor mechanical advantage and may be unable to pull the joint back into flexion. This issue could have been solved by integrating a small guide pulley at the finger joints to increase mechanical advantage.

Another important result of this test shows that the range of motion in the thumb about the CMC joint was actually a great enough angle, but the problem that caused the hand to perform poorly on the extension grip type test was simply that the range was set to far away from the palm. This problem would be easier to resolve, simply by making the piston slightly shorter. Finally, a major limiting factor in the lateral grip type test was the fact that the bionic hand lacked a mechanism to laterally rotate the thumb about the MCP joint. This simplification was largely down to concerns about how this joint could be measured on the control glove, but simply altering the range of motion boundaries for the CMC joint should make the hand able to perform more favorably in the lateral grip type test.

17.3 Strength

The strength of the bionic hand was not tested extensively due to fact that the full prototype would have been difficult to assess without being 100% functional and operated by a full control glove, but also because strength was mostly limited by the servos and power supply, therefore budget. Grip type testing did reveal the hand to be perfectly capable of supporting a range of objects statically with the servos turned off i.e., objects were supported only by mechanical friction in the gears of the servo and tension in the control wire. With all servos turned on and operational, and improvements such as having a more suitable grip surface at the finger tips, the hand would no doubt be much stronger and capable of supporting heavier still objects.

17.4 Speed

Once again, a serious limiting factor of speed would be budget because of the importance of servo choice as well as the power supply, but since the time taken to contract was an important element as laid out in the PDS, the speed was tested. Through analysis of video footage of the prototypes in which the glove was used as a controller, the time taken to fully contract a single finger from a neutral position to full flexion was roughly 0.46 seconds (14 frames with a 30*fps* video file). This value is under the 0.5

second target defined in the PDS and substantially less than the target proposed by Chappell (2016) of 1 second. This time includes the delay between the control glove (and human hand) performing the action and the bionic finger mimicking the motion.

This test was performed with the first finger prototype, and although the second prototype had a wide range of improvements the speed did not appear to increase substantially due to the limits of the servos used.

17.5 Build Quality

A number of minor issues exist with the function of the bionic hand and are discussed in their respective sections. As far as the build quality as it relates to reliability and robustness etc the bionic hand is well-built. All parts fit together well without the need for a large amount of post-processing, largely due to the simplicity of shapes in the components making them ideal for printing on basic machines. Friction between moving parts is mostly very low because, where possible, surfaces that would come into contact with each other were printed face down in the 3D printer, meaning these surfaces are effectively as smooth as the glass of the print bed.

17.6 Summary

Starting in the wrist, the design permits movement in two axes – laterally (from side to side) and in flexion/extension. A true wrist is also capable of supination and pronation (twisting), but the bionic hand did not include this feature due to time and budget constraints. Both of these mechanisms were tested with the full hand attached and found to function as intended, but the final prototype had a fixed wrist in order to reduce the amount of compressible guide cable that would be used. The total range of motion in the wrist was slightly under reference values for flexion and extension, and hypermobile in lateral movement, but these ranges of motion would be high enough for most users. Since wrist flexibility can be made up for at the elbow or shoulder, and variation in wrist flexibility amongst people is very high, the wrist mechanism was deemed perfectly suitable for the bionic hand.

The thumb in a real hand consists of a very complex CMC saddle joint at the base, giving it 5 total degrees of freedom when factoring in the movement of the thumb's phalanges. The bionic hand has a slightly simplified design with 4 DOF but this was shown to be adequate for all mechanical grip functionality testing. One drawback to the design however was that the piston design did restrict the thumb's flexion about the CMC joint somewhat, this was apparent in the "extension" grip type wherein the hand struggled to hold thin box shapes. The actual range of motion in degrees was in fact good enough, however the boundaries of the range were set at too great an angle from the palm. In future iterations of the design this mechanism could easily be redesigned to have a range of motion shifted closer to the palm.

The bionic hand's palm is capable of flexing via the movement of the ring and middle metacarpals. As mentioned in the "sphere" grip type assessment, this functionality allows the hand to grasp some objects more intimately by wrapping the palm around them. This mechanism was proven to work, and the ROM was adequate although shortcomings in the construction and material choice of the final prototype meant that the performance was disappointing. This functionality is very important in setting this project apart from other similar ones, but by altering the mechanism slightly and using better materials the mechanism could be greatly improved.

The fingers have 4 DOF each – two simple hinges and a more complex 2-axis hinge at the base (MCP joint). Originally the MCP had been intended to twist inwards as it moved from side to side. This functionality is useful in real hands whenever fingers need to directly oppose one another, such as the "tripod" grip type in which the index and middle fingers must meet at a point. Another drawback of the full prototype's design was the choice of material because the PLA shell on the fingertips was far too low-friction to grasp some smooth objects. Either by using an entirely TPU printed fingertip or alternatively printing the part in two different materials using a dual extruder printer, the hand would have enough friction to hold smooth objects. Overall, the fingers of the bionic hand work well and were shown to be capable of several unique grip types as defined by the Southampton Hand Assessment Procedure. Speed was tested in the fingers despite the fact that the main limiting factor in speed and strength was budget, and it was found that the mechanism could fully contract in under half a second, including electronic delay from the controller. This movement speed was excellent considering the time proposed by Chappell (2016) was 1 second, based on research with people using prosthetic hands.

The actuation system consists almost entirely of servos attached to pulleys which actuate joints remotely using a cable and sheathe system similar to brake cable in bicycles. Various methods are used to return the joints to a neutral position including compression springs, torsional springs integrated into the centre of the pivot point and elastic materials. Overall, the actuation concept does appear to work well but a more suitable guide cable should be selected which cannot be compressed. Ideal materials may be PTFE tubing similar to what was used in early prototyping but much thinner and more flexible, or spring wire housing. PTFE would likely be more rigid in this context than spring wire housing and could still be compressed, but it would be lighter. Spring wire housing would be totally incompressible but may be heavier and is substantially harder to source. In addition, several of the springs and elastic materials are either too strong or too weak for the joint they actuate, mainly due to unforeseen sources of resistance along the chain of subsystems involved in actuating the hand.

Finally, there are a number of small problems with the design that could be fixed easily in future design iterations. These include:

- Some shell components obstruct each other, the guide cables or other moving parts. Simply changing their shape would fix this problem.
- Some bolts fixing the actuation cable in position protrude too far and prevent ideal biomimetic motion. These parts could be changed for more low-profile bolt-

types or the design of the phalanxes could be changed to clamp the cable closer to the centre.

- Bolts acting as pivot points in the fingers were too short to reach the nylon portion of the nyloc bolts, meaning that they are prone to loosening. This problem came from small errors in 3D printing building up over several components until some joints ended up with a very poor tolerance. Printing with greater precision should fix this issue, in addition the fingers could be designed to be more compact.
- The finger joints all have slightly too much resistance than would be ideal, making the 3D printed surfaces which come into contact with each other smaller may reduce this friction.
- With regards to the actual building of the model, the number of components in the design vastly increases assembly time and somewhat increases the model's weight due to the greater number of fasteners necessary. Although this design was chosen to enable 3D printed parts high quality even on very basic machines, some compromise should be struck between this feature, weight and construction time.
- Routing of the guide cables could be neater – although no pulleys were found to be getting stuck, having built-in channels would reduce the likelihood of this happening
- Axels used in the wrist assembly were poor quality, so future components should be machined with greater care and attention to detail.
- Bolts used as pivot points in the fingers should ideally be unthreaded bars where moving parts have to pivot on them, because the threaded stainless steel against printed PLA results in some unwanted friction.
- MCP joint of the ring and little finger should be offset more to the outside of the palm, so that fingers can splay further. Actual ROM in these joints is adequate, but the end points should be shifted out.

Using all suggested improvements, a table was created to list each issue categorised by sub-system to make future redesigns easier. This table is shown in Figure 21.71

18.1

18 Control Glove Evaluation

Mechanical Summary

A full prototype was not built for the control glove, due to time and budget constraints. However, the prototype which was based on a single finger proved that the design could measure up to two axes of rotation about a single joint – the maximum which would be required at any point in the bionic hand.

The control glove took readings using a small potentiometer mounted adjacent to each joint (in the middle of each finger segment) using two bars suspended over the joint in order to avoid obstructing the motion in the wearer's hand. For joints such as the MCP of the fingers, two potentiometers were mounted one on top of the other, allowing side-to-side motion as well as flexion and extension. This design was found to limit the precision of the lateral potentiometers, but despite this all potentiometers had an acceptable precision.

The build quality of the design as far as the actual 3D printed mechanisms was found to be very robust, as no issues were found with the design throughout the prototyping and testing process. There was however a major issue with the choice of base glove – the leather glove restricted motion too much and also prevented the nylon rivets from properly engaging. Although this issue was a major limiting factor, using a cotton or thin synthetic fabric glove should markedly improve the design, so long as the material chosen does not stretch substantially.

18.1.1 Testing

In use, the glove was found to be relatively comfortable, although the leather did appear to severely restrict motion and prevent the rivets from fully engaging. In future iterations, a thinner material should be used but care should be taken to choose a glove than does not deform substantially, otherwise readings will be inaccurate. The actual construction appeared very robust other than the issue with the rivets, and no mechanical issues were encountered with the glove at any time.

In general, the glove appeared to function excellently as no substantial problems were found with its functionality. Using the serial plotter, each sensor was tested individually by visual inspection of the response curve as the glove was moved through a range of motion. A smooth curve indicated a reliable signal and the height of each oscillation could be used to verify that the readings were accurate and repeatable. Figure 18.1 shows an example of the response curves with all potentiometers plotting a curve simultaneously.

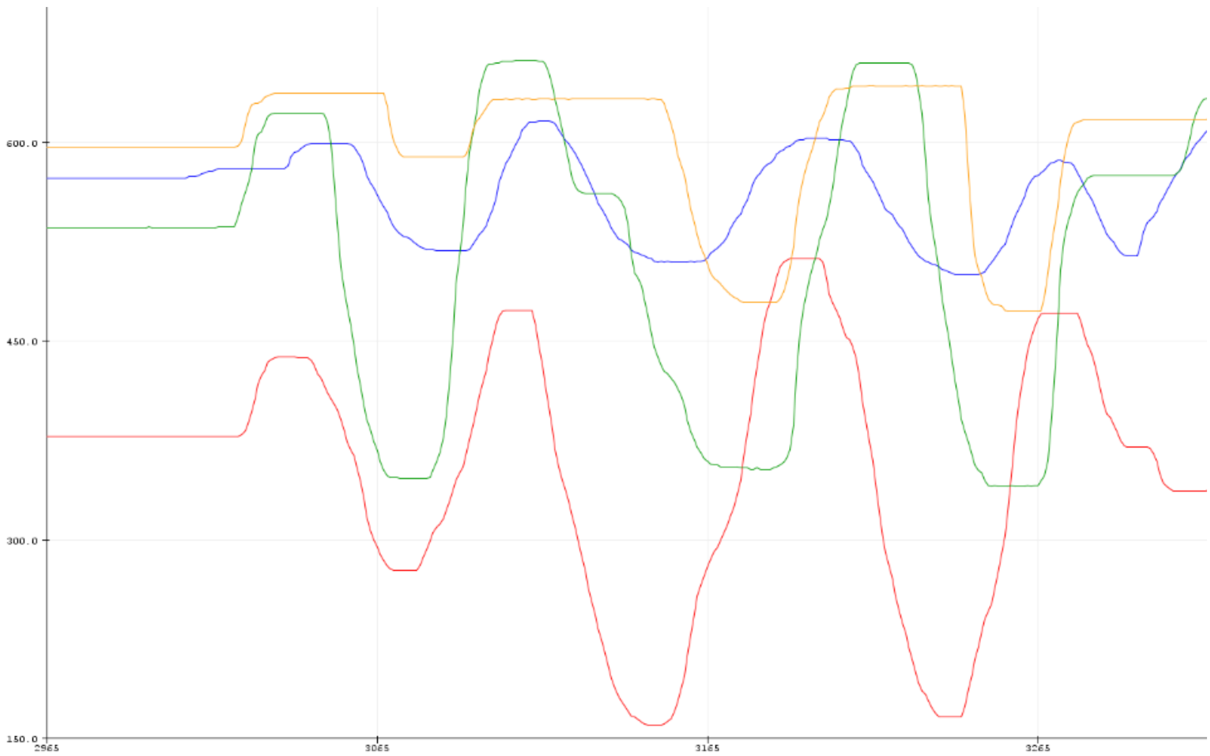


Figure 18.1 - Responses of all four potentiometers simultaneously in Arduino IDE serial plotter

One issue highlighted by the graph is that the curves appear to flatten out at either extreme of their motion. This was due to friction in the potentiometers which prevented them from turning at some positions, because the movement was "made up for" by slight deformations in the leather glove. The solution to this issue would be to use smoother potentiometers, a design that produces a greater moment at the potentiometer or a design that attaches the finger segments more firmly to the user's hand.

The glove was tested using the first single-finger prototype before improvements had been made. Despite the poorer quality finger design the glove was shown to work very reliably. At this stage the fingertip had not been integrated into the prototype but based on analysis of the response curves prior to this experiment, the sensor did appear to function well. Videos were recorded as the parts were tested, wherein it can be seen that the bionic finger is the major limiting factor with the glove functioning very well.

18.2 Precision and Accuracy

Through simple inspection of the motion path of the bionic finger prototype during testing, the glove did appear to give reliable and accurate readings. A more in-depth analysis using the Arduino IDE serial plotter found the curves generated from each potentiometer to be smooth and repeatable, indicating low noise (either from mechanical issues like friction in the mechanism or electrical interference) and accuracy.

Using data about the range of motion in each joint of a real hand as well as the range of values received from each potentiometer, the precision at each sensor was found to be around 0.2° – 0.4°. This value cannot be considered completely accurate however, since there exists a certain amount of flexibility within the assembly and friction in the potentiometers which means that a certain threshold of force must be reached before the potentiometer moves. Measuring the true precision would be very difficult because the glove would either need to be taken out of context of a human hand to be moved by a machine with a known change in angle, or a perfectly accurate way to measure the hand’s movement would need to be used for comparison.

19 Conclusion

The objective of the project was to design and build a biomimetic bionic hand, capable of greater ranges of motion, increased response time and, in general, motion that more closely imitates real human motion relative to most prosthetic hands currently in use. Alongside the development of the hand, a glove was to be developed which would showcase the movement of the hand by taking measurements of a real hand and, through the use of a microcontroller, driving the bionic hand to imitate these positions and motions.

At the start of the project, the anatomy and biomechanics of real hands were analysed in depth to establish a list of kinetic requirements such as range of motion, degrees of freedom and speed. In particular the Southampton Hand Assessment Procedure (SHAP) was researched as a way to evaluate the function of hands including bionic ones.

Limitations on the project including time, budget and mitigating circumstances meant that the bionic hand was never fully completed to a point where the entire model could be controlled from a control glove, but a full model was constructed, and all motors were electronically tested. Through mechanical analysis of the hand as a whole and isolated electronic tests of all subsystems, the bionic hand has a plethora of evidence that the design is suitable and meets the targets set out at the start of the project. Using a prototype glove controller, the fingers of the hand were found to move fluidly, quickly and with high dexterity. All other joint types in the design including the palm, thumb and wrist were tested individually and found to perform as intended, although some tweaks would be necessary to optimise the design.

The bionic hand was shown to be capable of all grip types described in the abstract shapes section of the SHAP and had similar ranges of motion in each joint as with real human hands. The hand was shown, in a simplified test including one finger, to be capable of contracting in half the time proposed by Chappell (2016) as an ideal target for people using prosthetic limbs including the electronic delay from the controller to the actual movement.

The control glove also could not be fully constructed by the end of the project, but a working prototype proved that a suitable design had been tested for both single axis hinge joints and dual axis joints that would not obstruct the motion of the user's hand. The prototype was tested alongside prototypes of single finger sub-assemblies from the bionic hand, and testing showed that the glove could accurately measure detailed fluid movements from a user's hand and use these to control the mechanism, with minimal electronic delay.

With the findings from this project, the foundations have been laid for a unique, powerful and ultimately biomimetic bionic hand concept to potentially replace the simplified designs currently being employed in prosthetic hands if myoelectric technology can advance sufficiently. In addition, through the design of a precise and dextrous control glove, an effective design has been developed for an affordable and high-precision telepresence robotics system. This design could greatly enhance current methods of hazardous materials handling, telepresence robotics and general robotic control.

19.1 Future Work

Beyond the end of this project, clearly the designs should be fully constructed and tested as thoroughly as possible. In the short term this should be achievable quickly and easily, since the full prototype of the bionic hand should only require a few replacement parts and electronic configuration to be fully operational, and the control glove also needs no major design changes to work fully.

Ideally however, the designs could be re-built from the ground up as the documentation provided in this report gives a clear list of necessary improvements to the design. In particular the table shown in Figure 21.71 provides an excellent summary of changes that would need to be made. The simple design and optimisation for 3D printers in the components means that future work will be easy and affordable with little more than a simple FDM 3D printer necessary for most construction work. In this way, there is potential for continued, collaborative efforts from anyone to further develop the designs.

In the longer term, once the design is well-established and robust, the bionic hand could be viable for prosthetic applications. From the start of the project the intention was to sidestep the limitations of myoelectric technology, but even with these limitations the bionic hand could still be useful as a replacement hand. Although currently it would not be possible to control the hand as intuitively as one controls their own hand, the use of pre-programmed movement sequences and grip patterns may mean that the design is useful for a far greater range of activities than the simple prosthetics used today. This may require the use of physical buttons to be pressed by the working hand or other unique control methods, but ideally myoelectric technology or perhaps even EEG could progress to a point where bionic hands can be used just as easily as real hands.

The design could also be used in situations where fine control is needed but a human cannot be physically present. With hazardous materials handling such a high degree of dexterity would not normally be necessary, but if the design can be made robust and affordable enough then there is no reason why a more dextrous robotic hand wouldn't be better than a simplified one. Conversely, in the world of telepresence robotics wherein the idea is to make the user feel as physically present as possible to themselves and observers of the robot, biomimicry is absolutely the primary concern and this concept would be ideal. If even more biomimicry is desired, a silicone jacket could be made for the hand such that it appears fully lifelike.

Building on the design, there is much potential for additional features to be added. For example, sensors could be integrated into the bionic hand and actuators into the control glove to give haptic feedback, increasing the immersion of the user by orders of magnitude. An alternate application of the design could be use of the control glove as a controller for virtual reality.

Clearly a great deal has been covered in this project, but the potential for future work is virtually limitless. The first priority of this work however must be to build a fully functional model, which can then be built upon.

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21 Appendix

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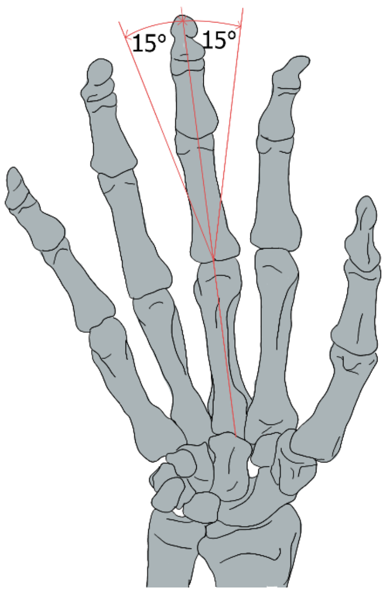


Figure 21.1 – Range of lateral motion in finger MCP

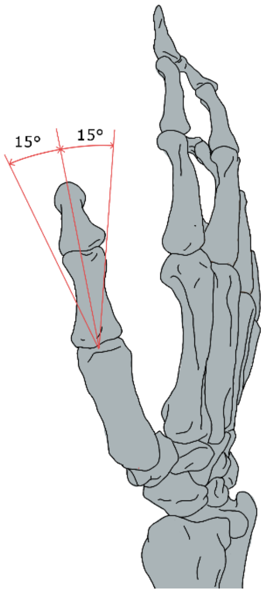


Figure 21.2 Range of motion in thumb MCP joint

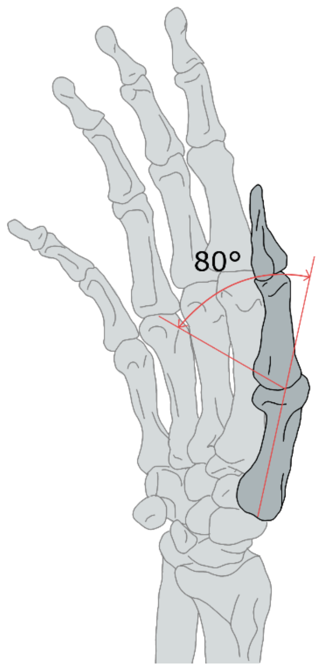
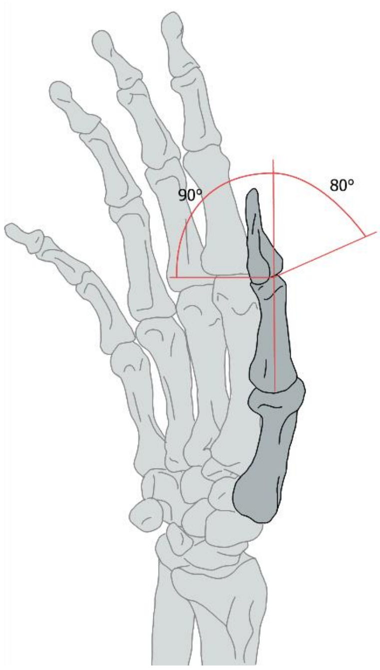


Figure 21.3 – Flexion/extension in thumb MCP joint



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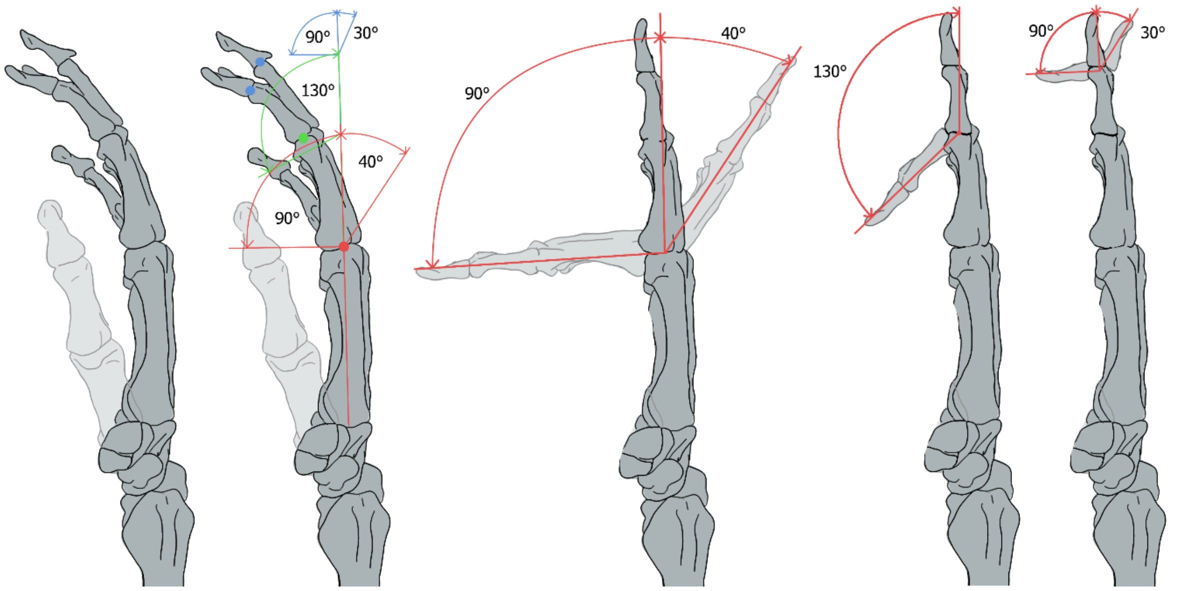

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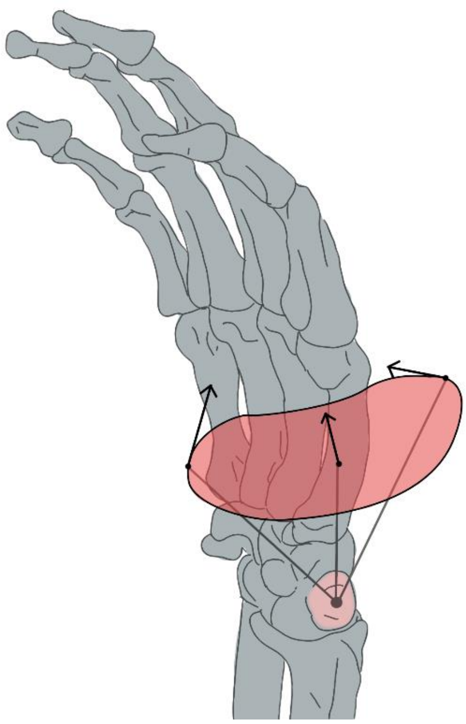

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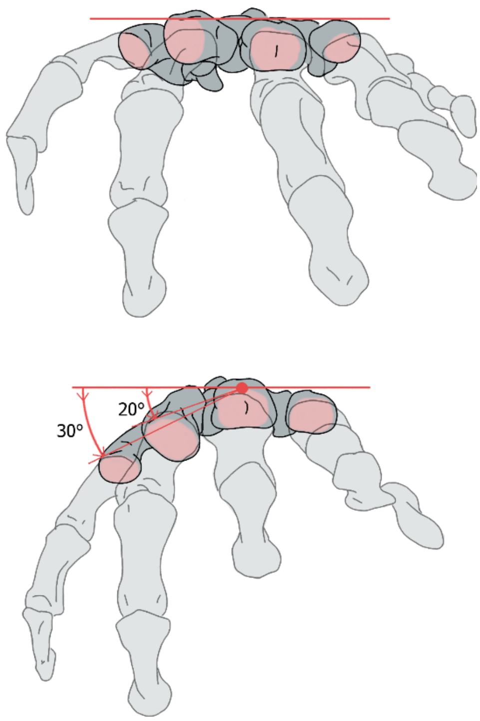

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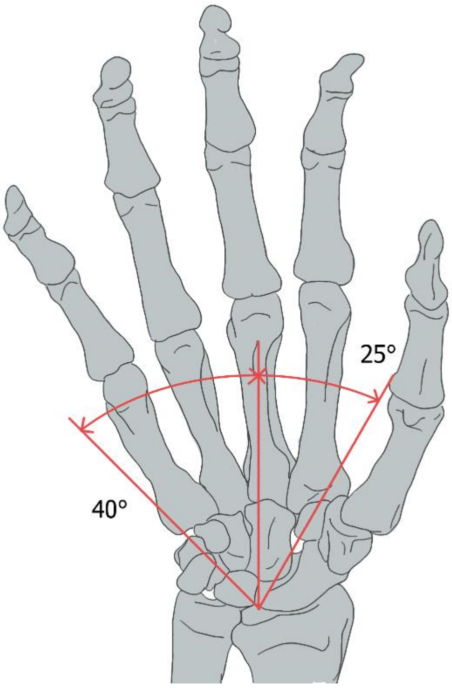

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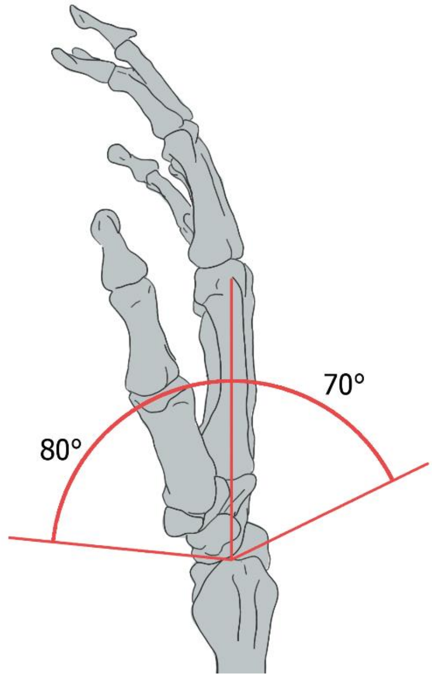

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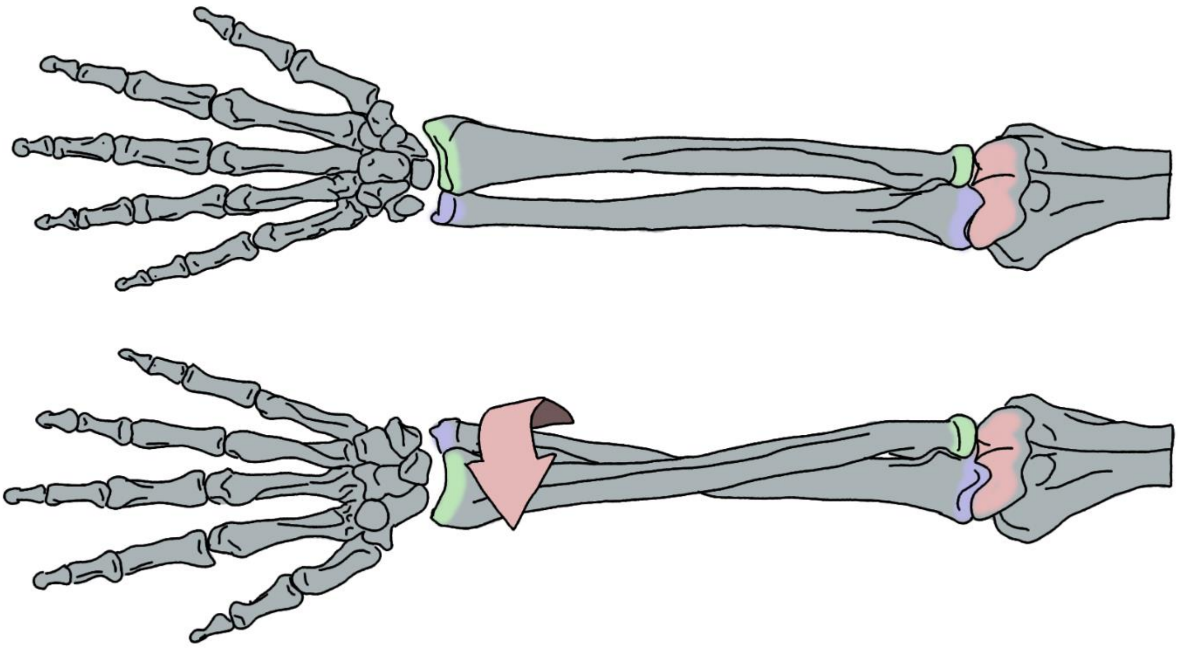

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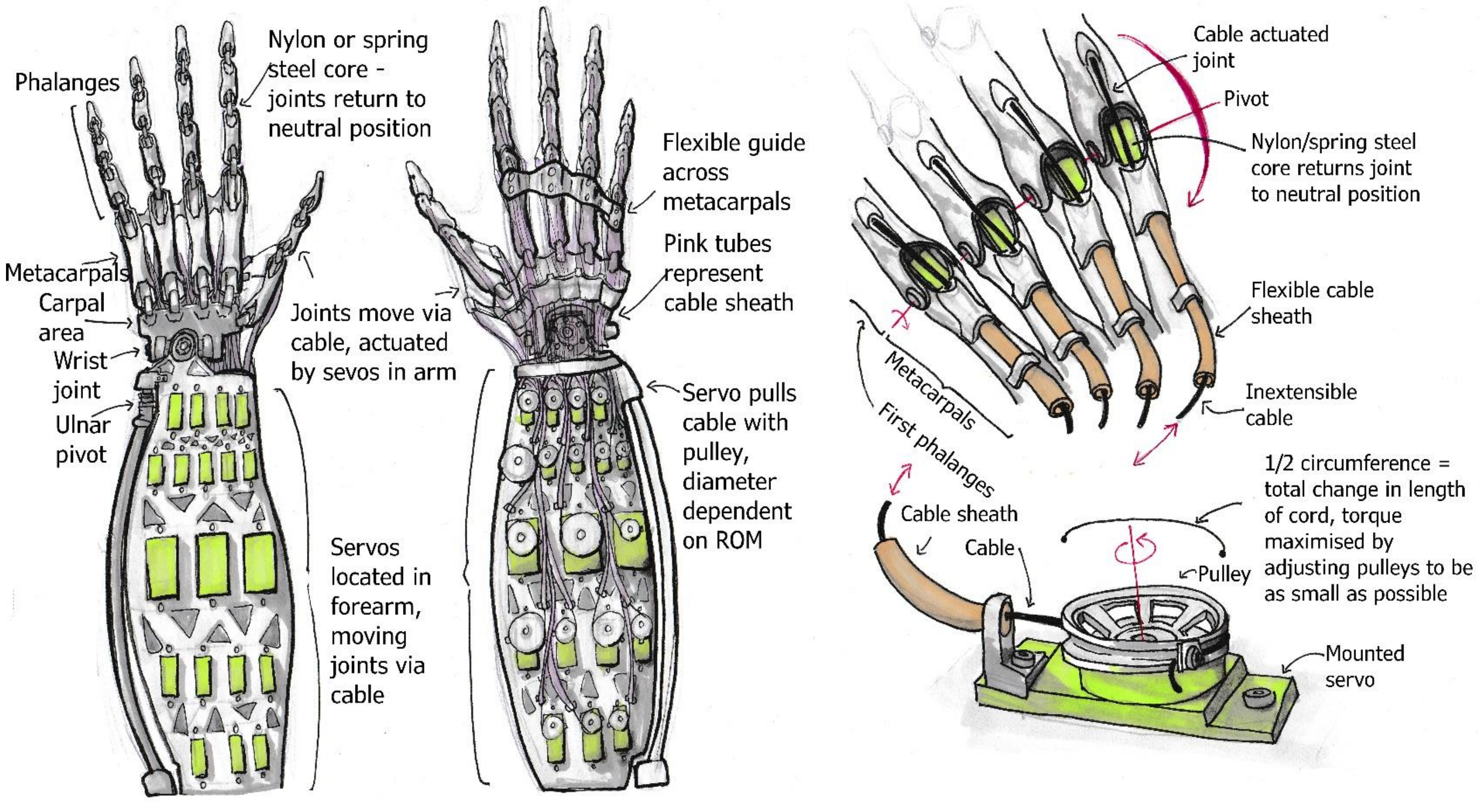

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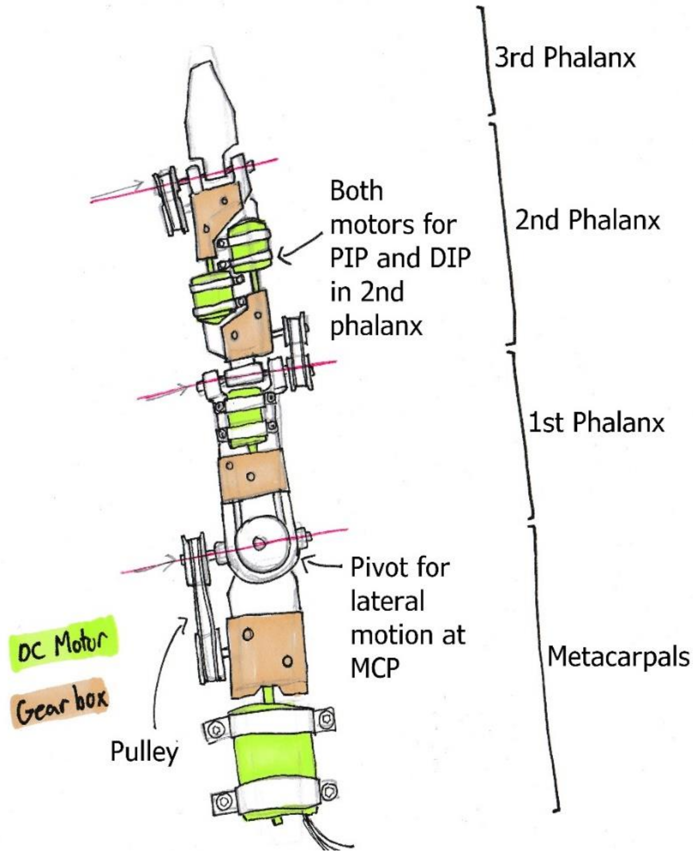

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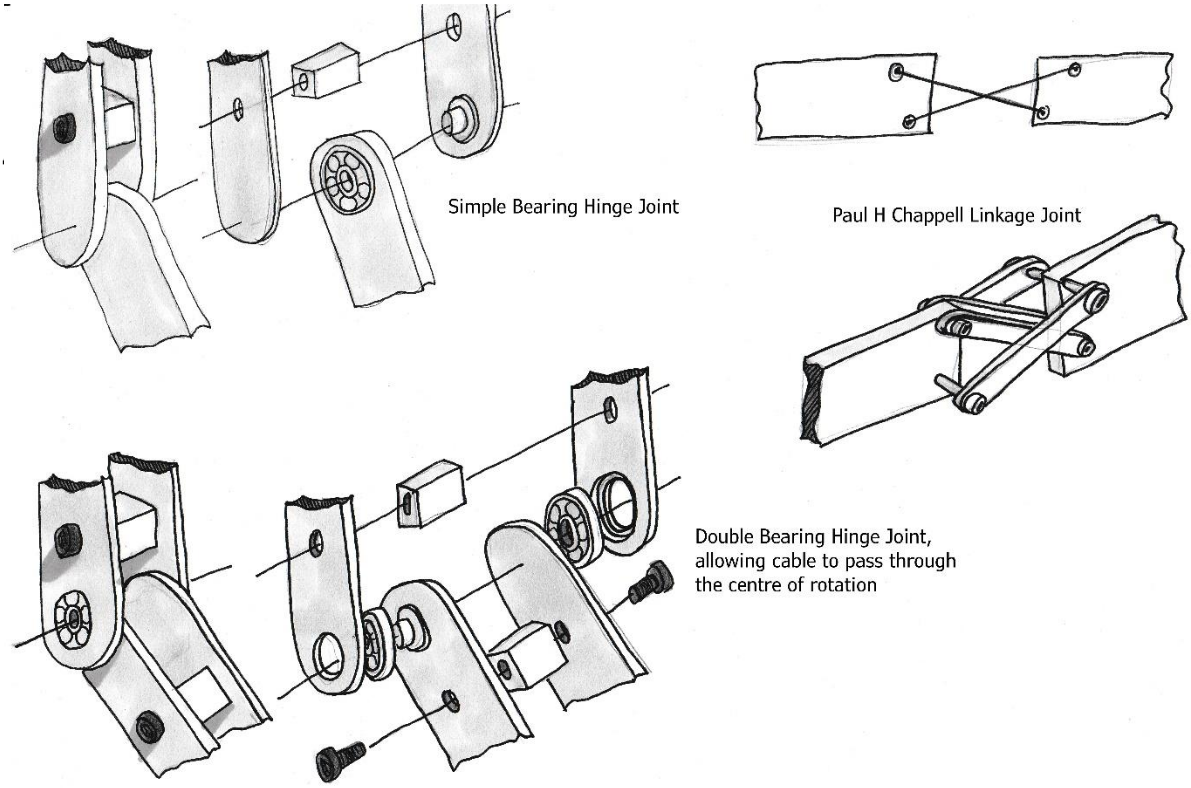

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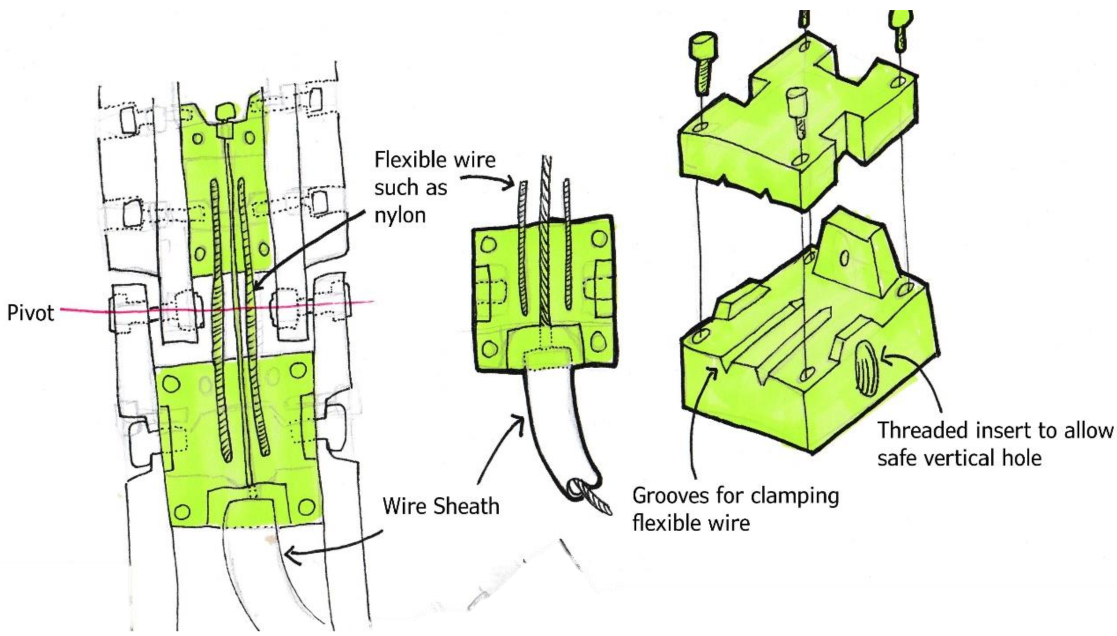

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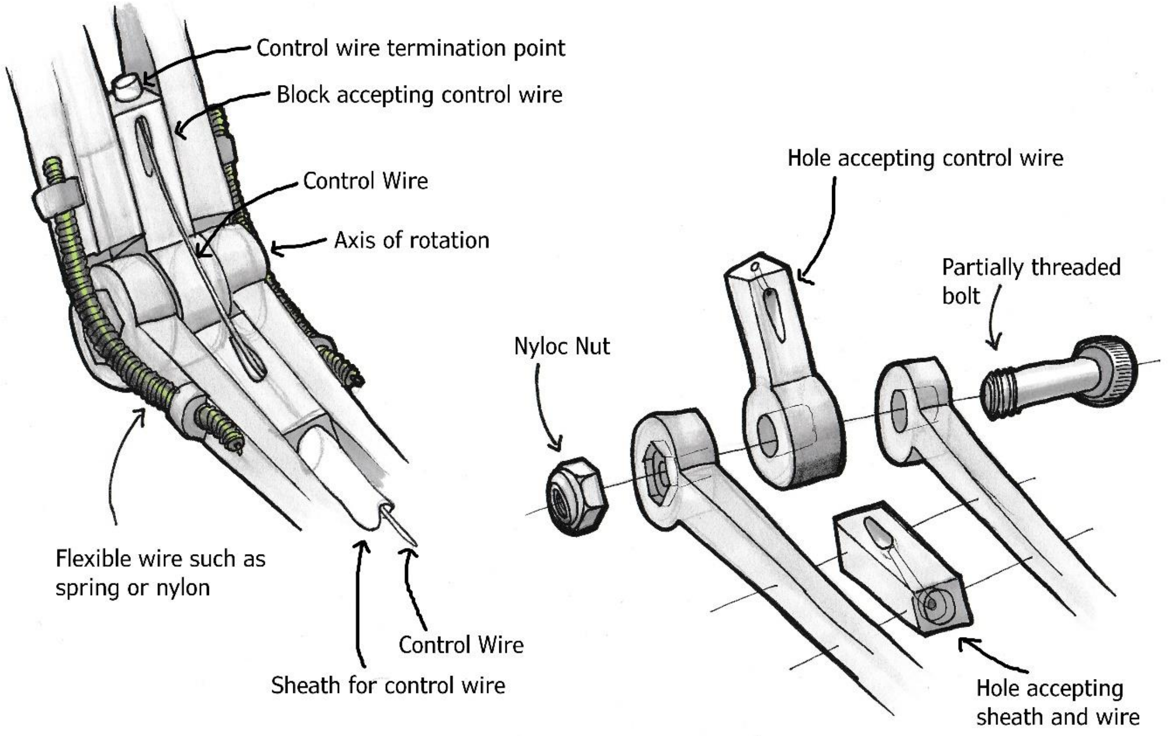

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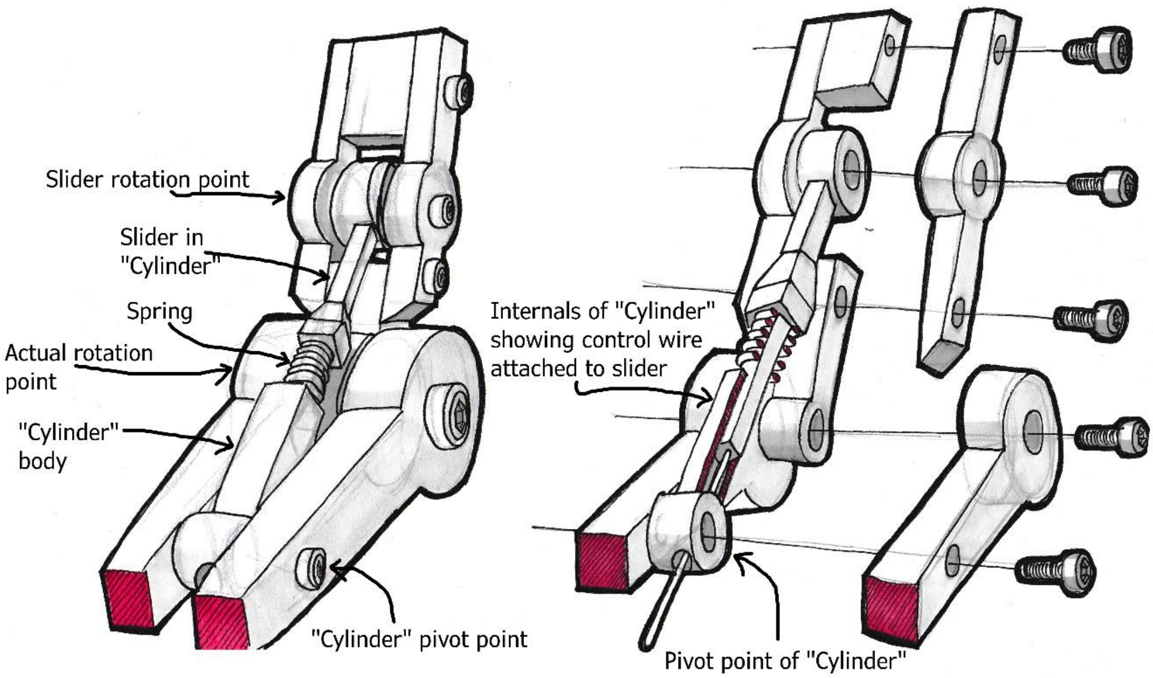

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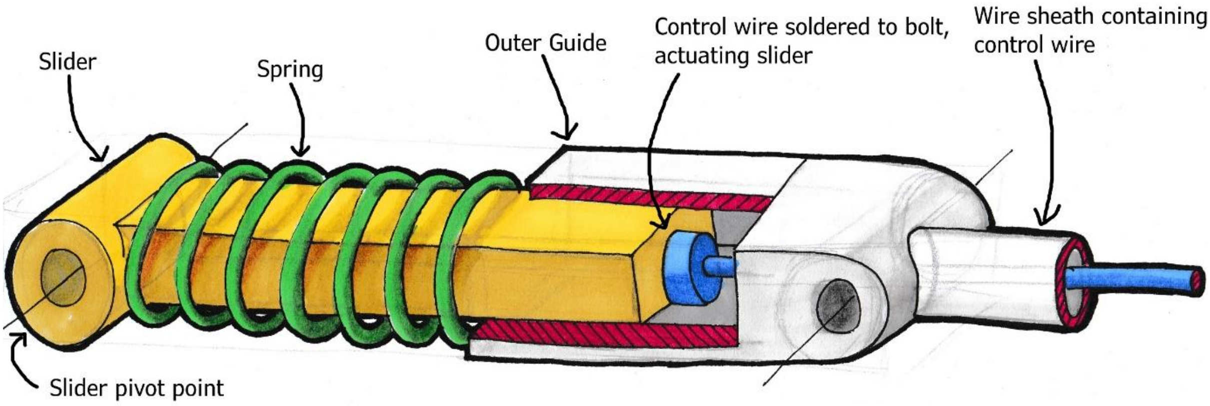

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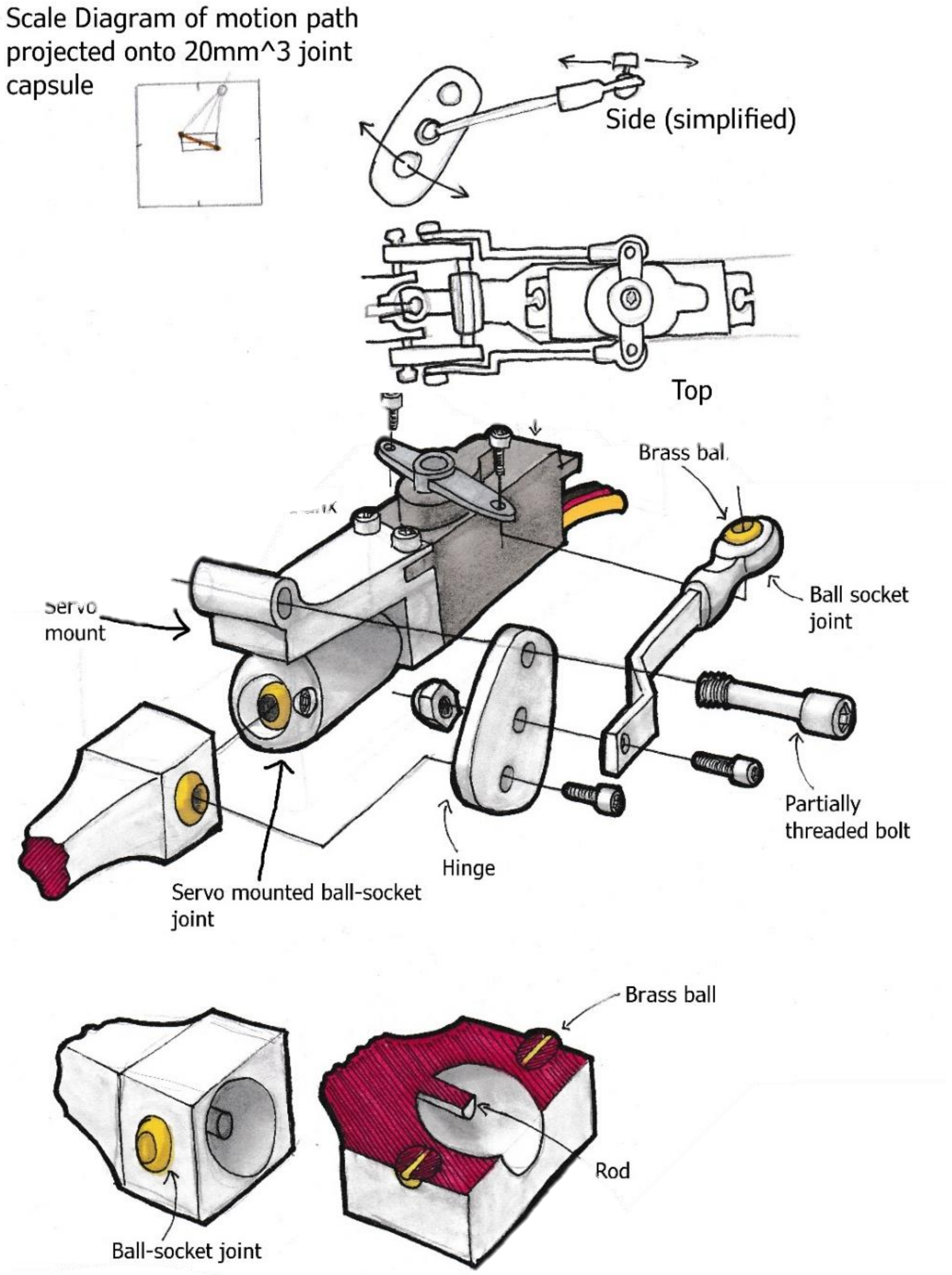

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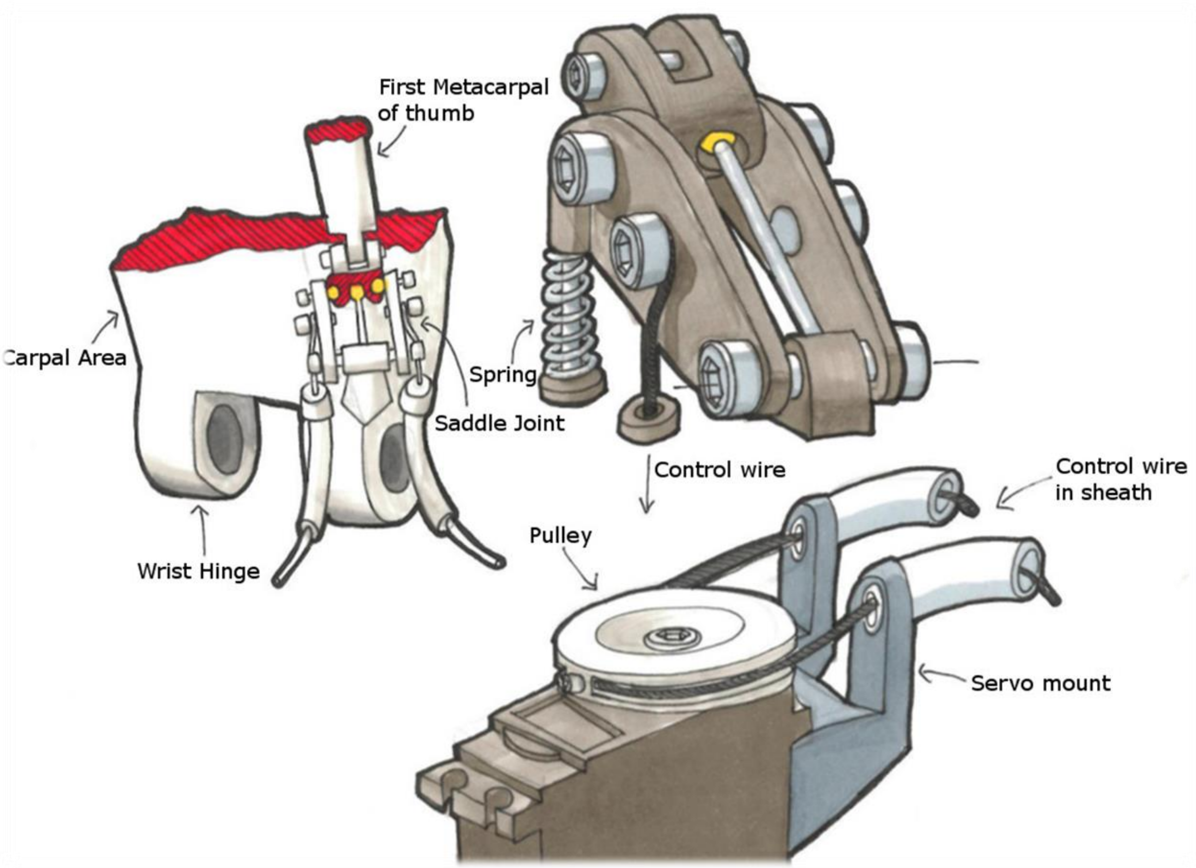

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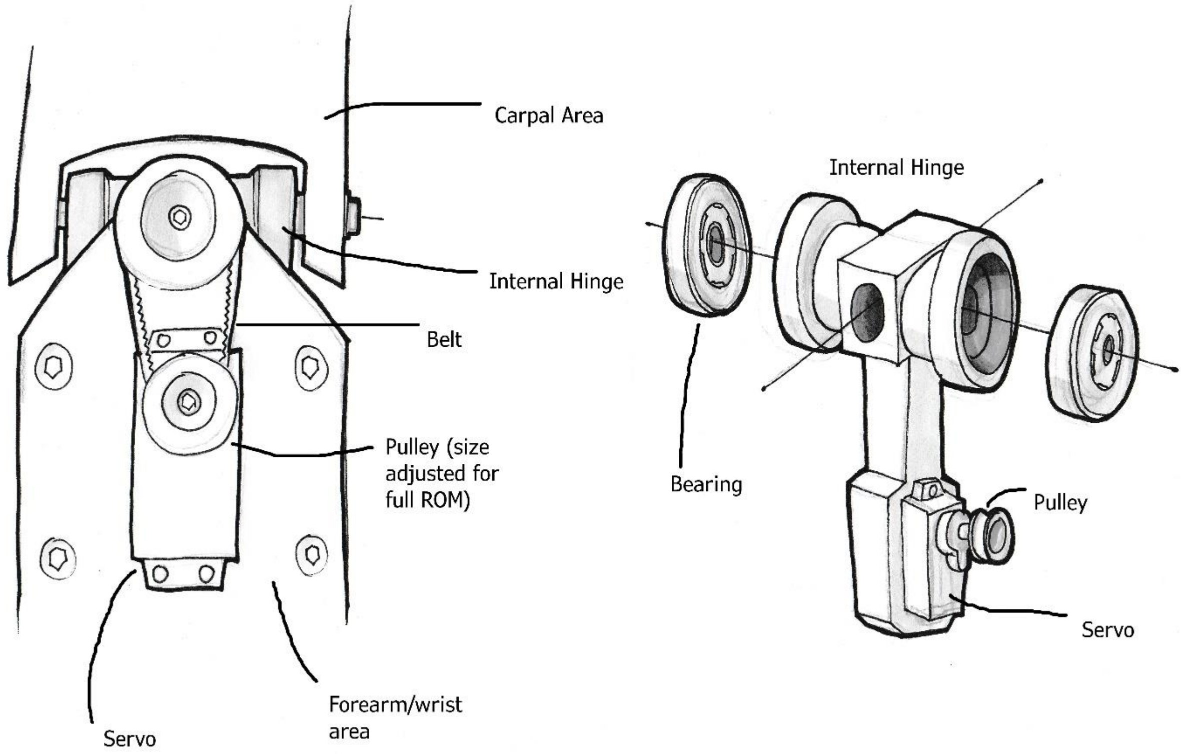

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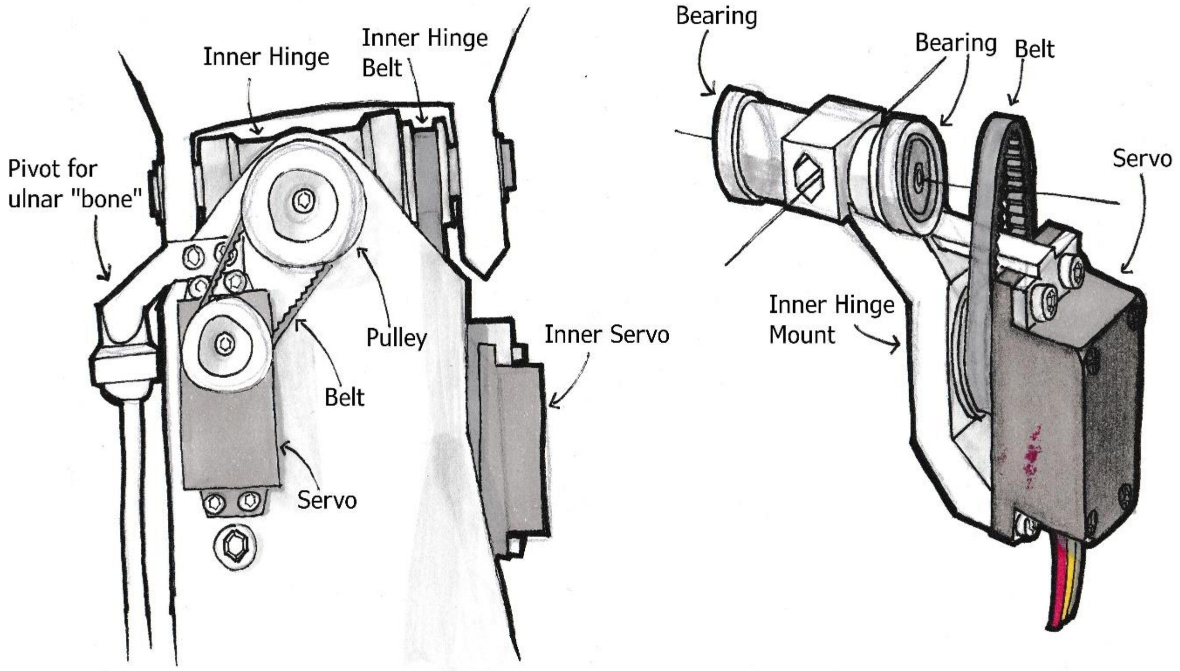

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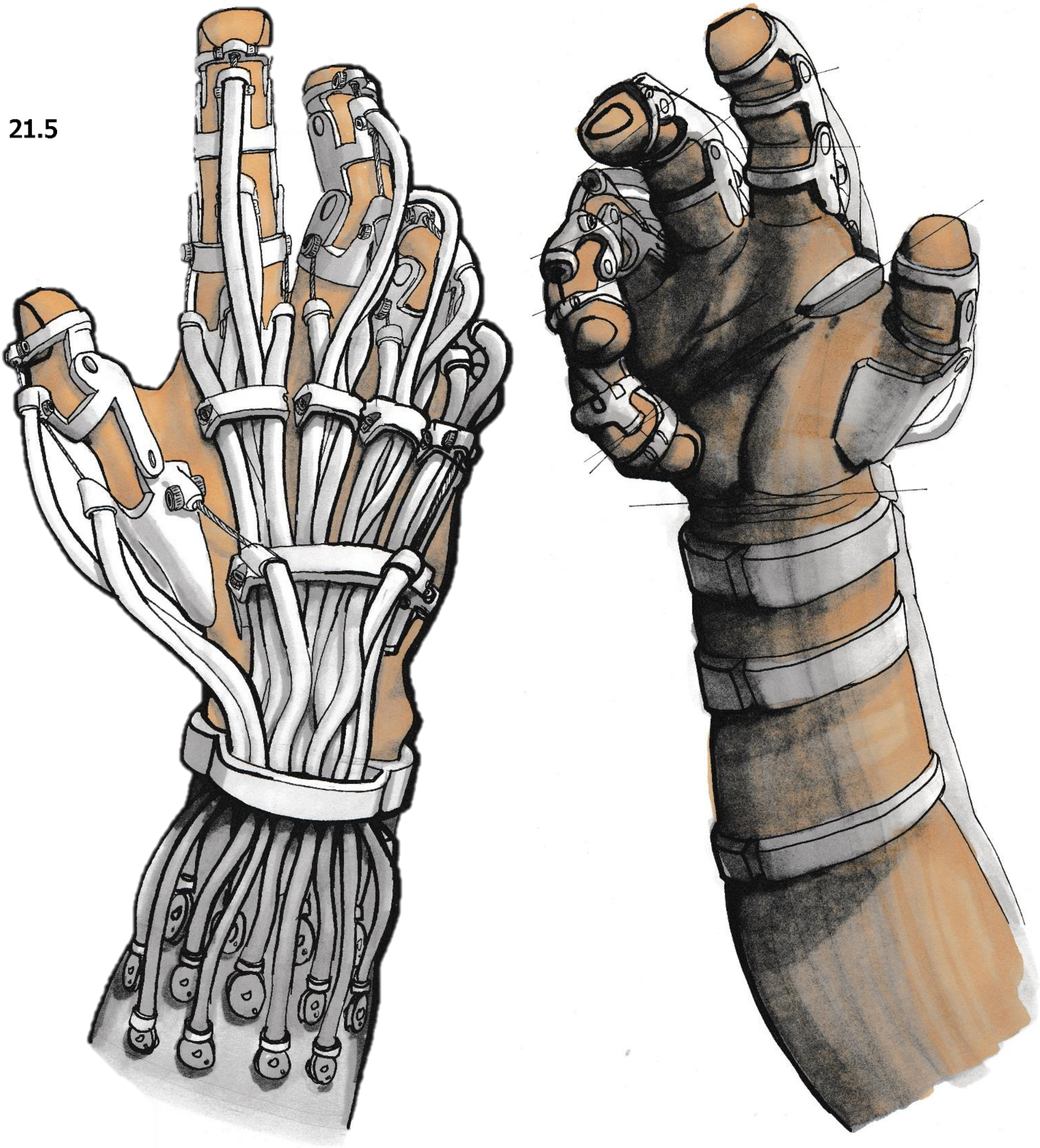

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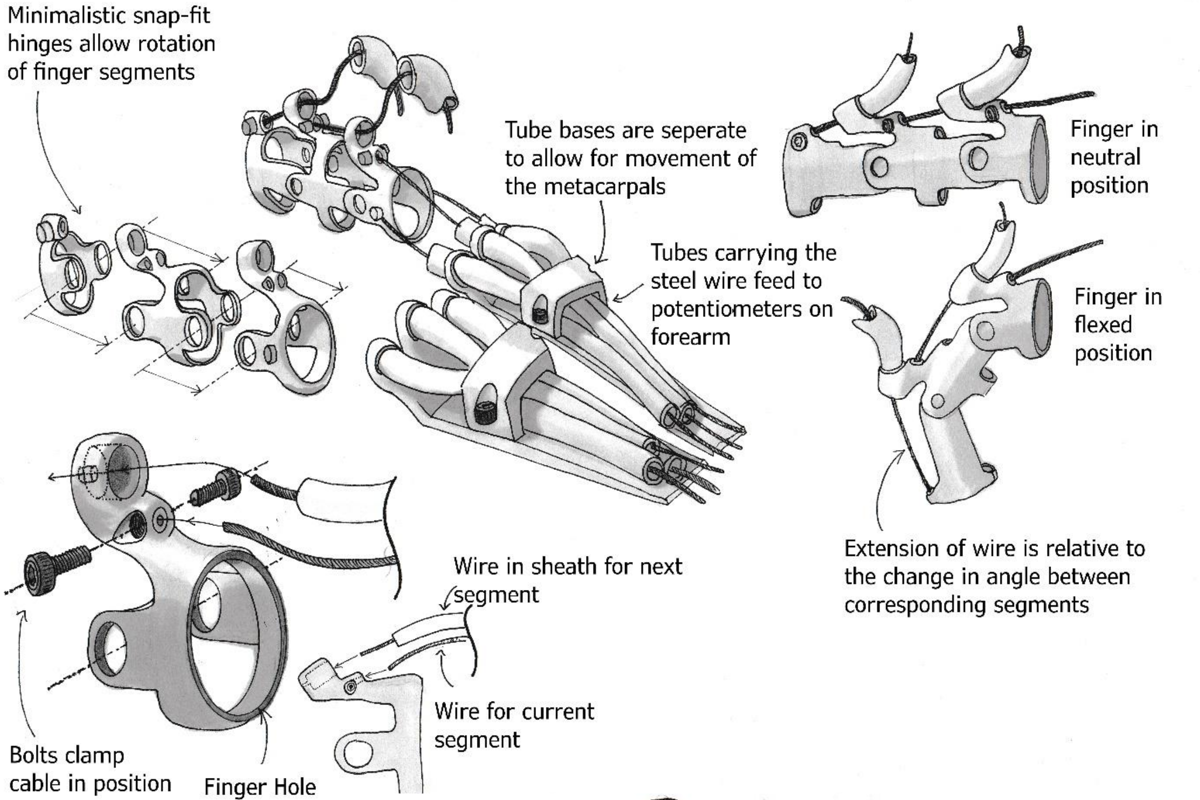

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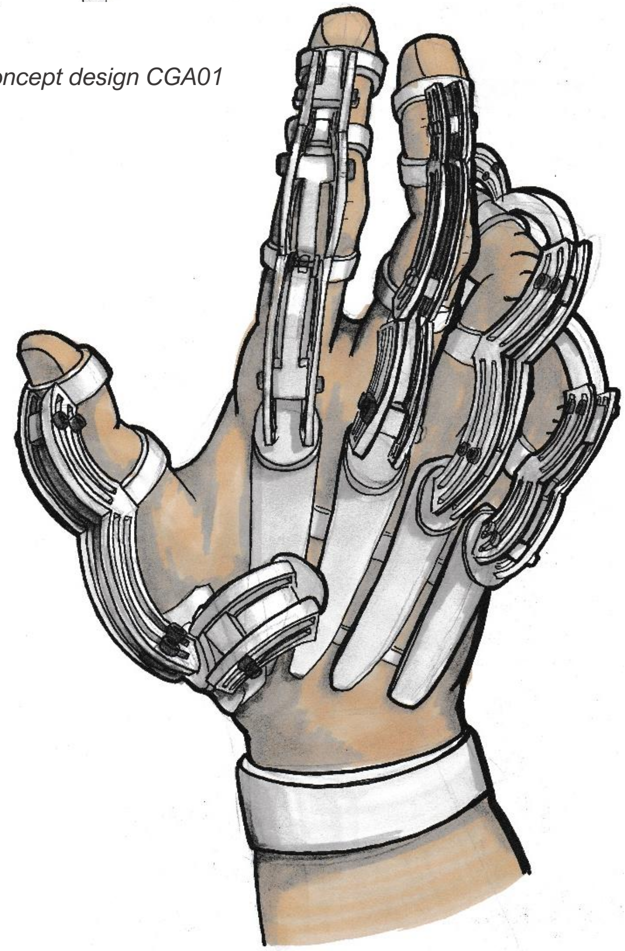

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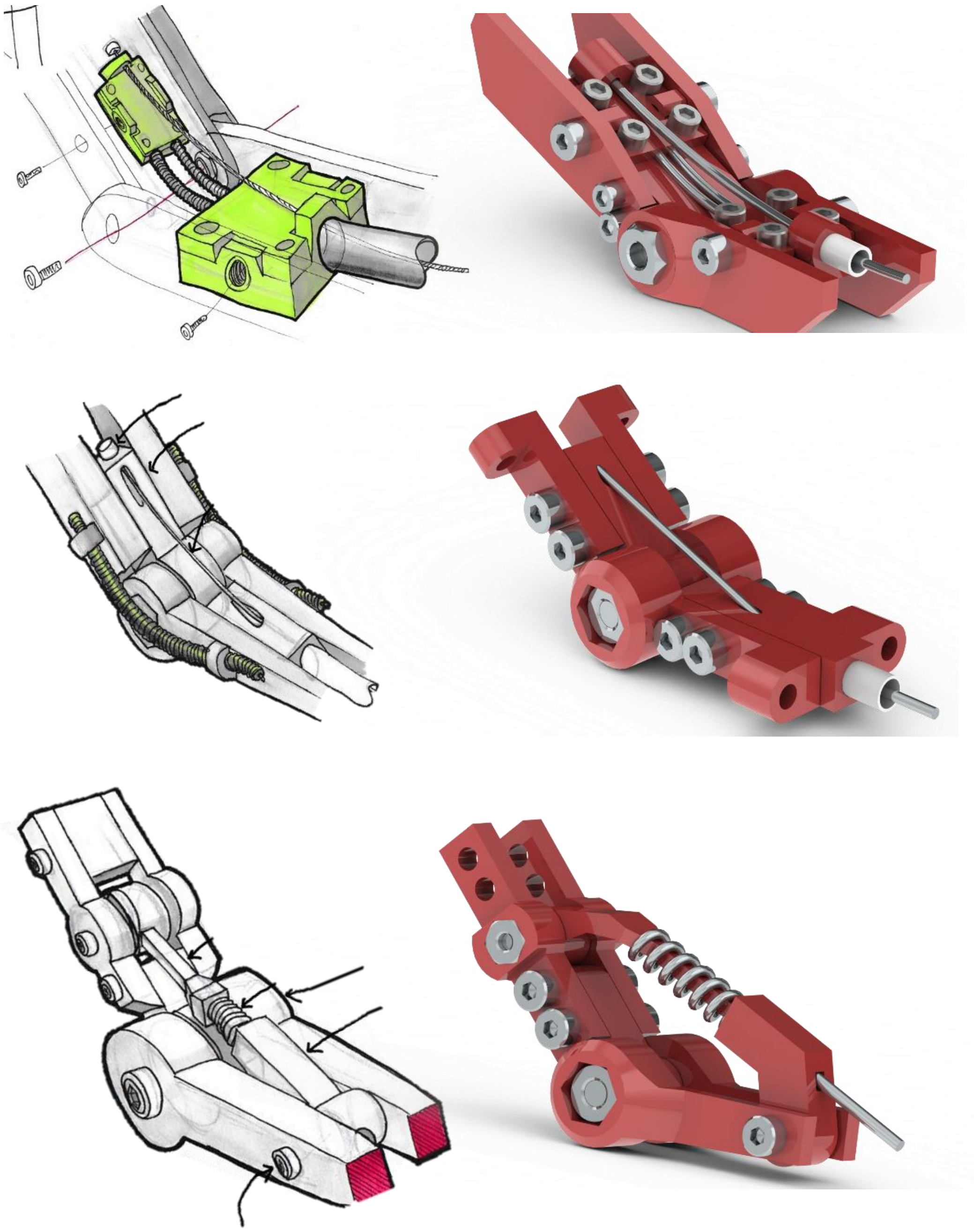

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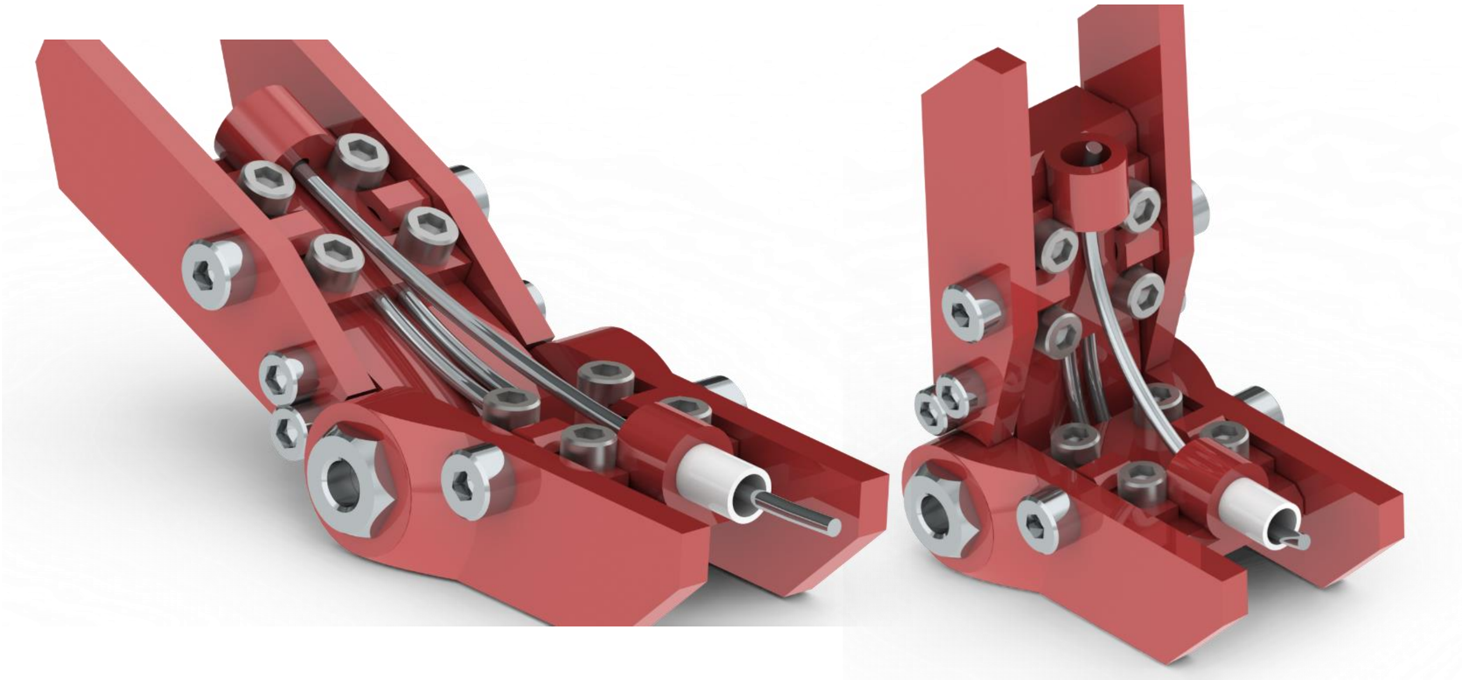

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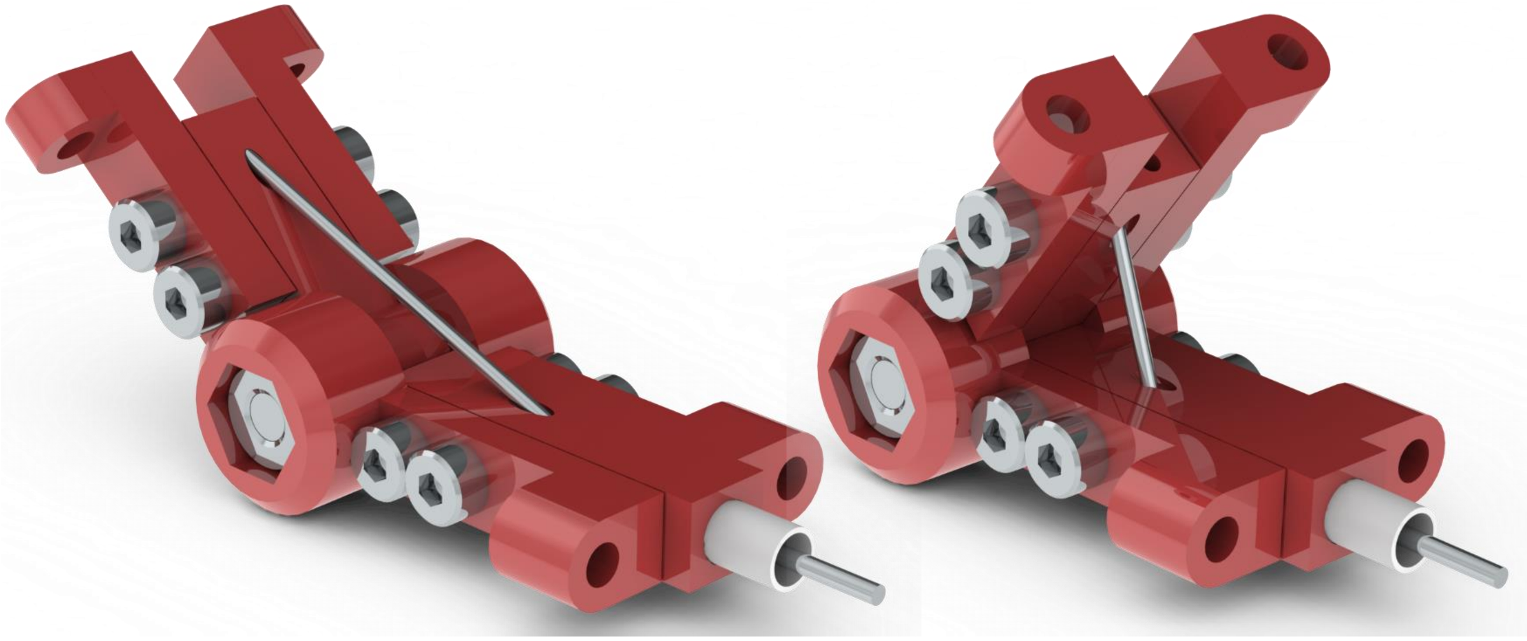

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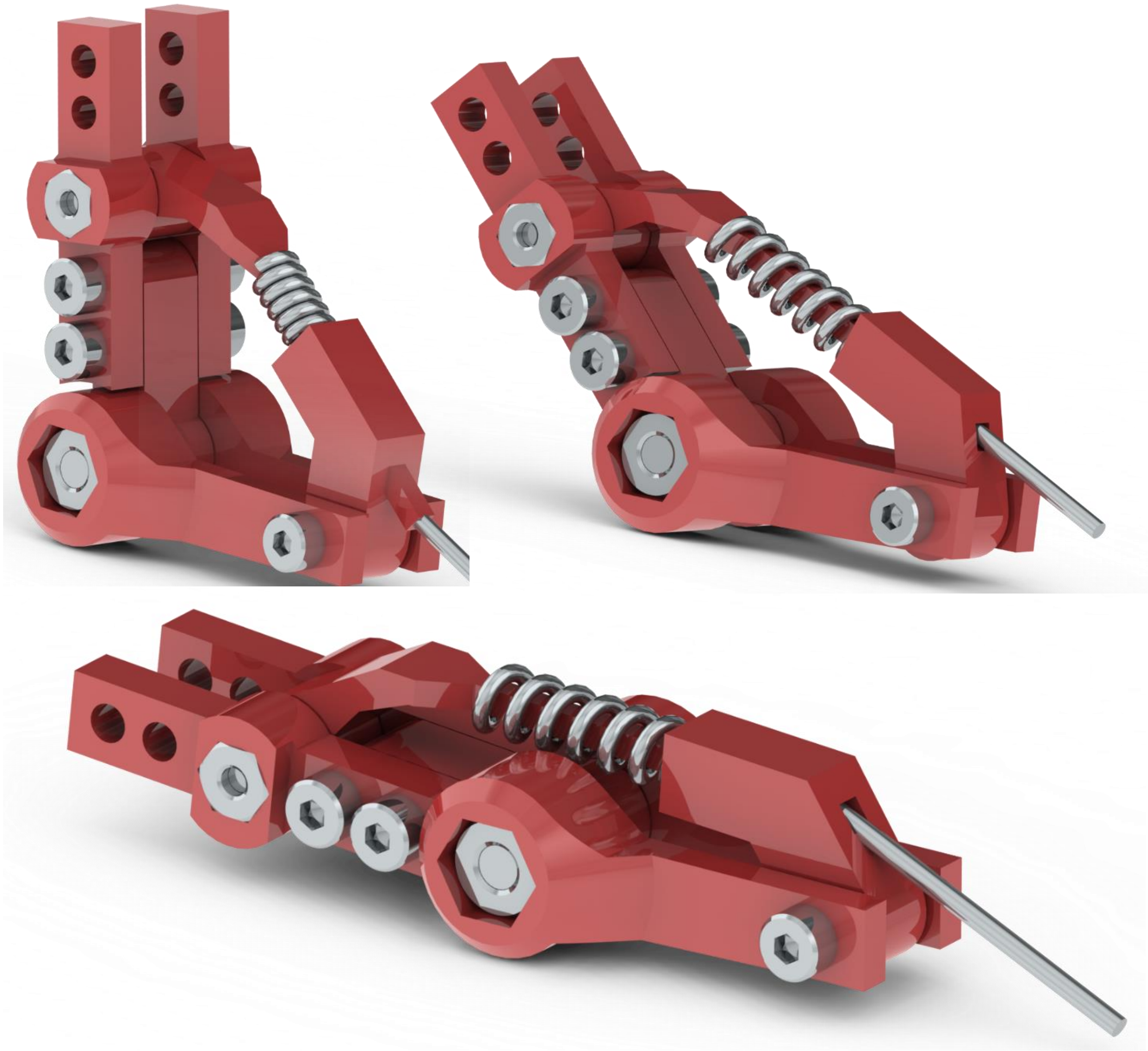

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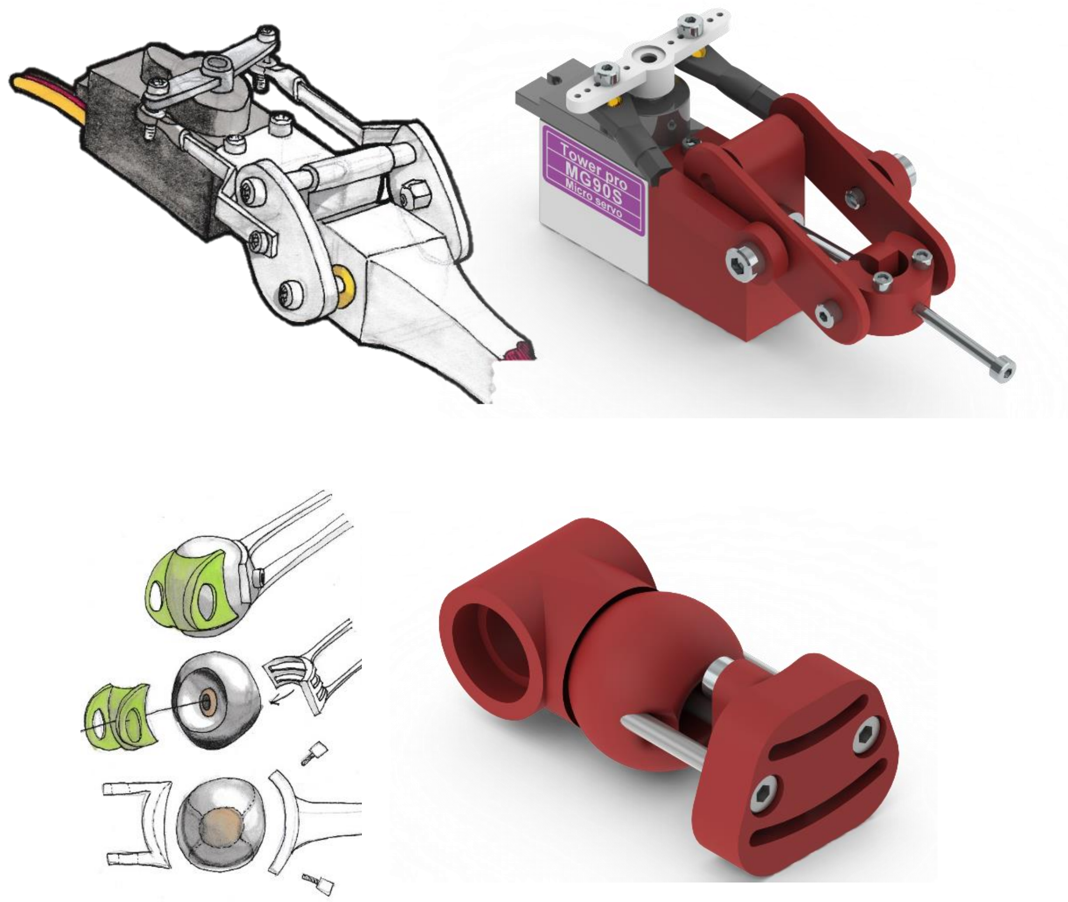

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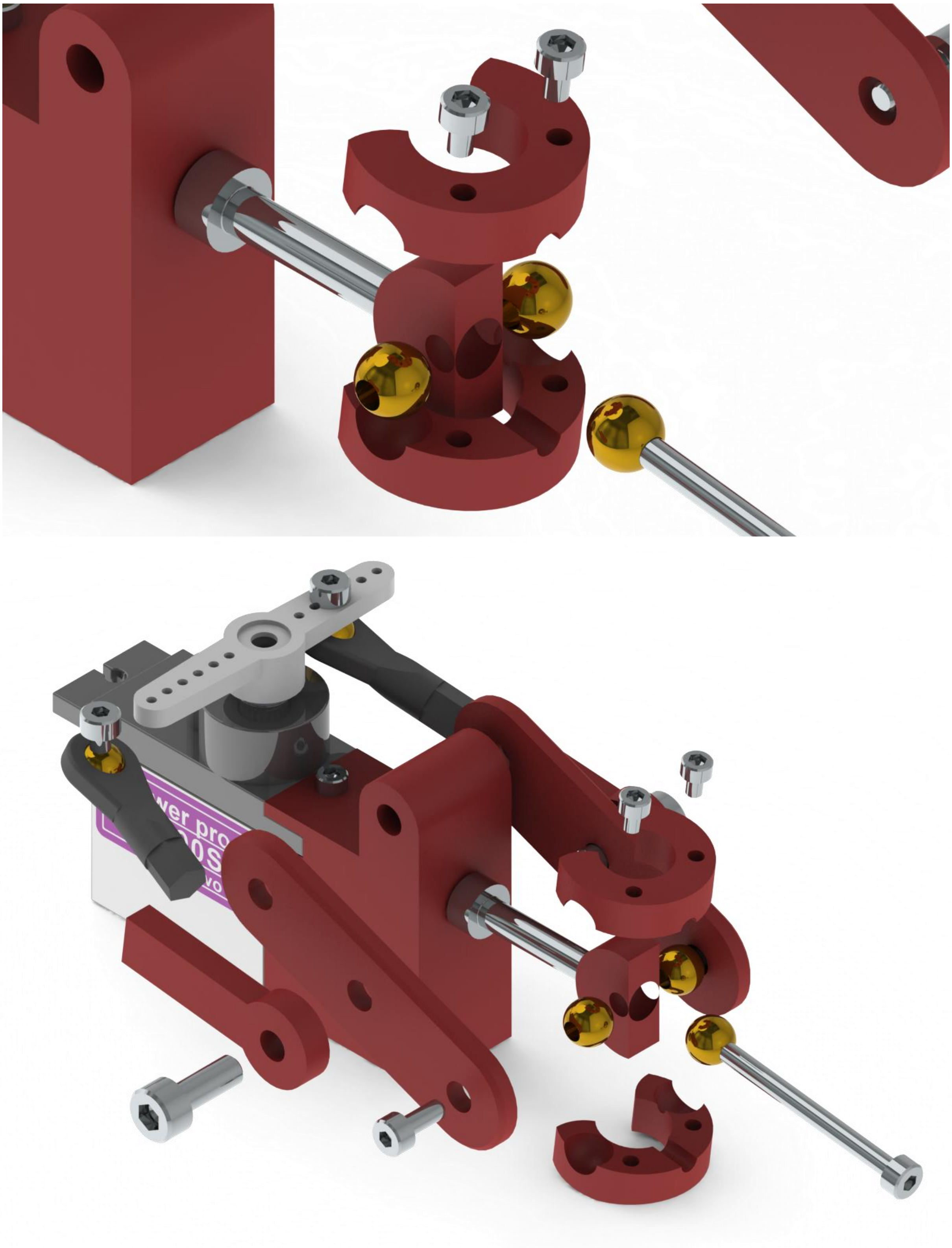

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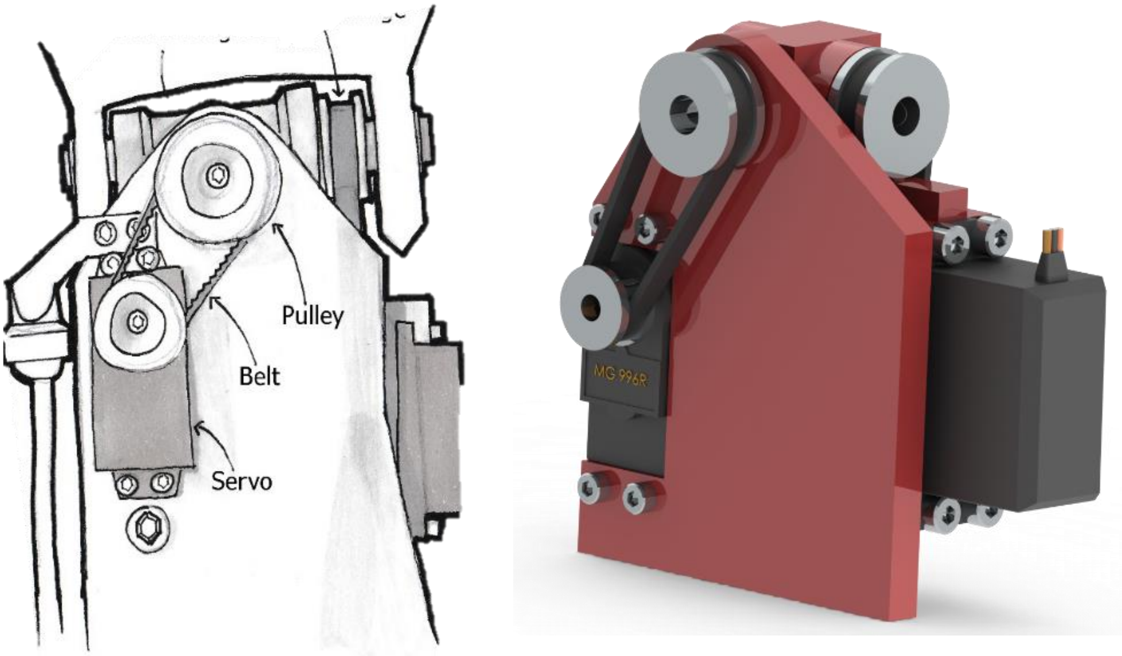

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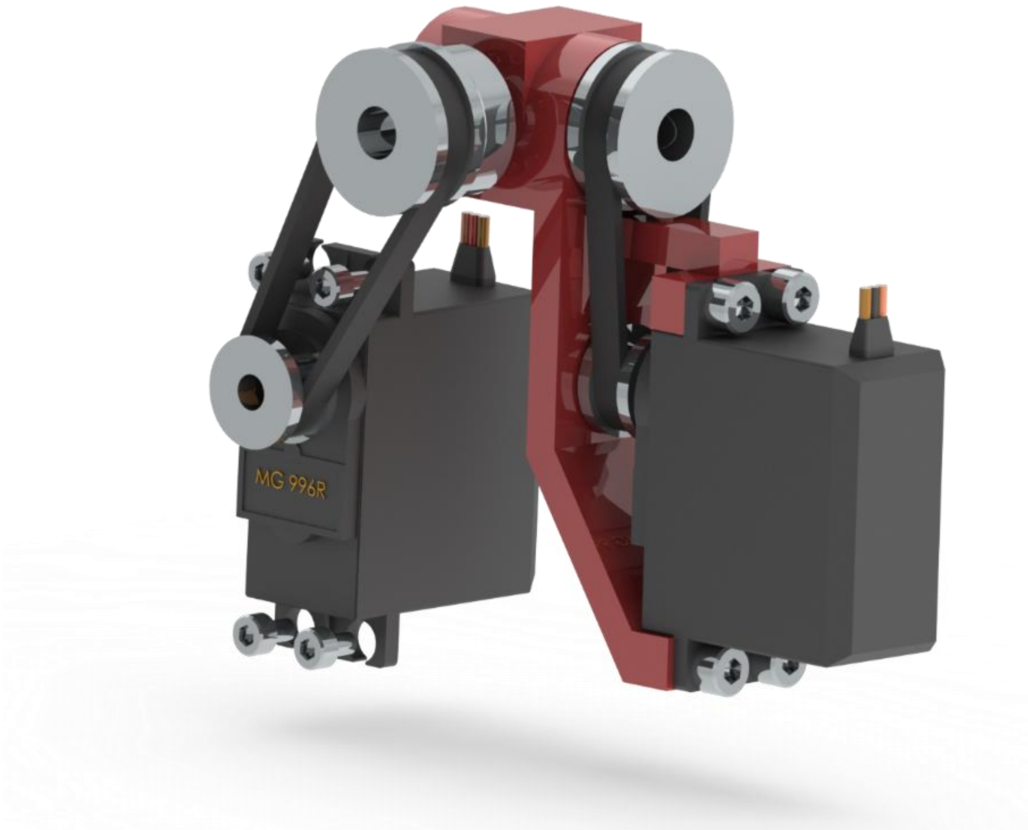

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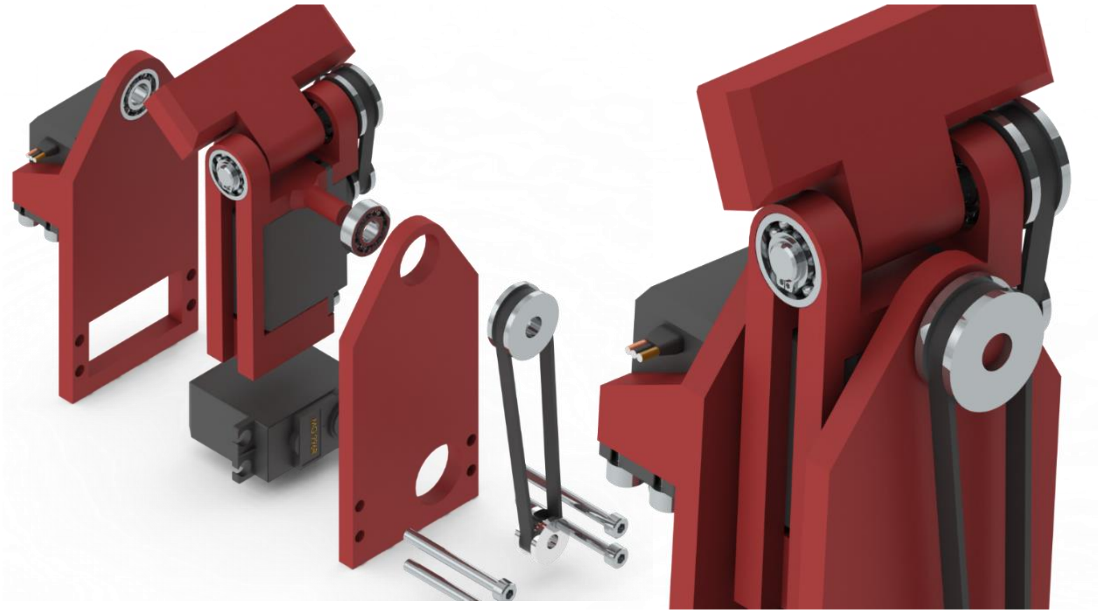

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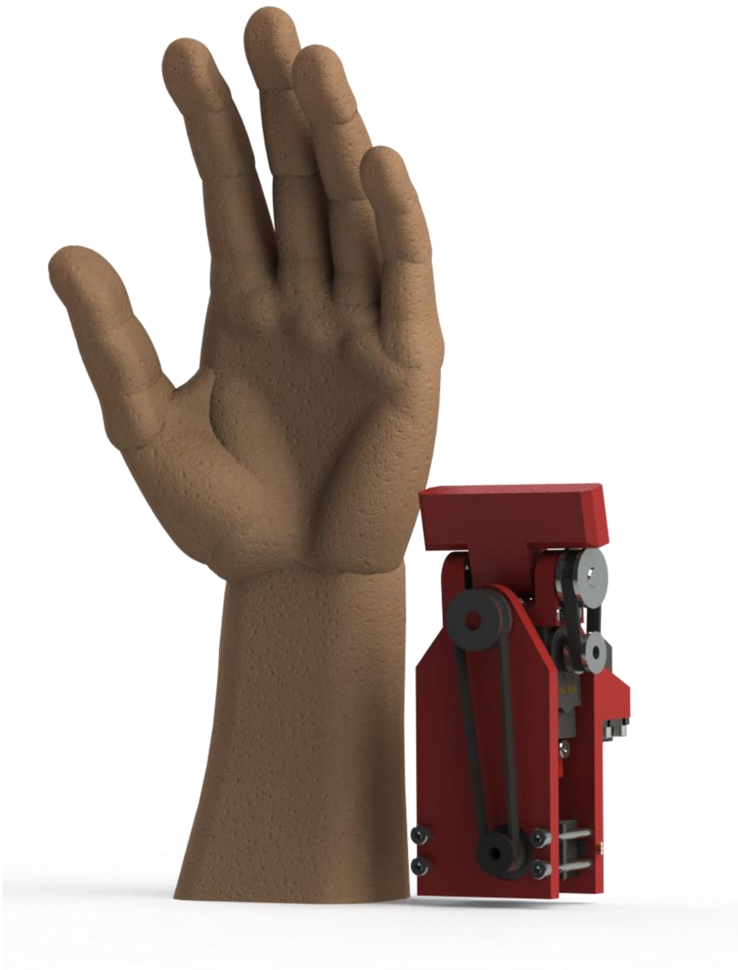

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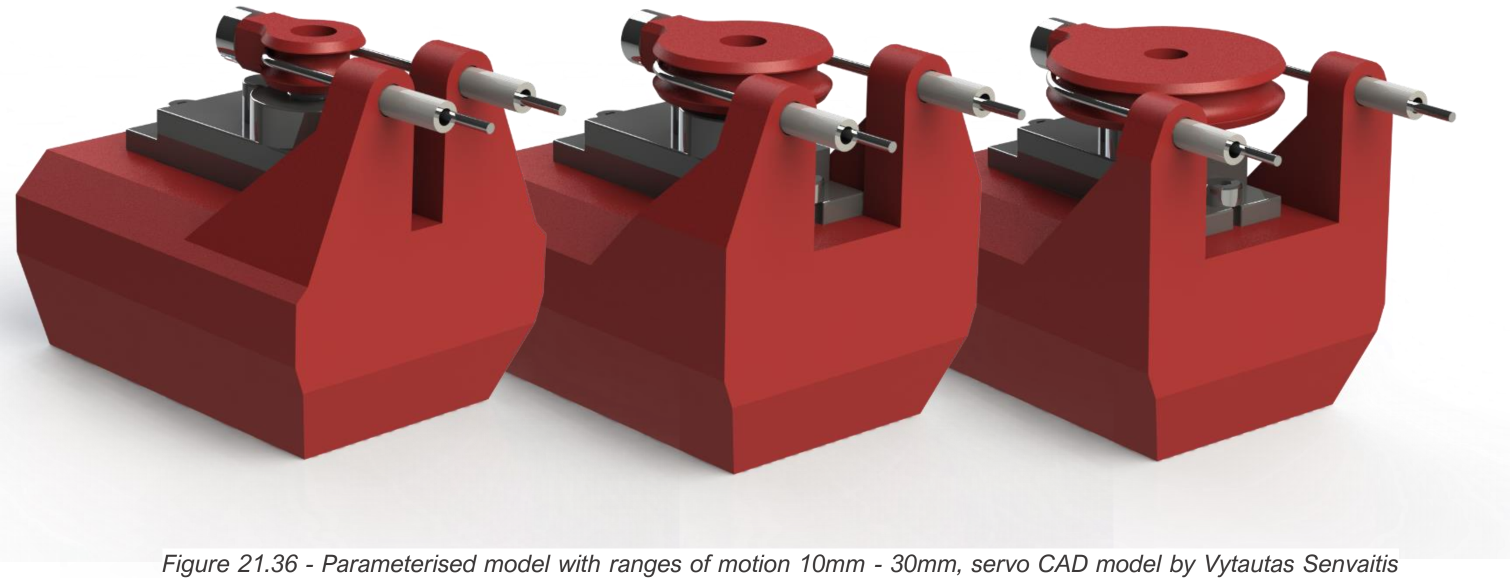

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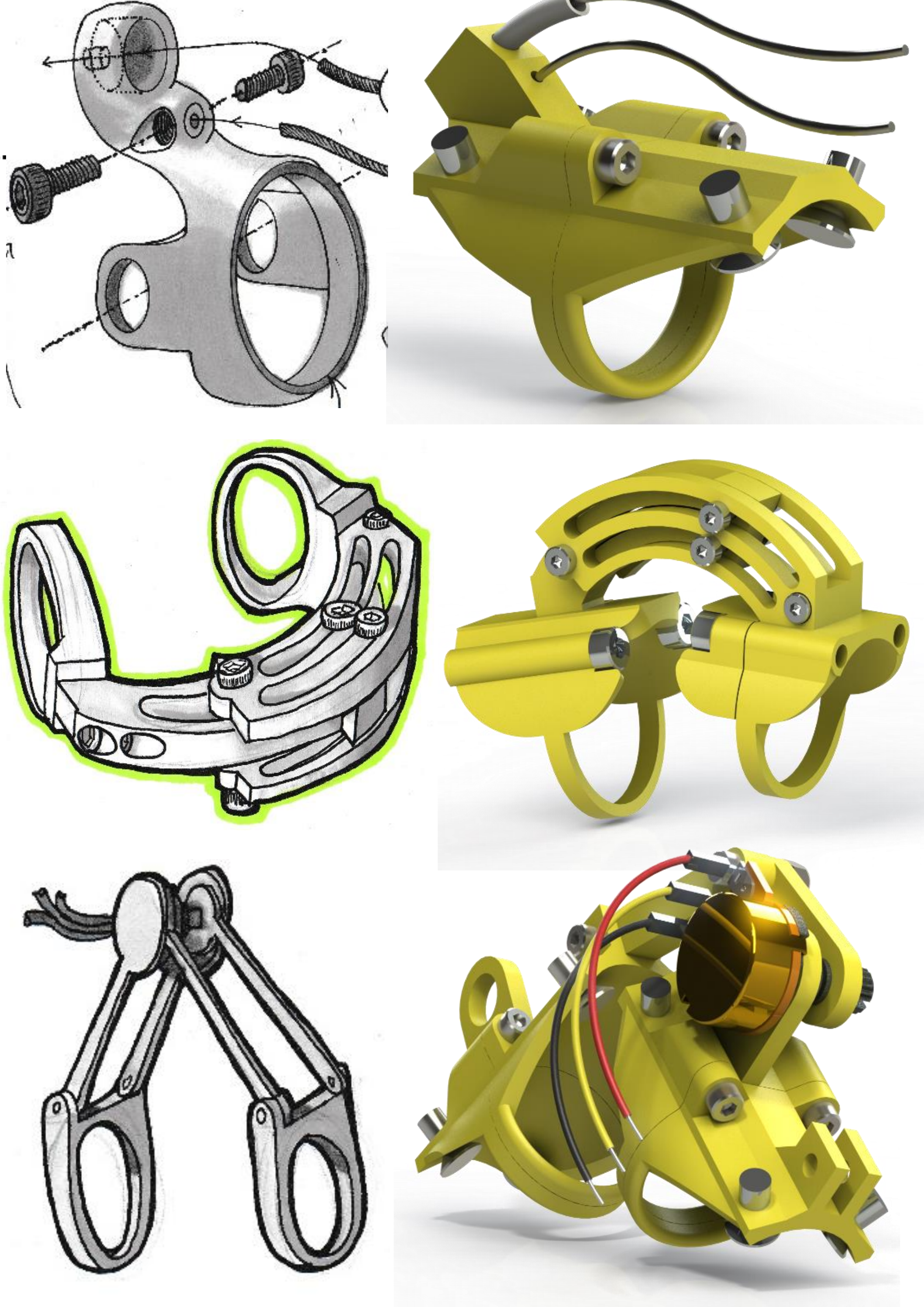

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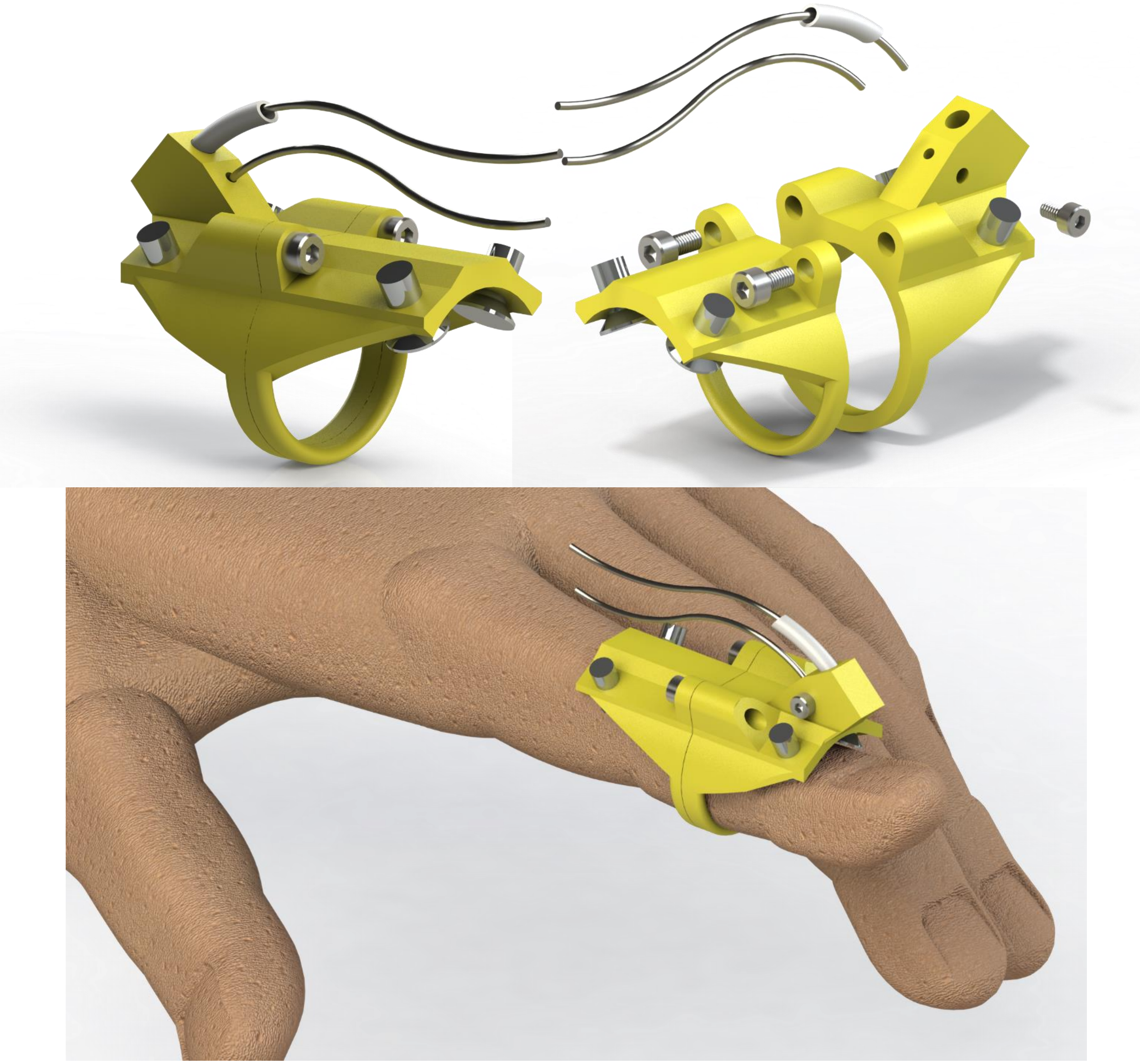

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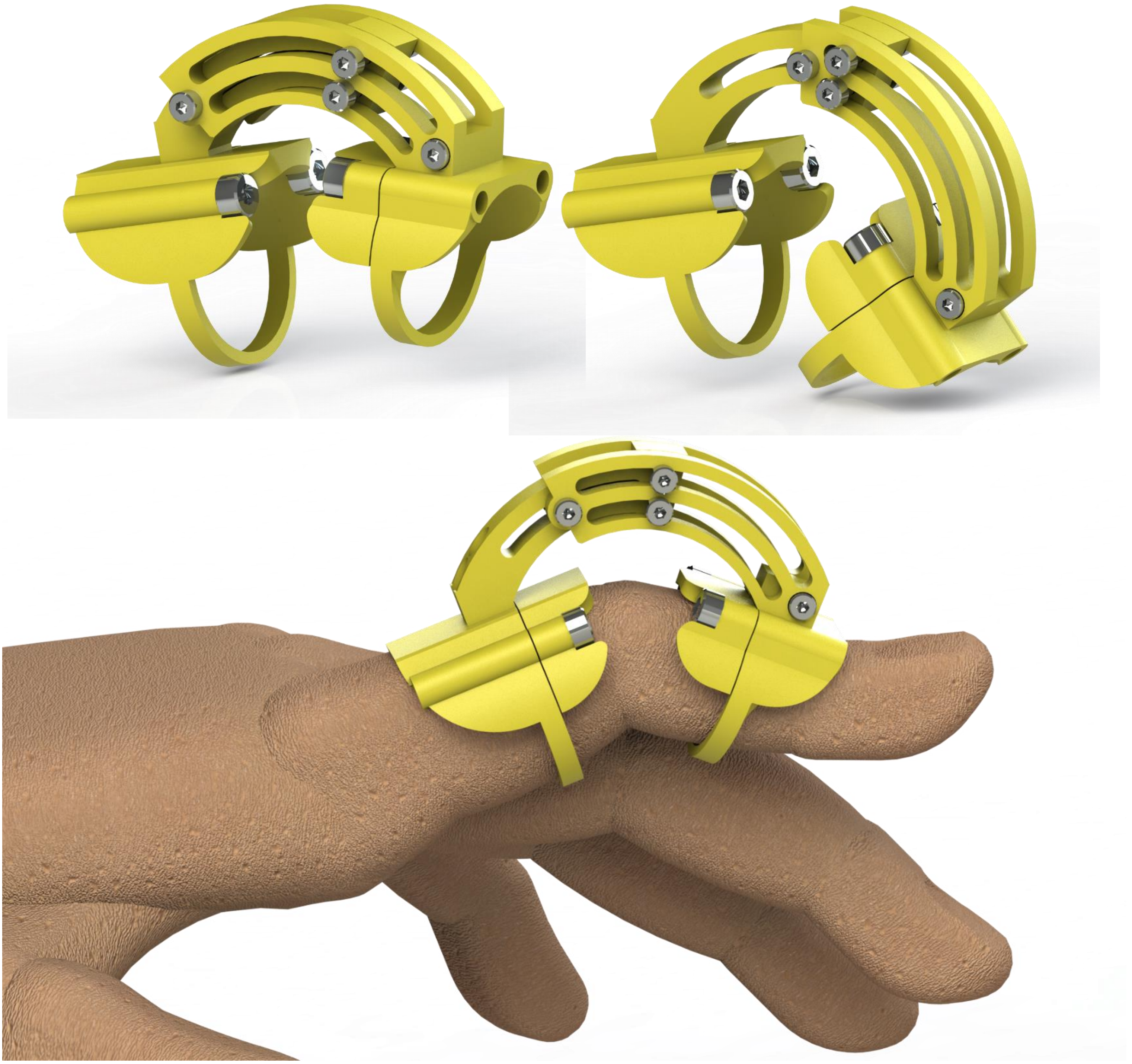

*Figure 21.39 - **CGA02** Alternative views with hand CAD model by Joerg Schmitt (2012)*

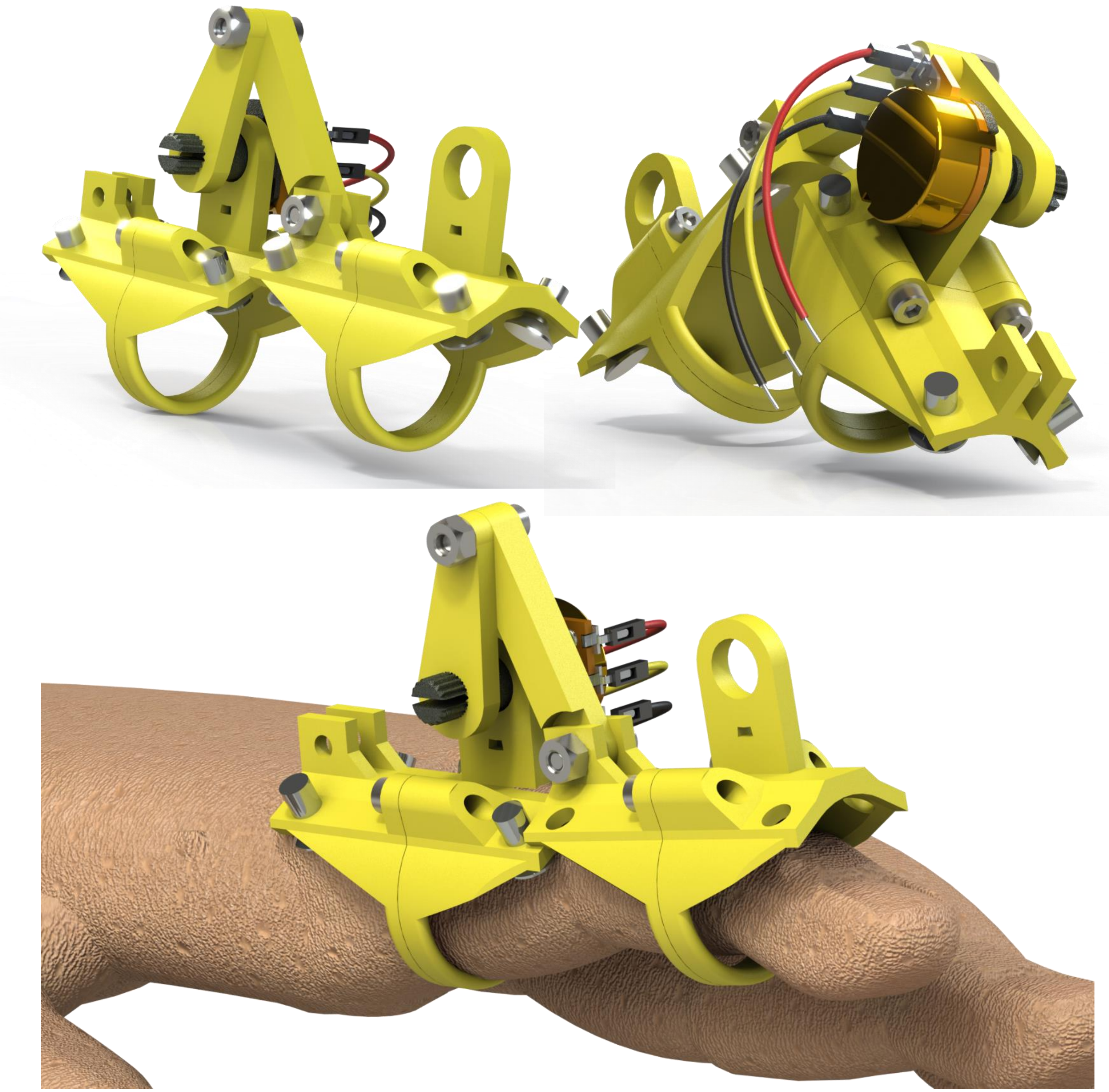

*Figure 21.40 - **CGA03** Alternative views with hand CAD model by Joerg Schmitt (2012)*

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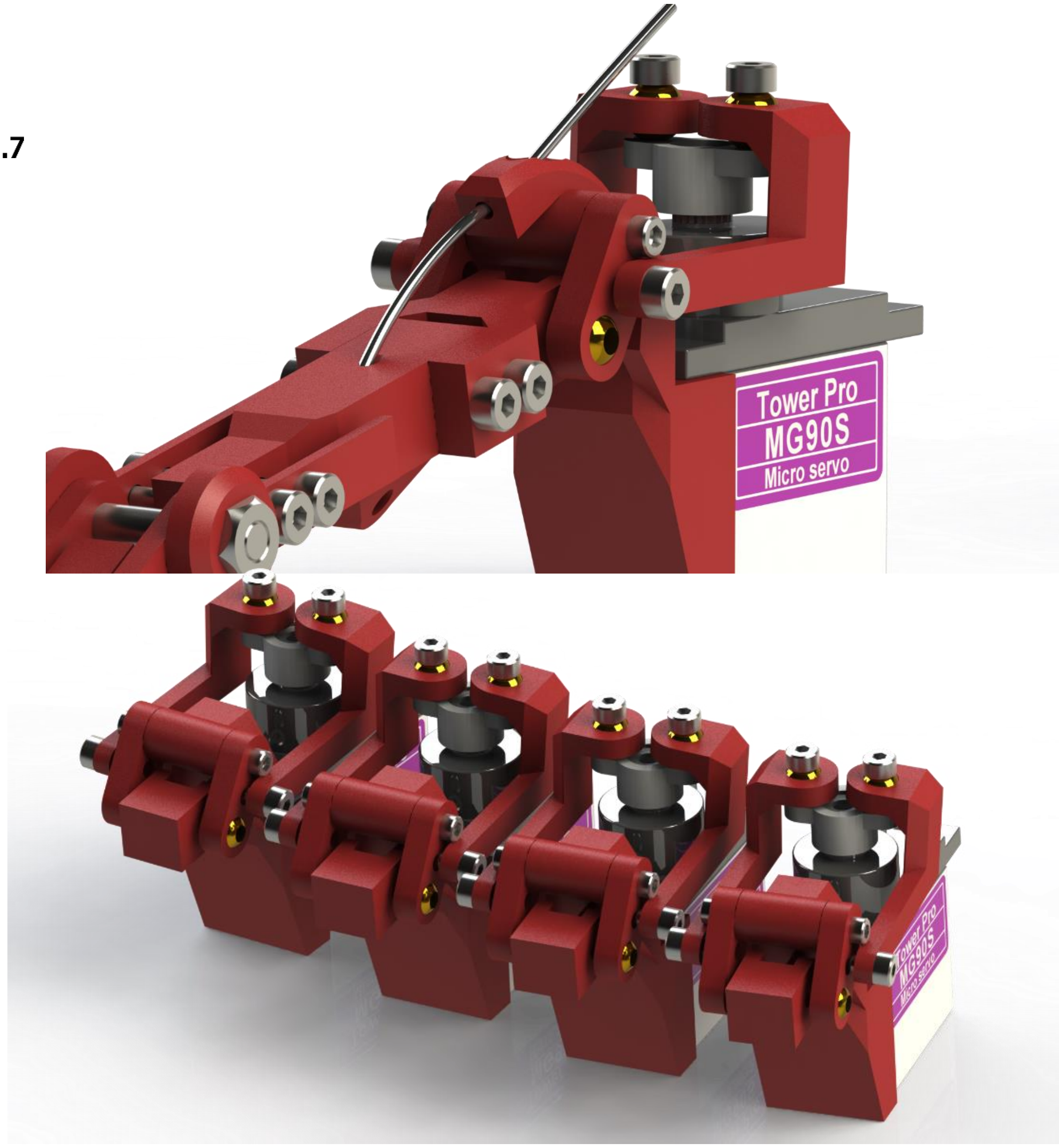

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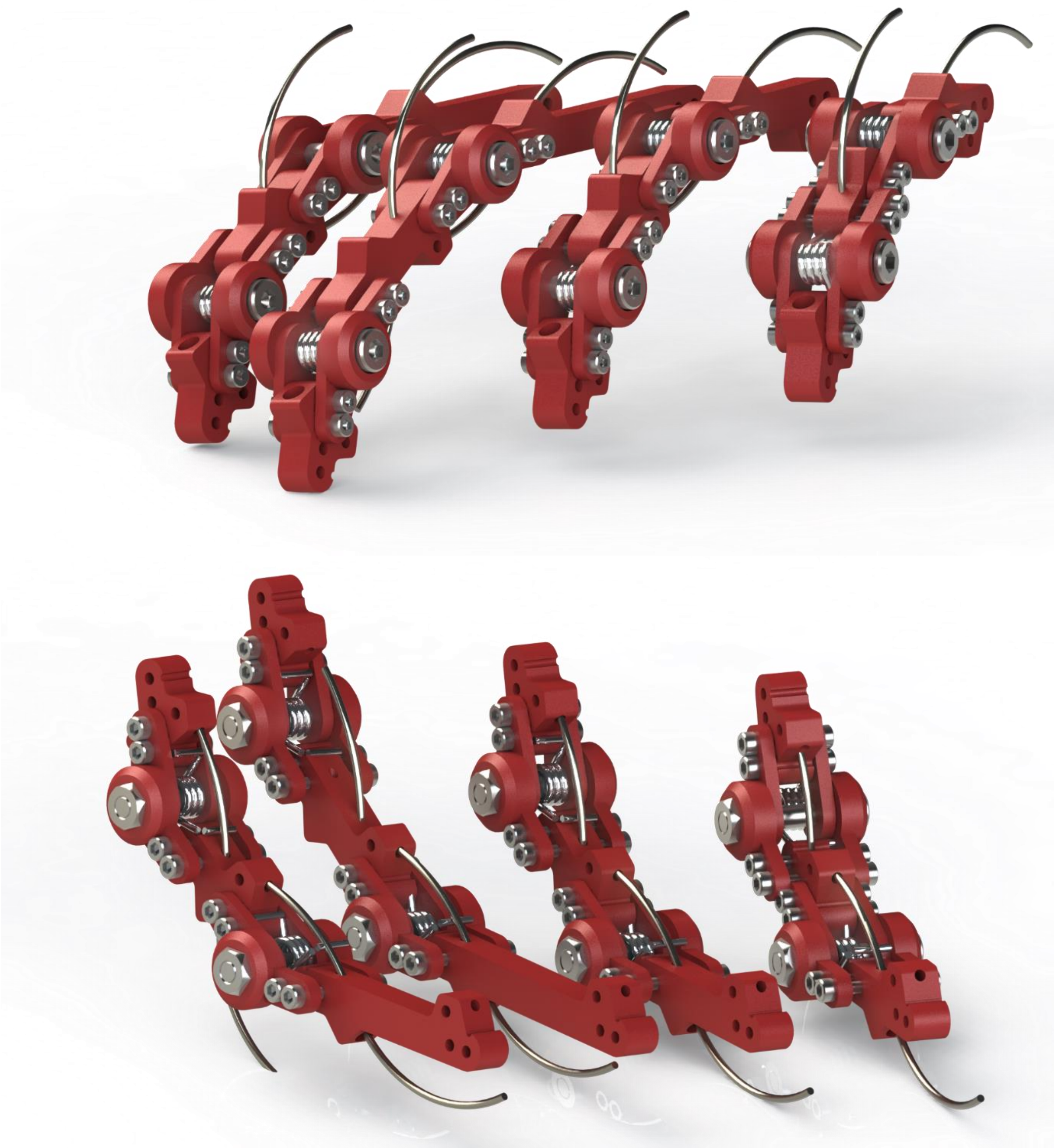

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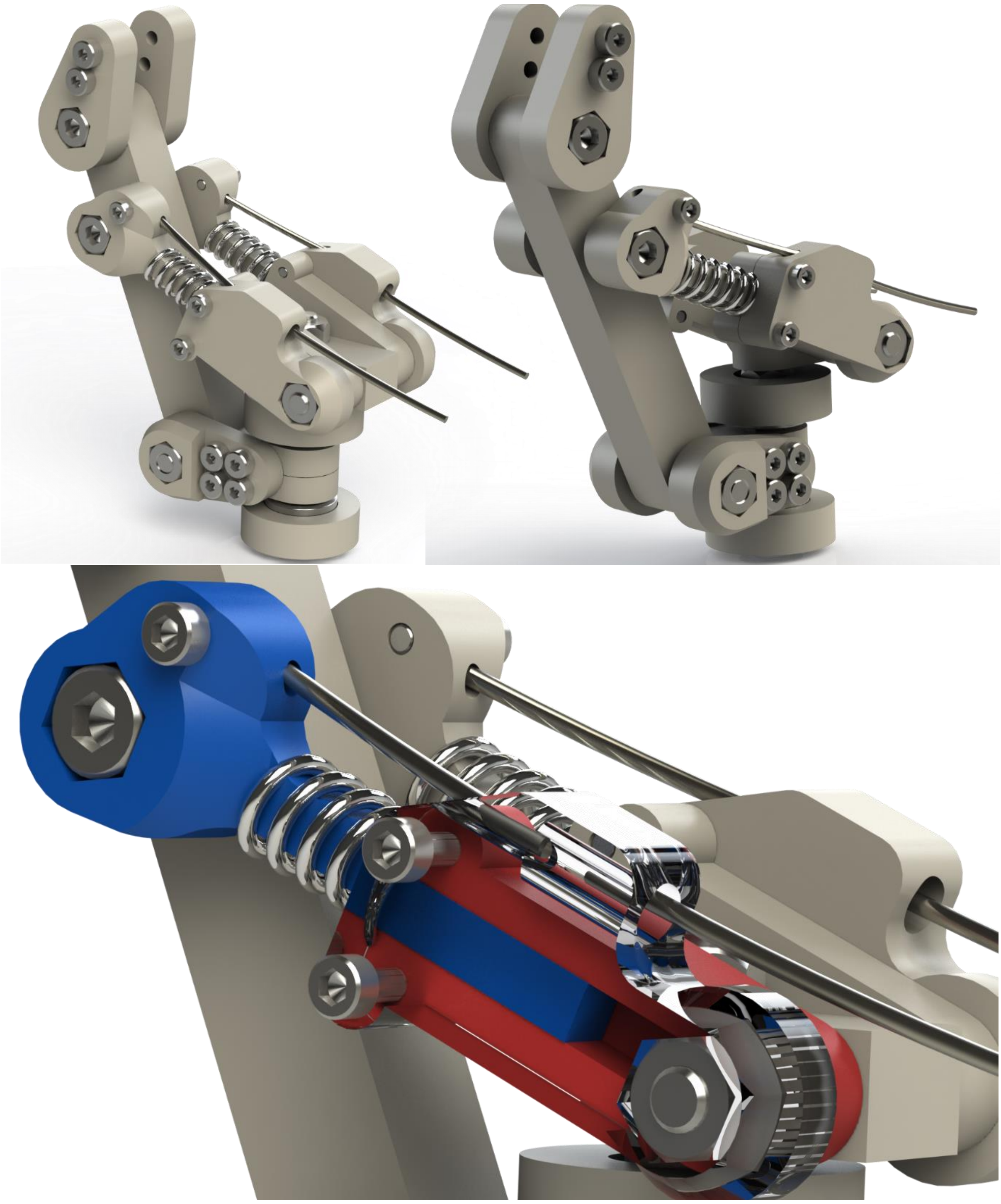

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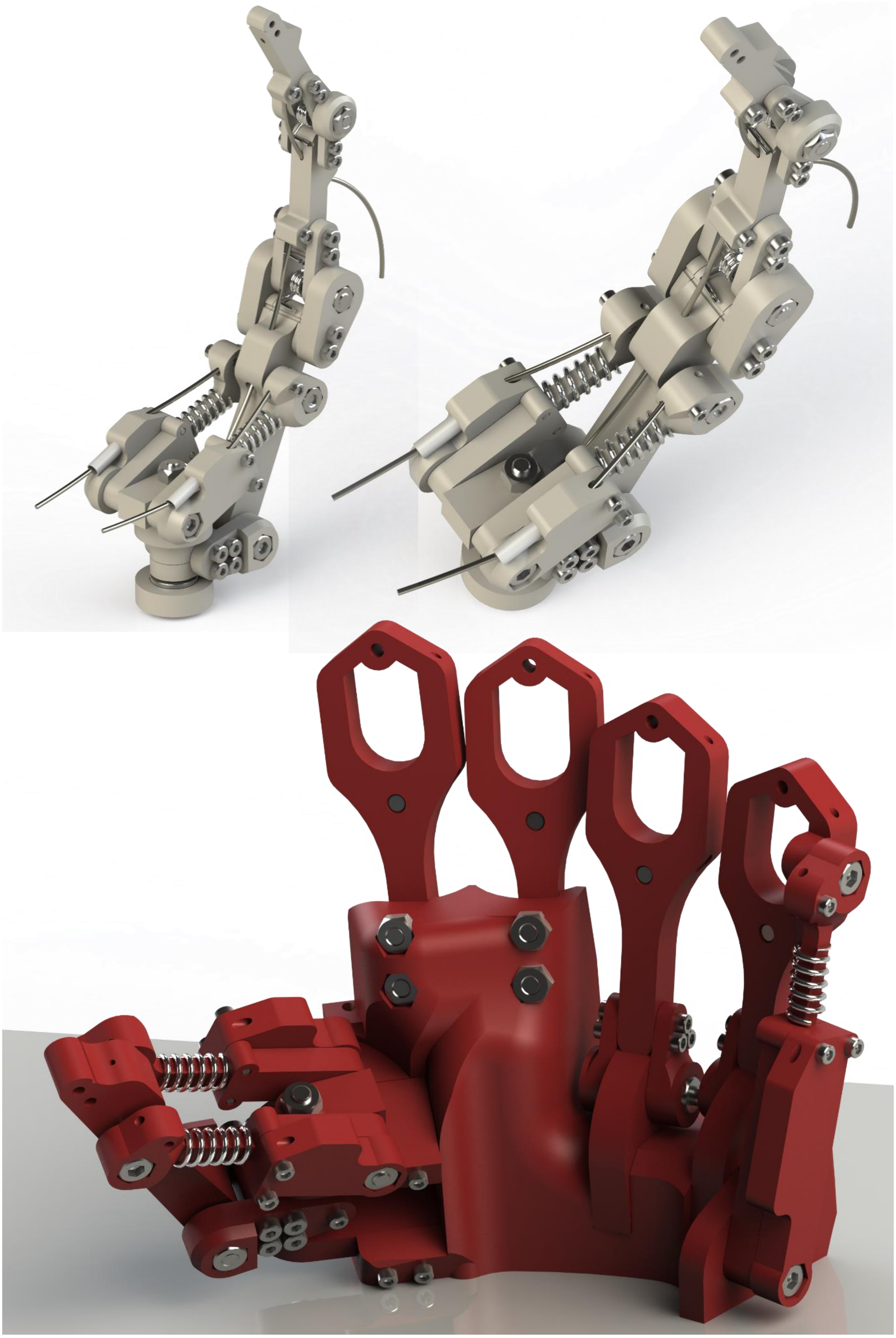

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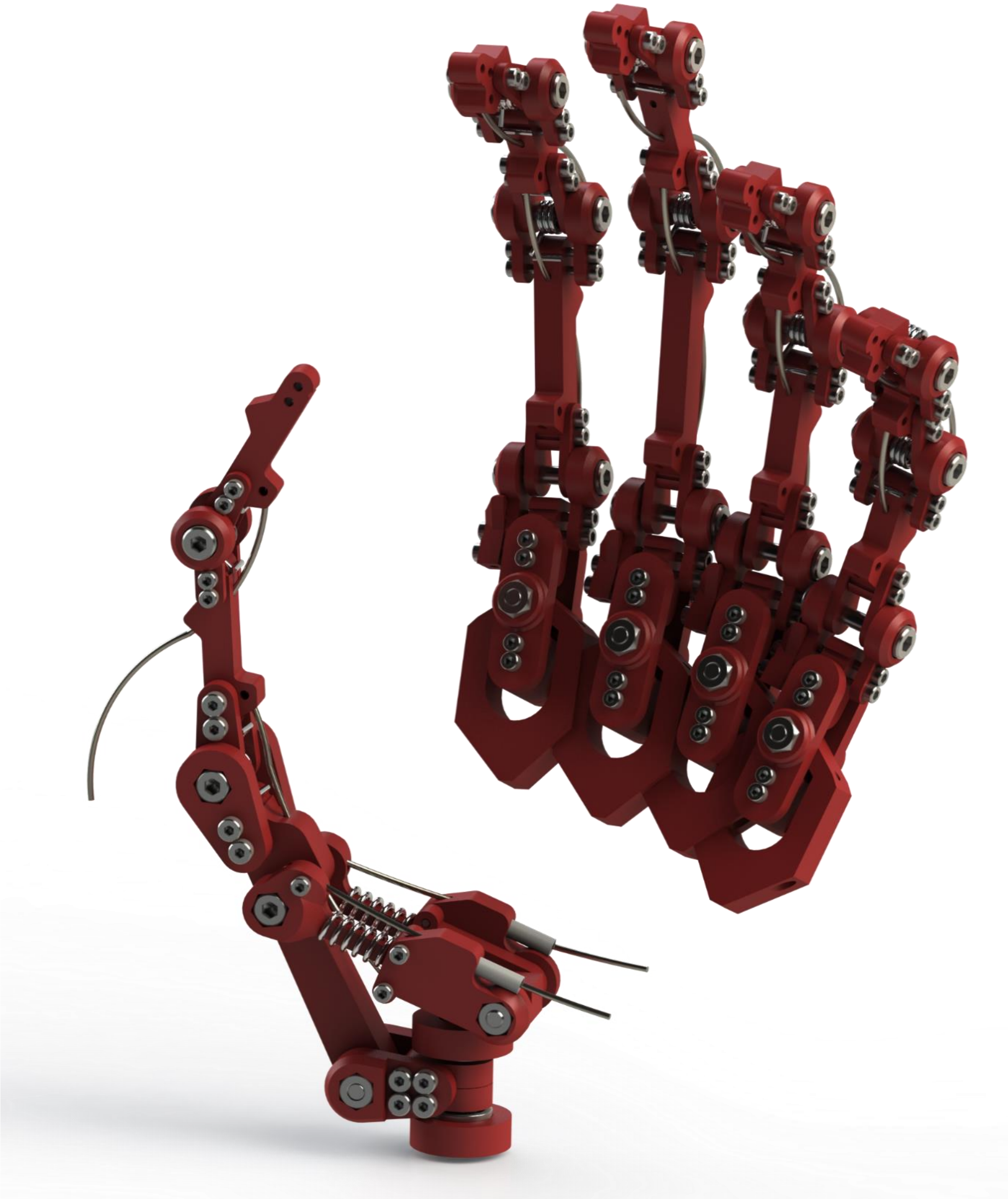


Figure 21.45 - All fingers and thumb arranged for development of carpal block

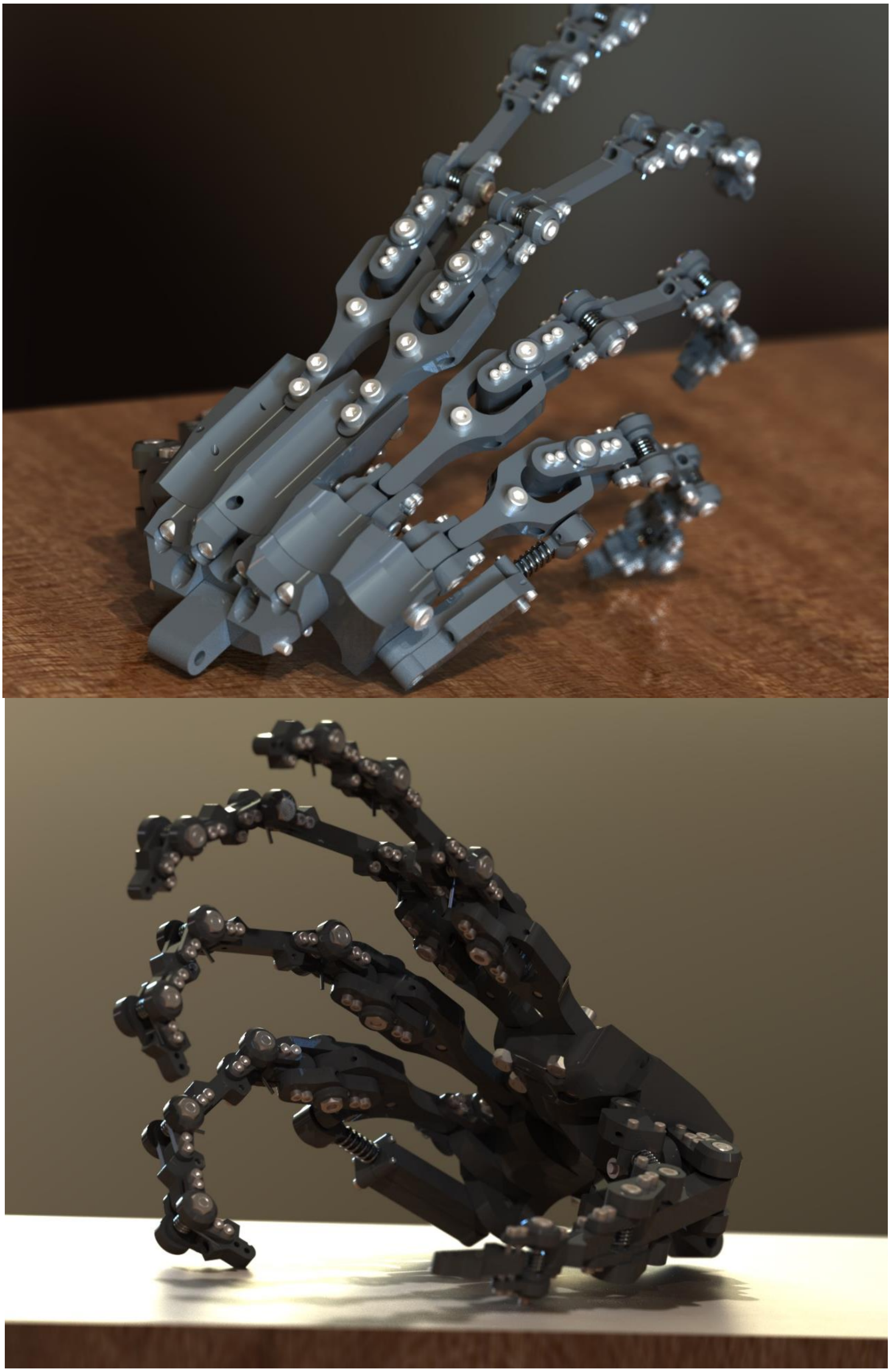


Figure 21.46 - Completed bionic hand skeleton

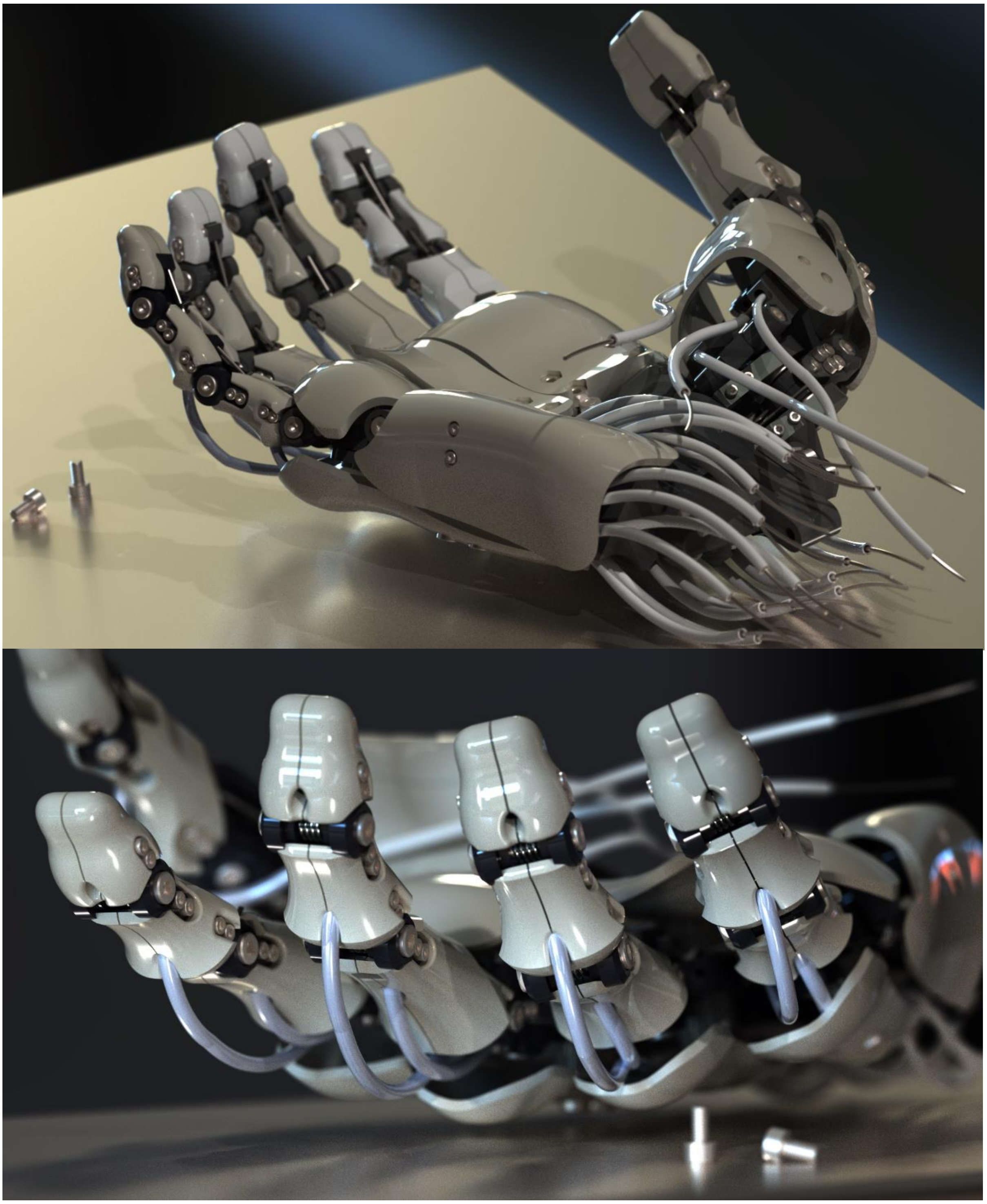
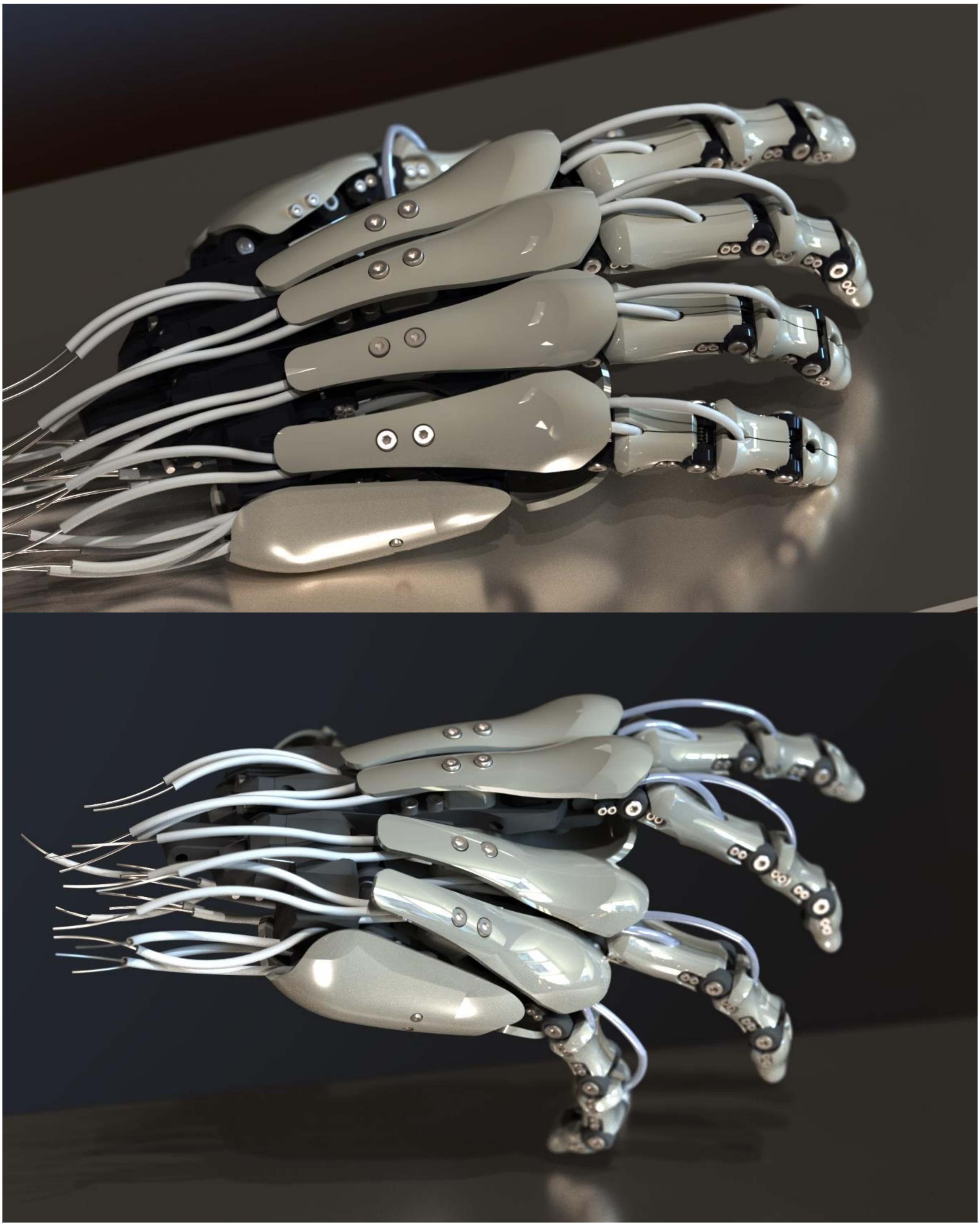


Figure 21.47 - Bionic hand first prototype renders 1



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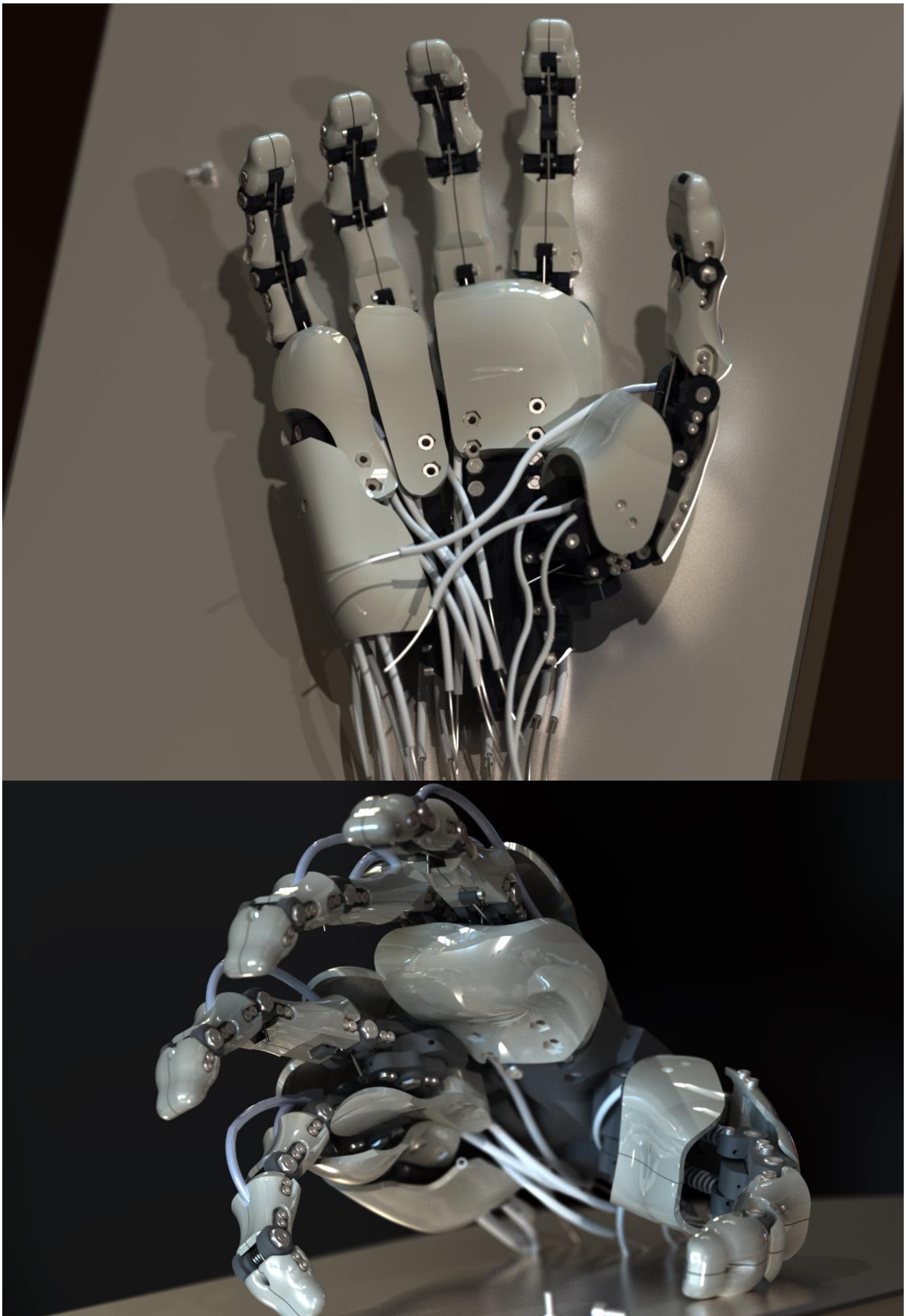

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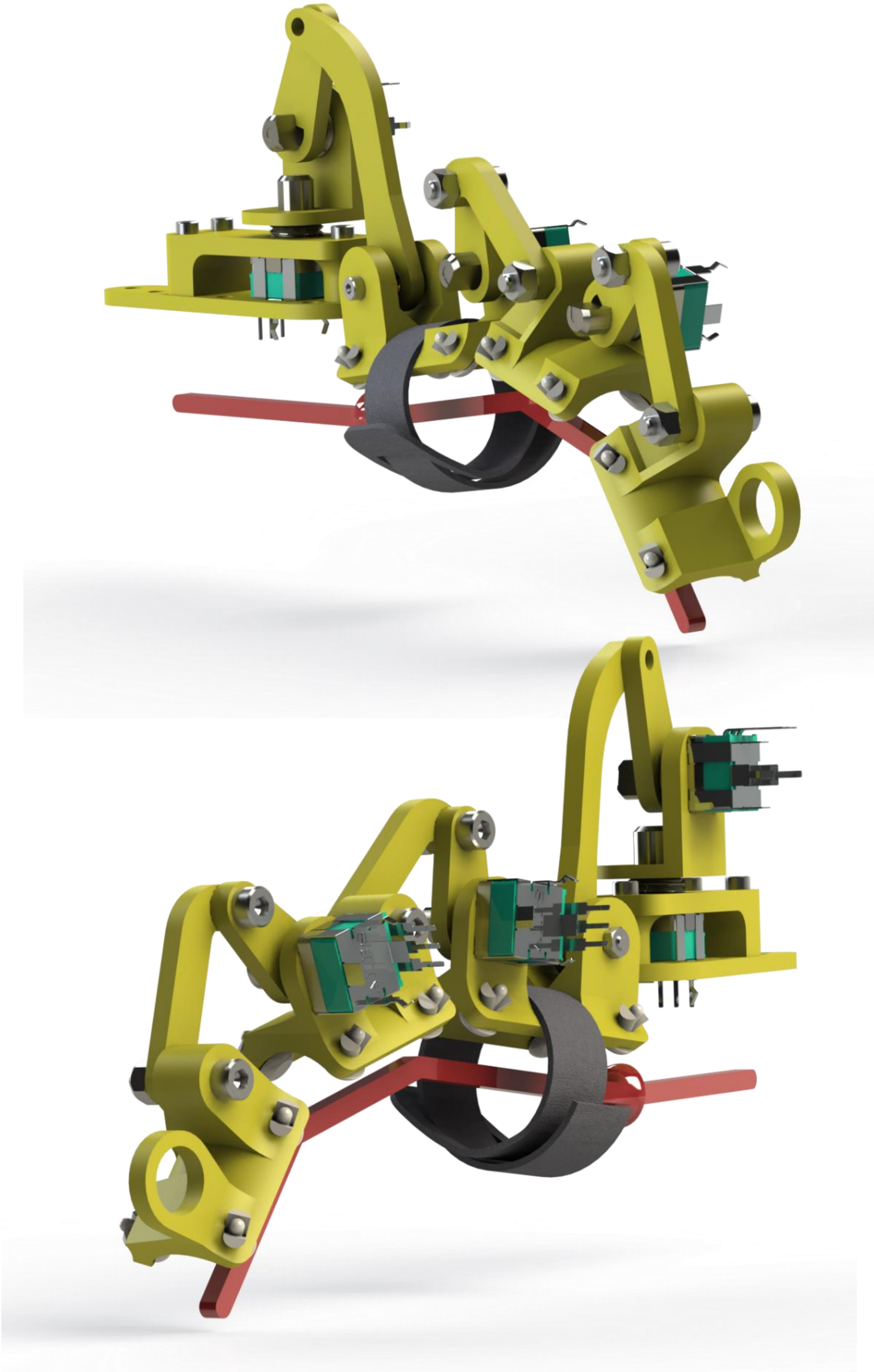

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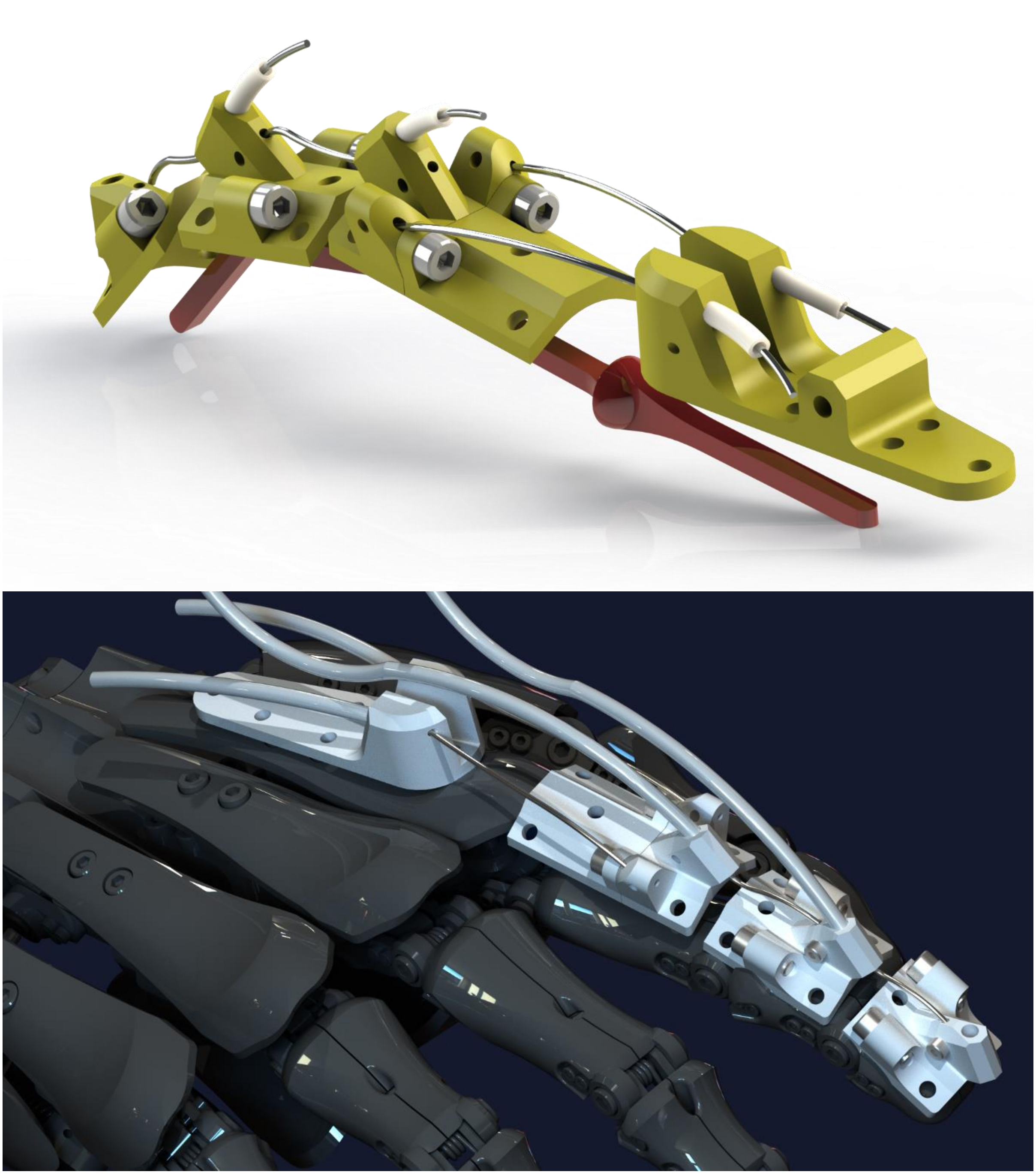

Figure 21.51 - Displaced sensor control glove alternative views

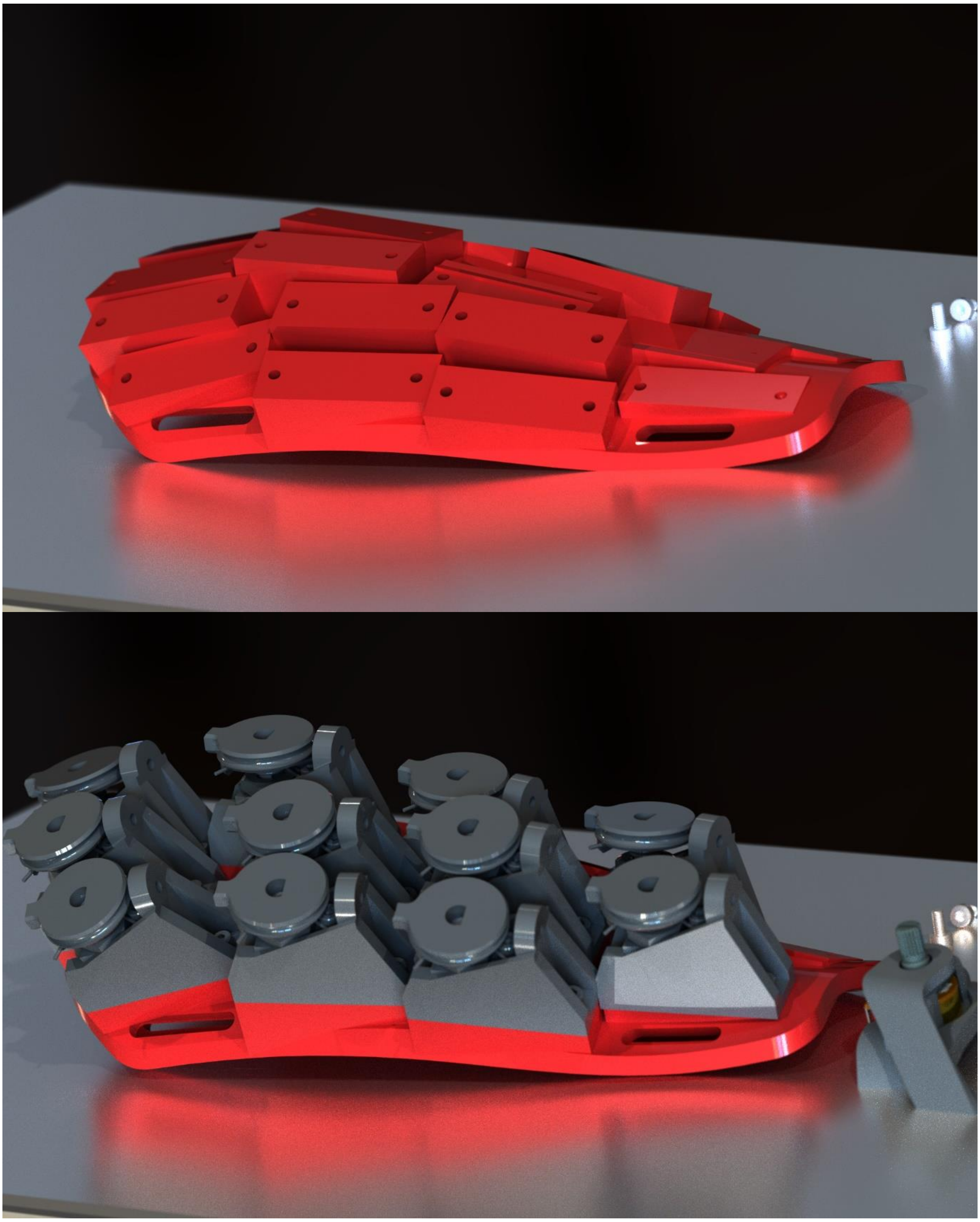

Figure 21.52 - Control glove sensor mount

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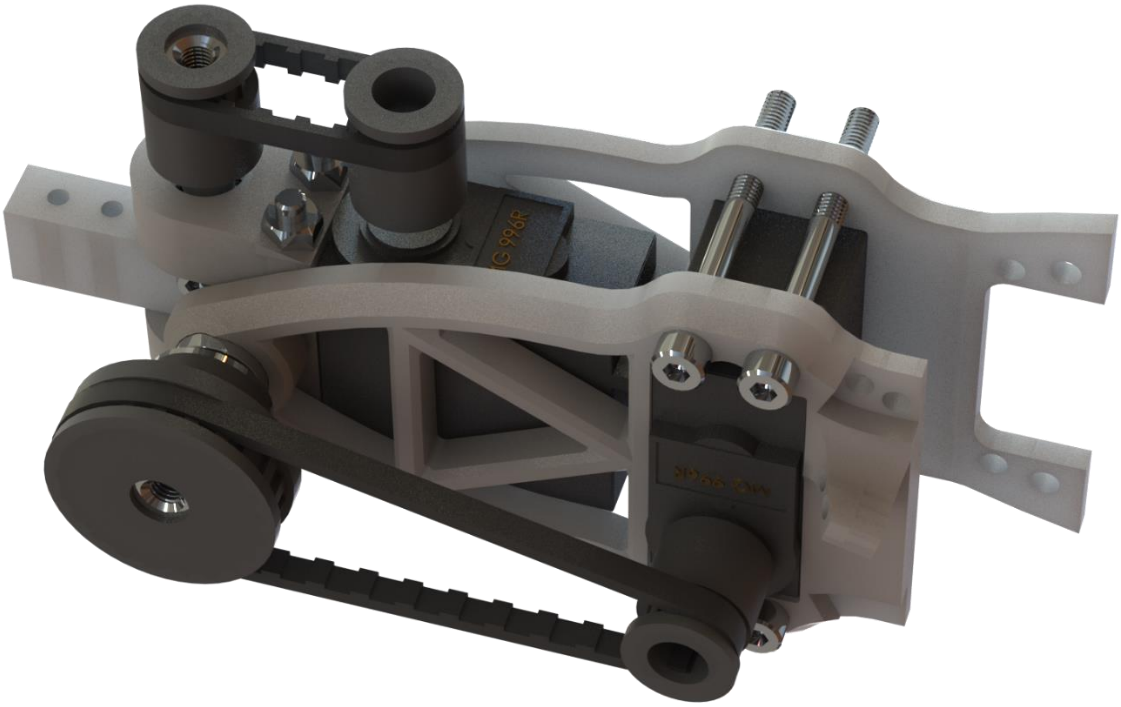

Figure 21.53 - Updated wrist mechanism

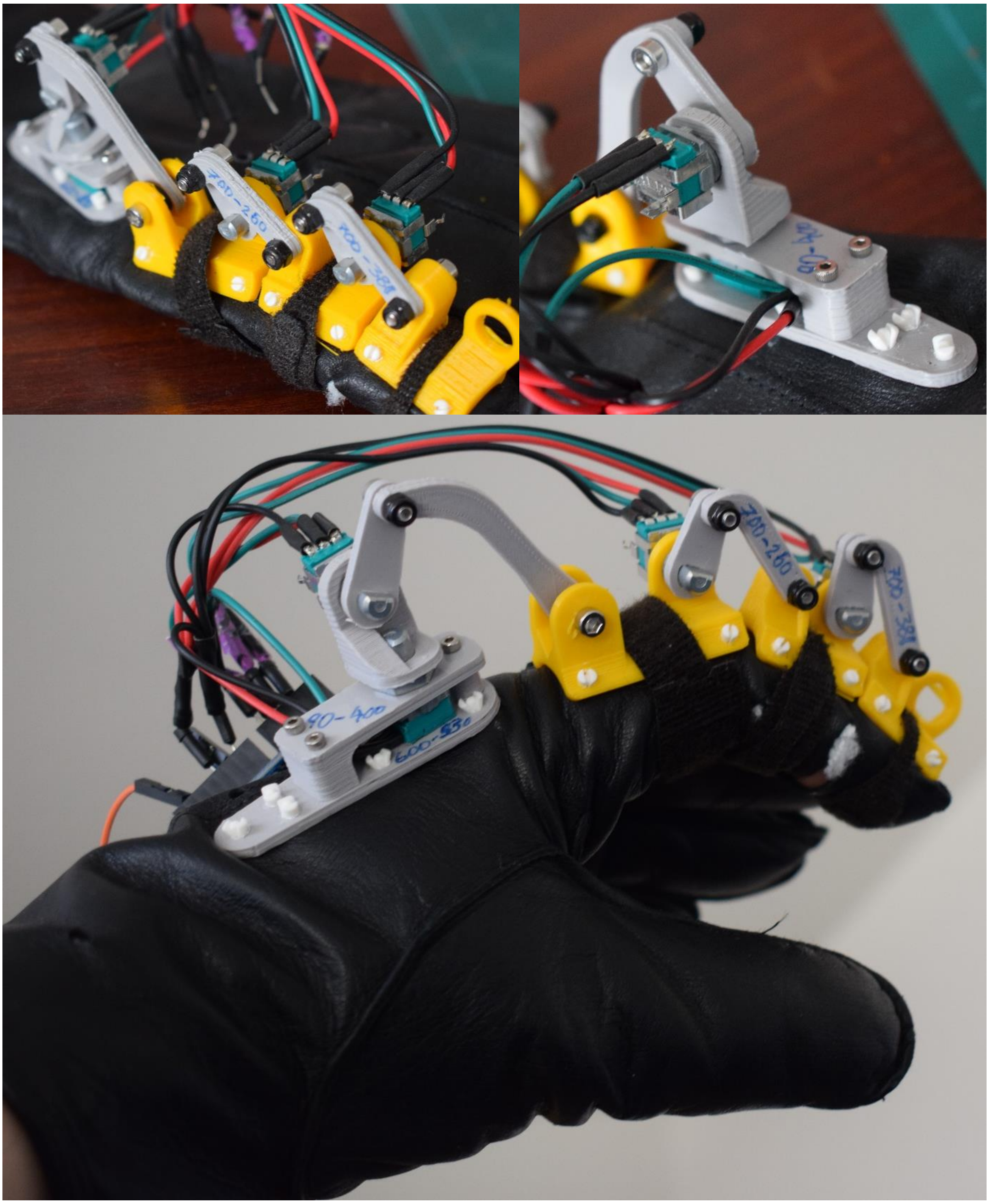

Figure 21.54 – Control glove views

_4_finger_output_sk

```
// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:
void loop() {
  // read the input on analog pins:
  int sensorValue0 = analogRead(A0);
   int sensorValue1 = analogRead(A1);
    int sensorValue2 = analogRead(A2);
     int sensorValue3 = analogRead(A3);

  // print out the value you read:
    Serial.print(sensorValue0);
        Serial.print(" ");  //Spaces added for readability
        Serial.print(sensorValue1);
        Serial.print(" ");
            Serial.print(sensorValue2);
            Serial.print(" ");
                Serial.println(sensorValue3);

      delay(300);        // delay in between reads for stability
}
```

Figure 21.55 – Control glove testing code

servo §

```
#include <Wire.h>
#include <Adafruit_PWMServoDriver.h>

#define SERVOMIN  90 // this is the 'minimum' pulse length count (out of 4096)
#define SERVOMAX  500 // this is the 'maximum' pulse length count (out of 4096)

int aPot;   //Define pot reading variables
int bPot;
int cPot;

int mapaPot;    //Variables used to store mapped values from potentiometers
int mapbPot;
int mapcPot;

// our servo # counter
uint8_t servonum = 0;

void setup() {
  Serial.begin(9600);
  Serial.println("16 channel Servo test!");

  pwm.begin();

  pwm.setPWMFreq(60);  // Analog servos run at ~60 Hz updates

  yield();
}

// you can use this function if you'd like to set the pulse length in seconds
// e.g. setServoPulse(0, 0.001) is a ~1 millisecond pulse width. its not precise!
void setServoPulse(uint8_t n, double pulse) {
  double pulselength;

  pulselength = 1000000;   // 1,000,000 us per second
  pulselength /= 60;   // 60 Hz
  Serial.print(pulselength); Serial.println(" us per period");
  pulselength /= 4096;  // 12 bits of resolution
  Serial.print(pulselength); Serial.println(" us per bit");
  pulse *= 1000;
  pulse /= pulselength;
  Serial.println(pulse);
  pwm.setPWM(n, 0, pulse);
}

void loop() {

  aPot = analogRead(A0);    //Read potentiometers
  bPot = analogRead(A1);
  cPot = analogRead(A2);

  mapaPot = map(aPot, 530, 600, 260, 370);  //Map readings on to desired servo angles
  mapbPot = map(bPot, 90, 400, 250, 500);   //  in terms of pulse length
  mapcPot = map(cPot, 260, 700, 350, 900);


  pwm.setPWM(0, 0, mapaPot);    //Actuate servos
  pwm.setPWM(1, 0, mapbPot);
  pwm.setPWM(2, 0, mapcPot);

  delay(50);    //Delay for stability


  }
```

Figure 21.56 – Glove and finger prototype testing code

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21.9

Figure 21.57 - CAD mockup of full prototype

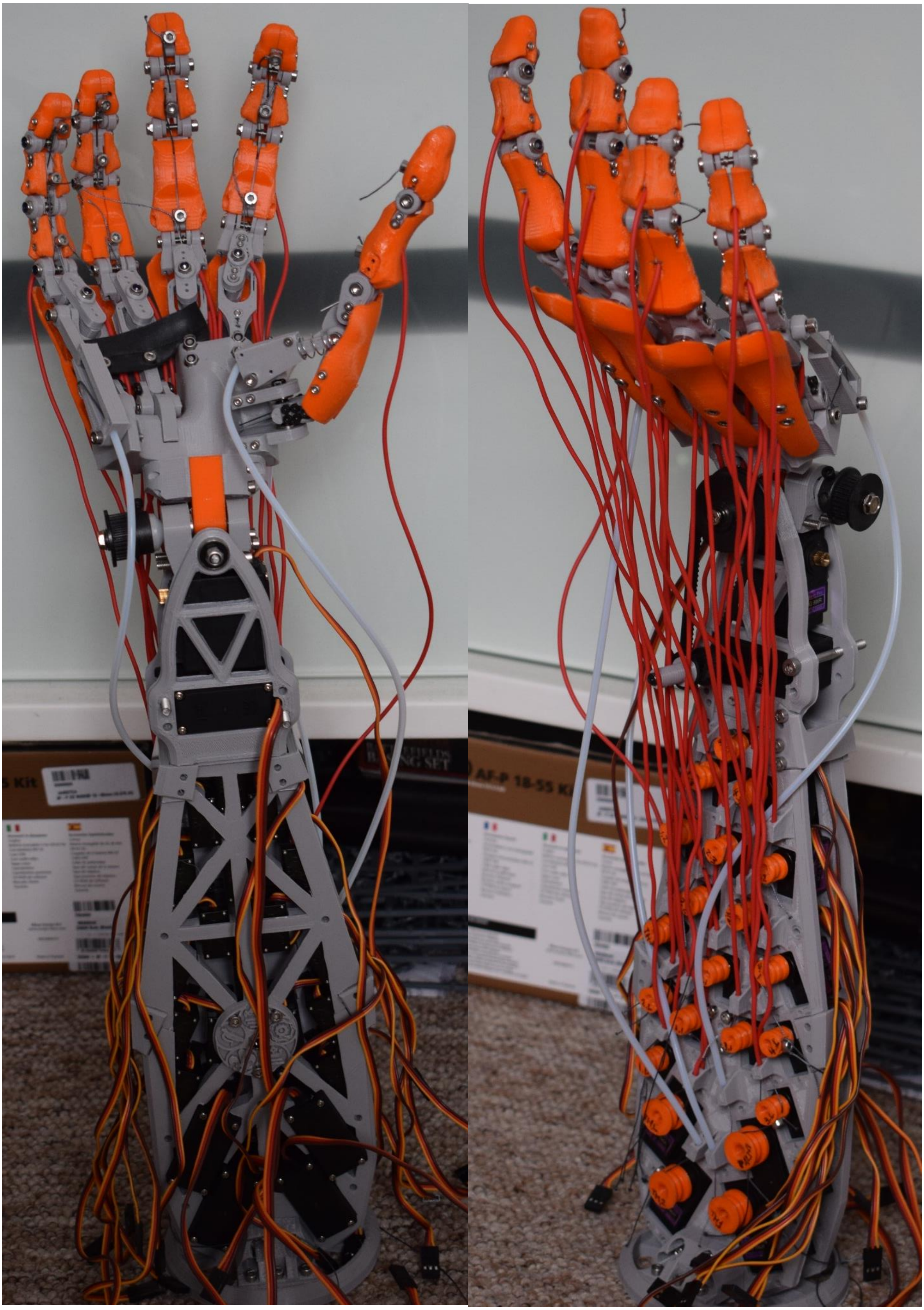

Figure 21.58 - Full prototype full views

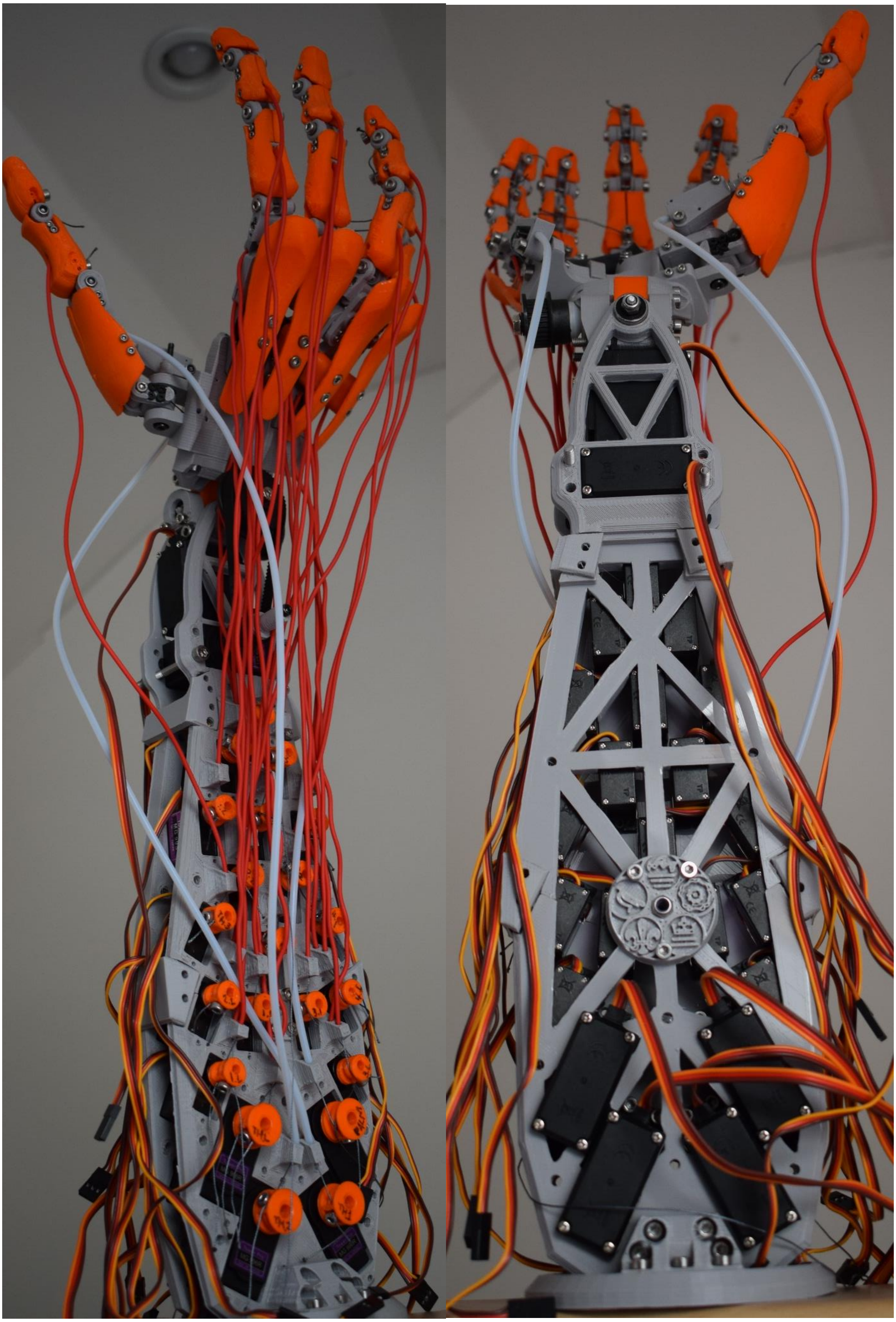

Figure 21.59 - Full prototype full views 2

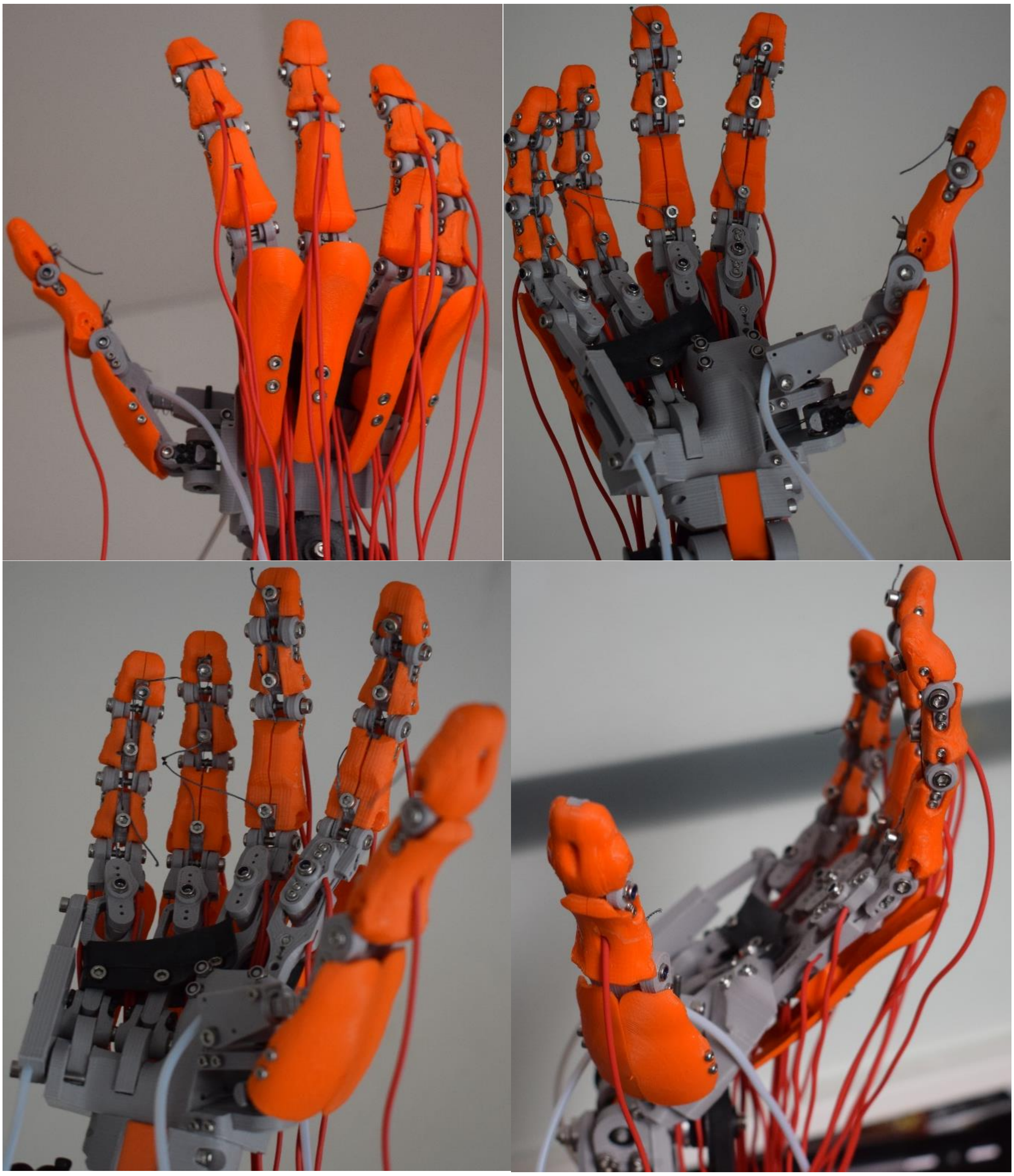

Figure 21.60 - Full prototype hand

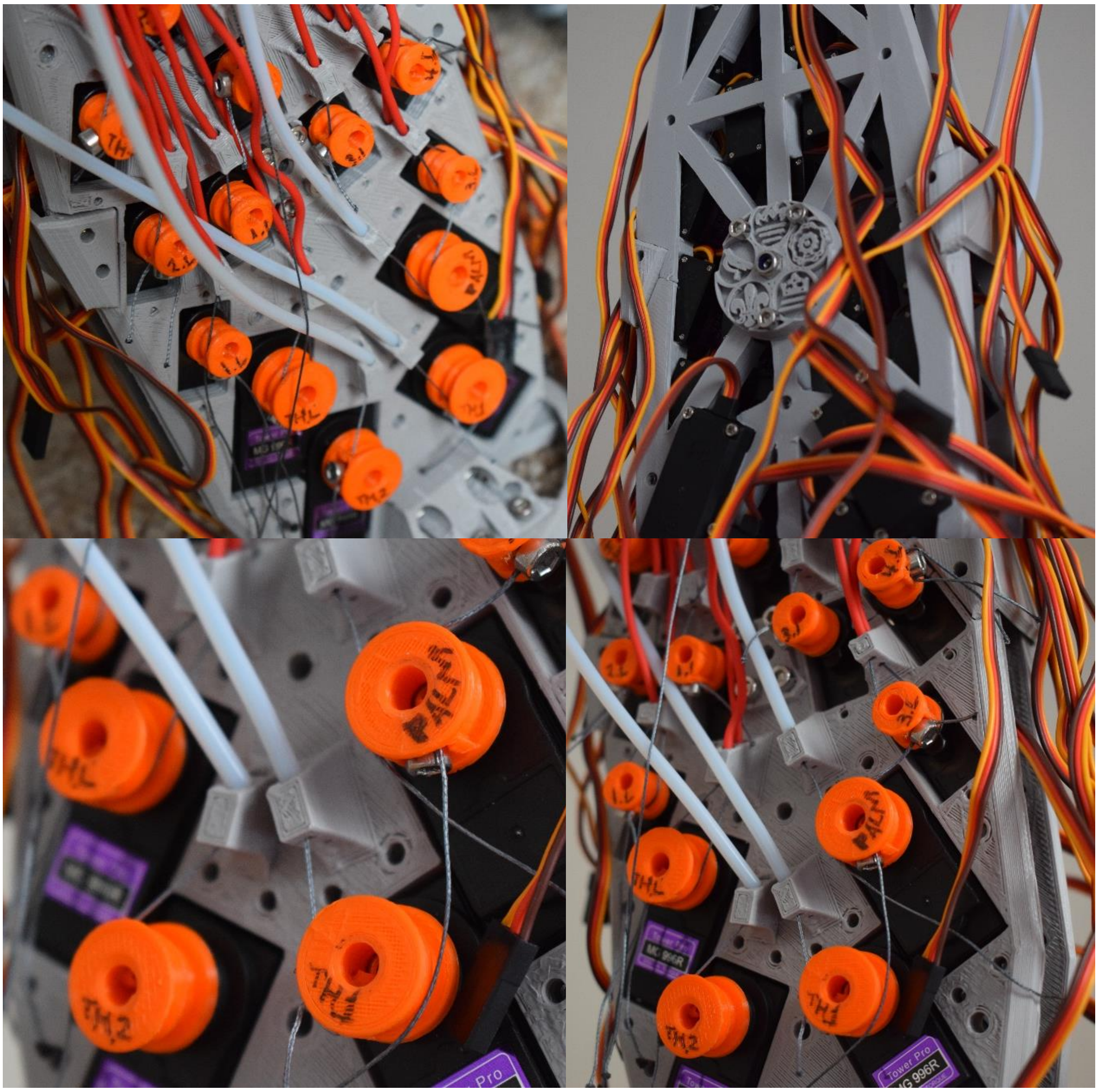

Figure 21.61 - Full prototype forearm closeups

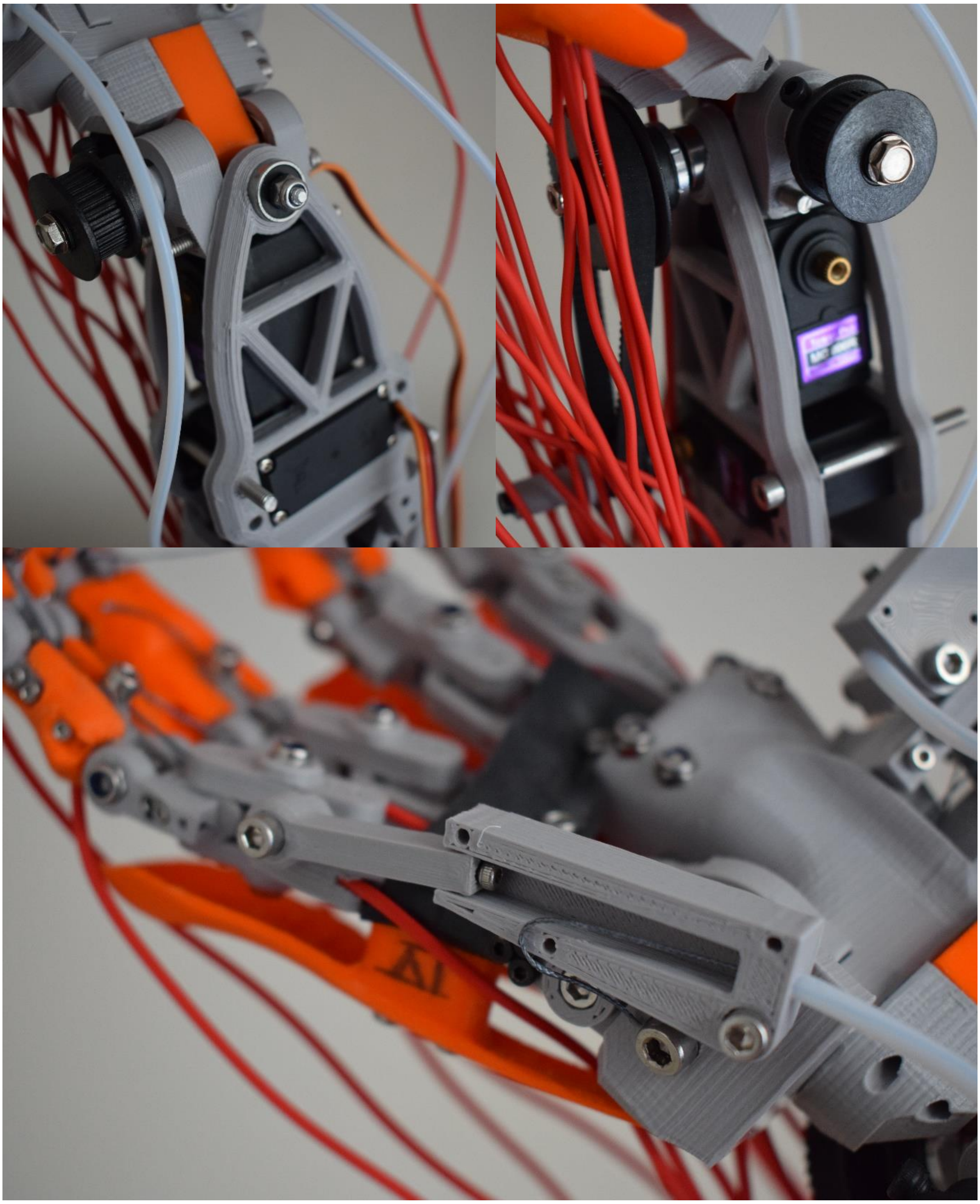

Figure 21.62 - Full prototype wrist and piston closeup

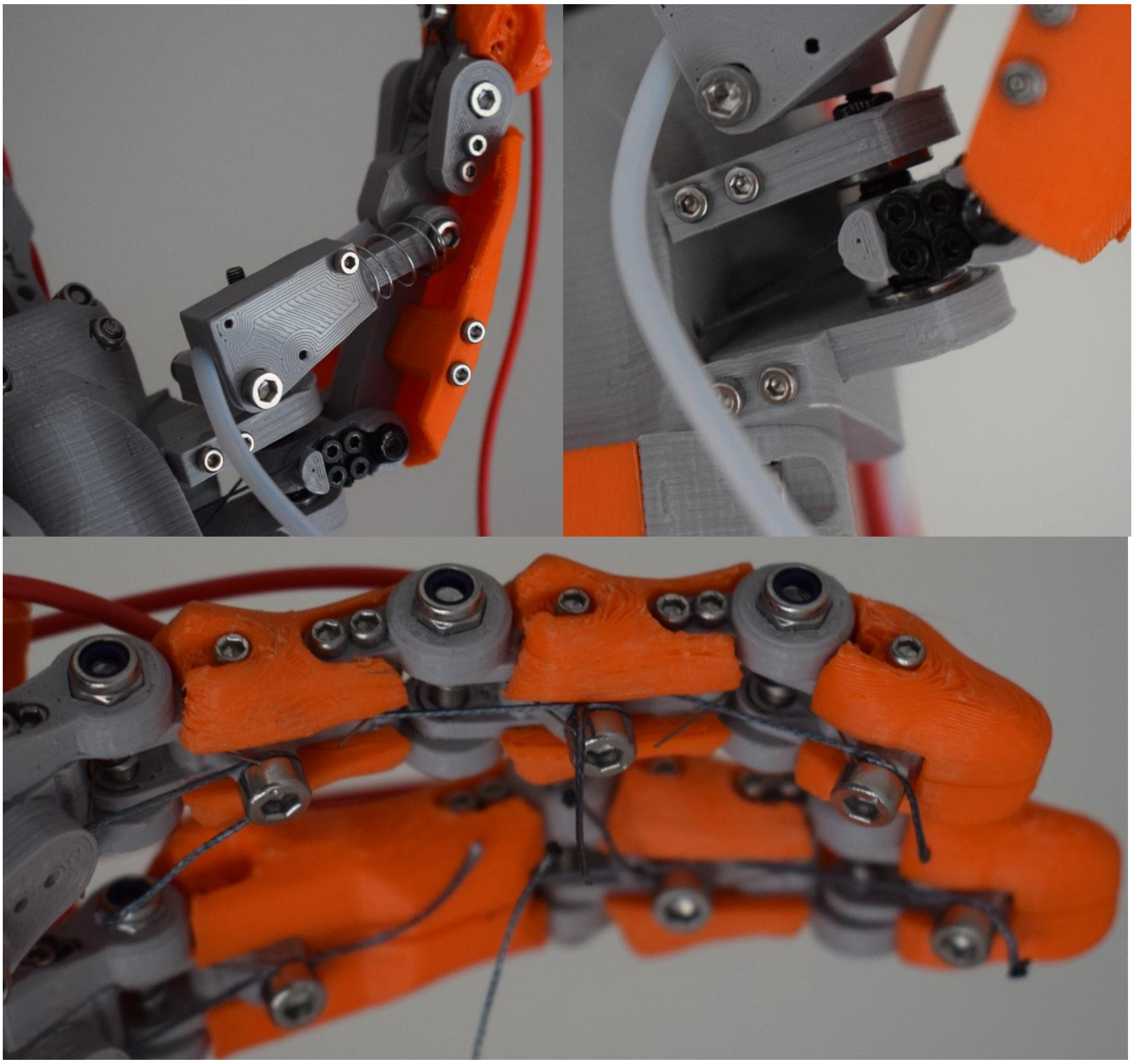

Figure 21.63 - Full prototype hand closeups

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21.

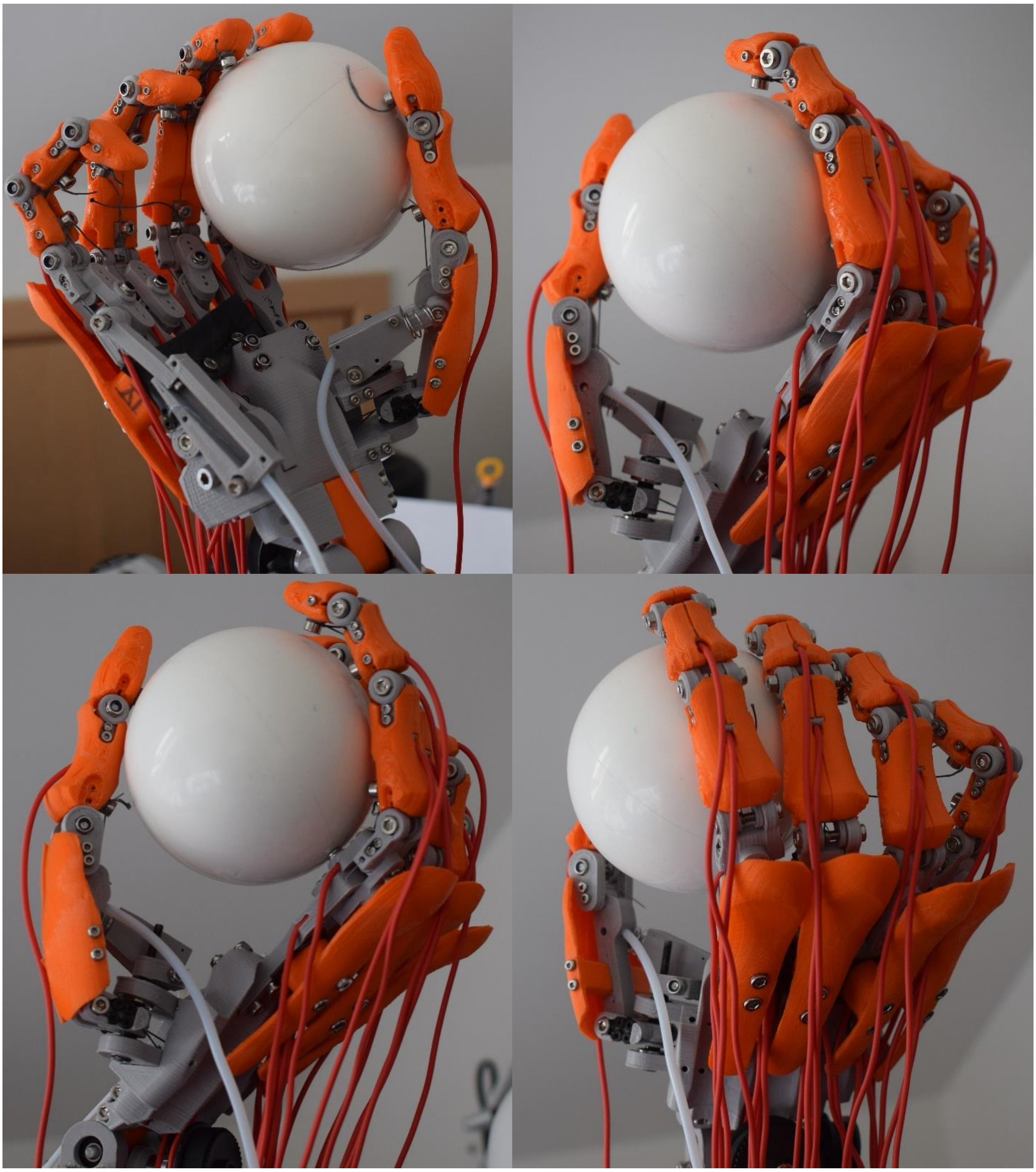

Figure 21.64 - Sphere grip type views

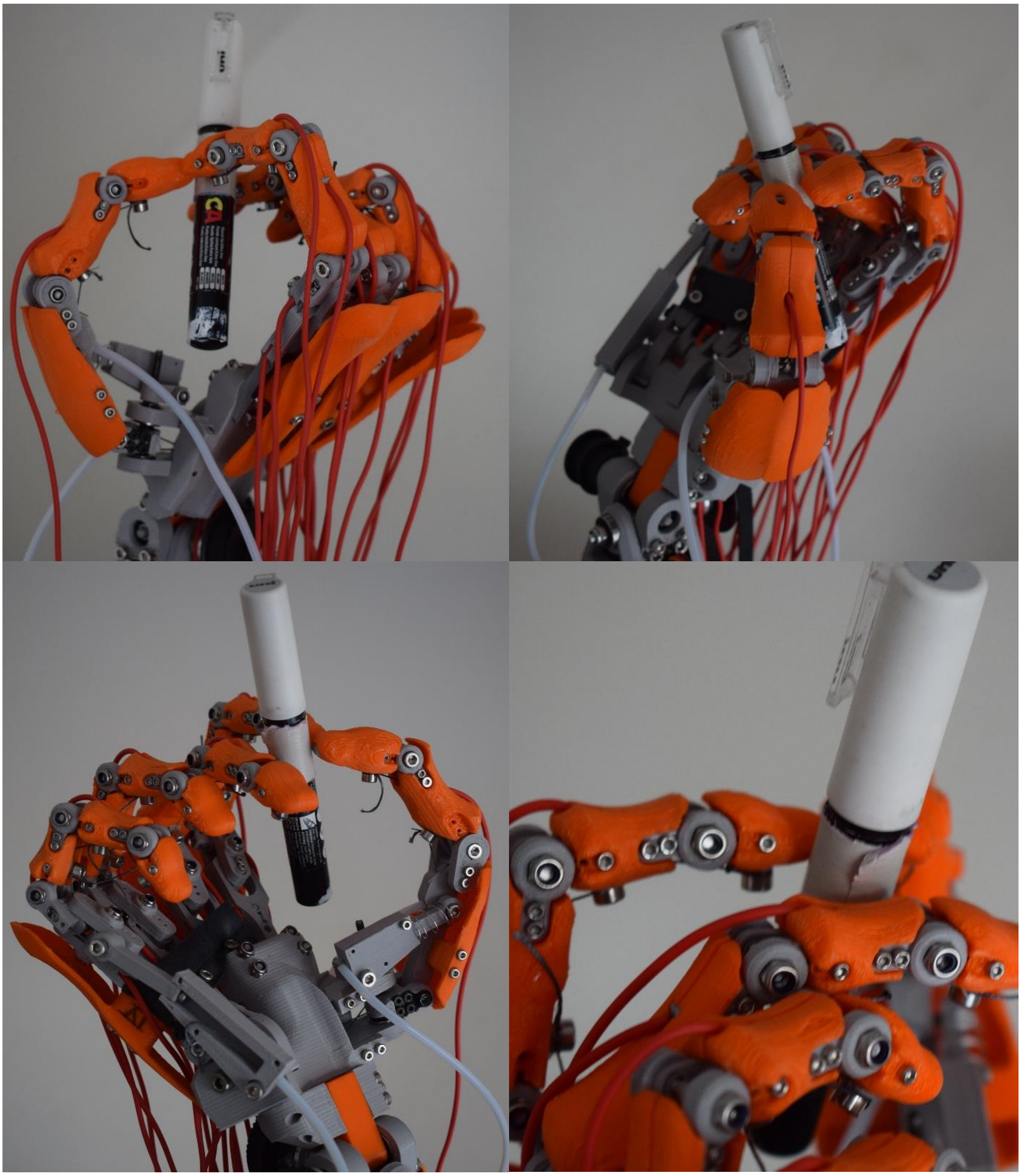

Figure 21.65 - Tripod grip type views

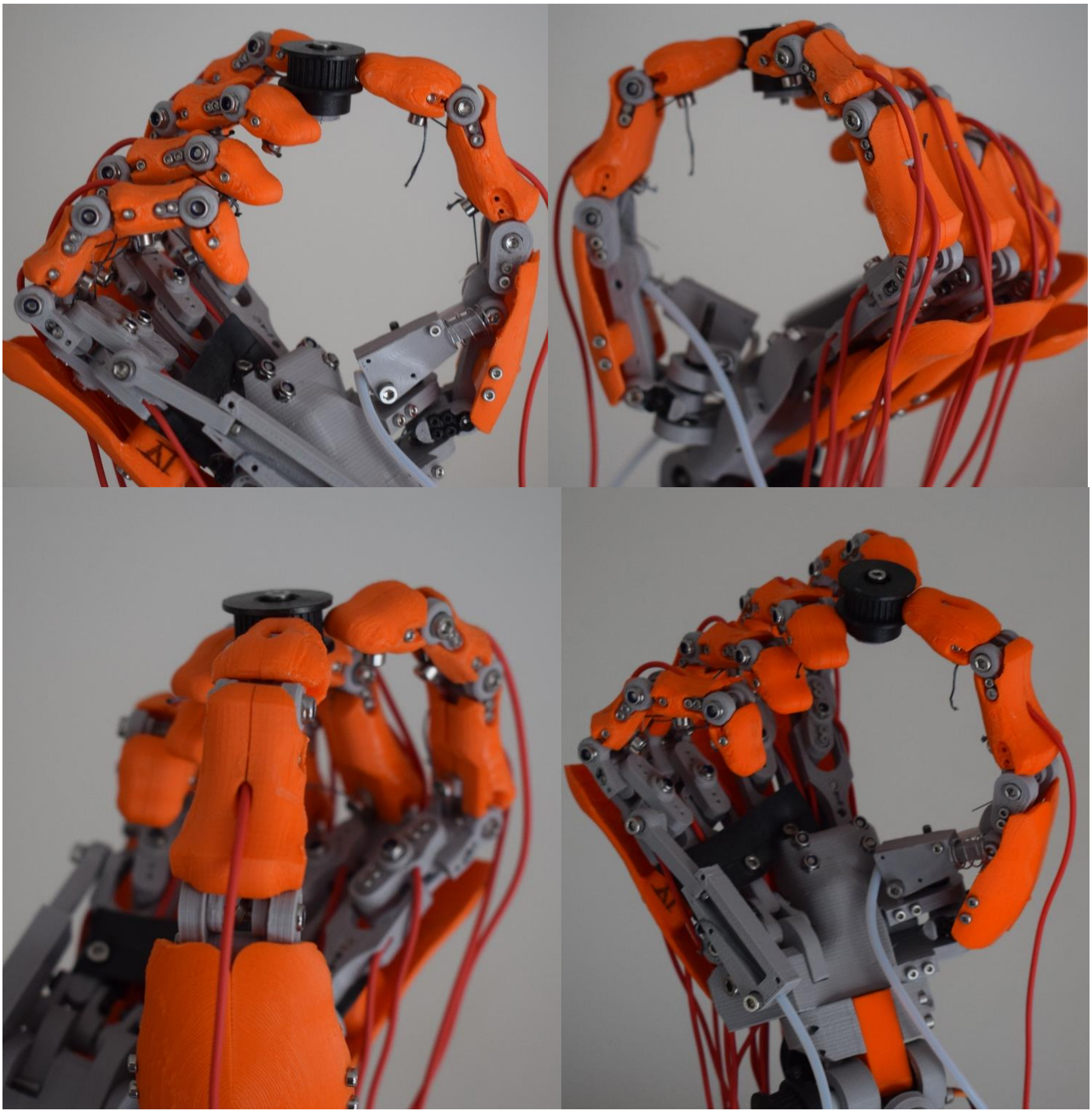

Figure 21.66 - Tripod grip type views alternate object

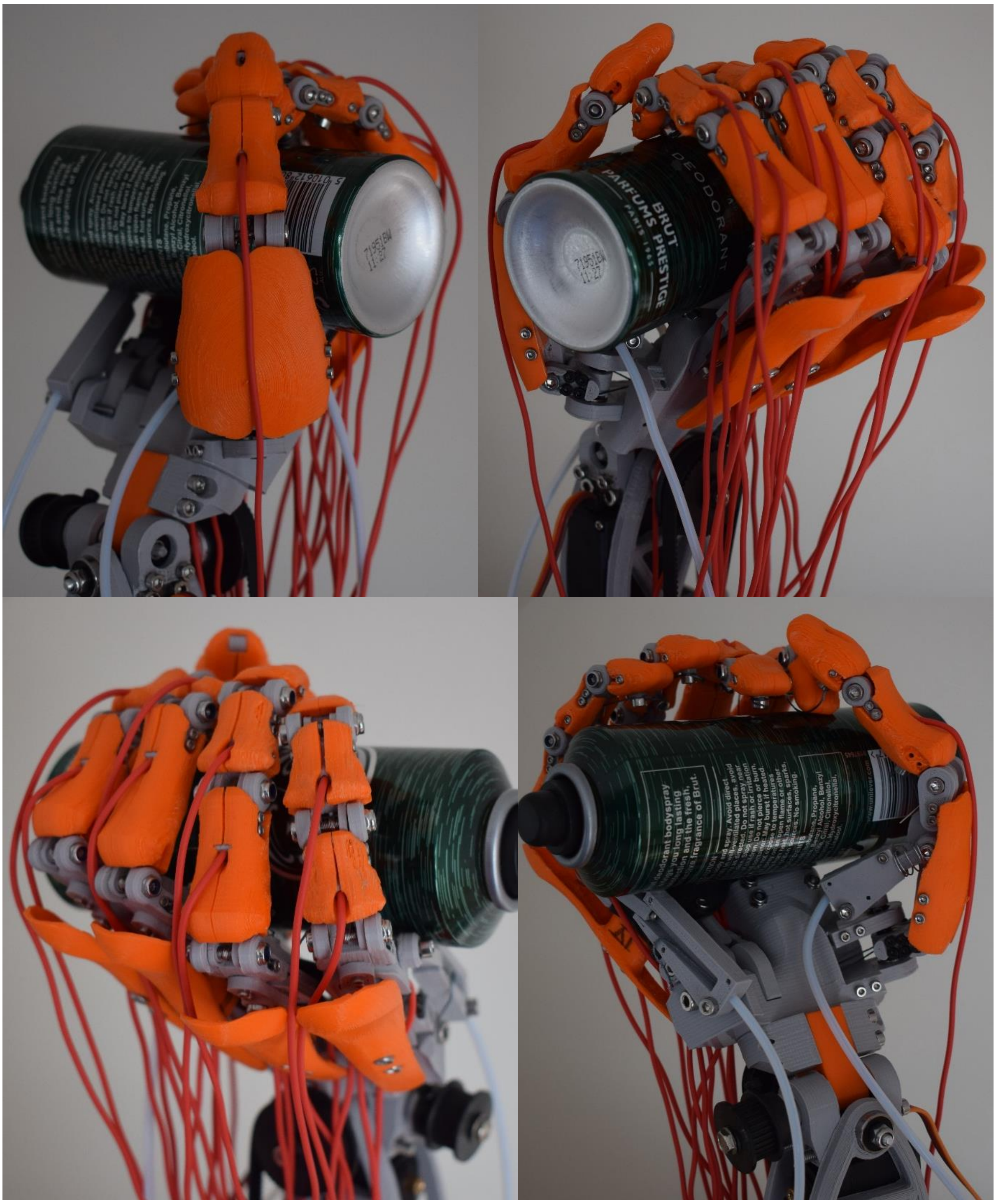

Figure 21.67 - Power grip type views

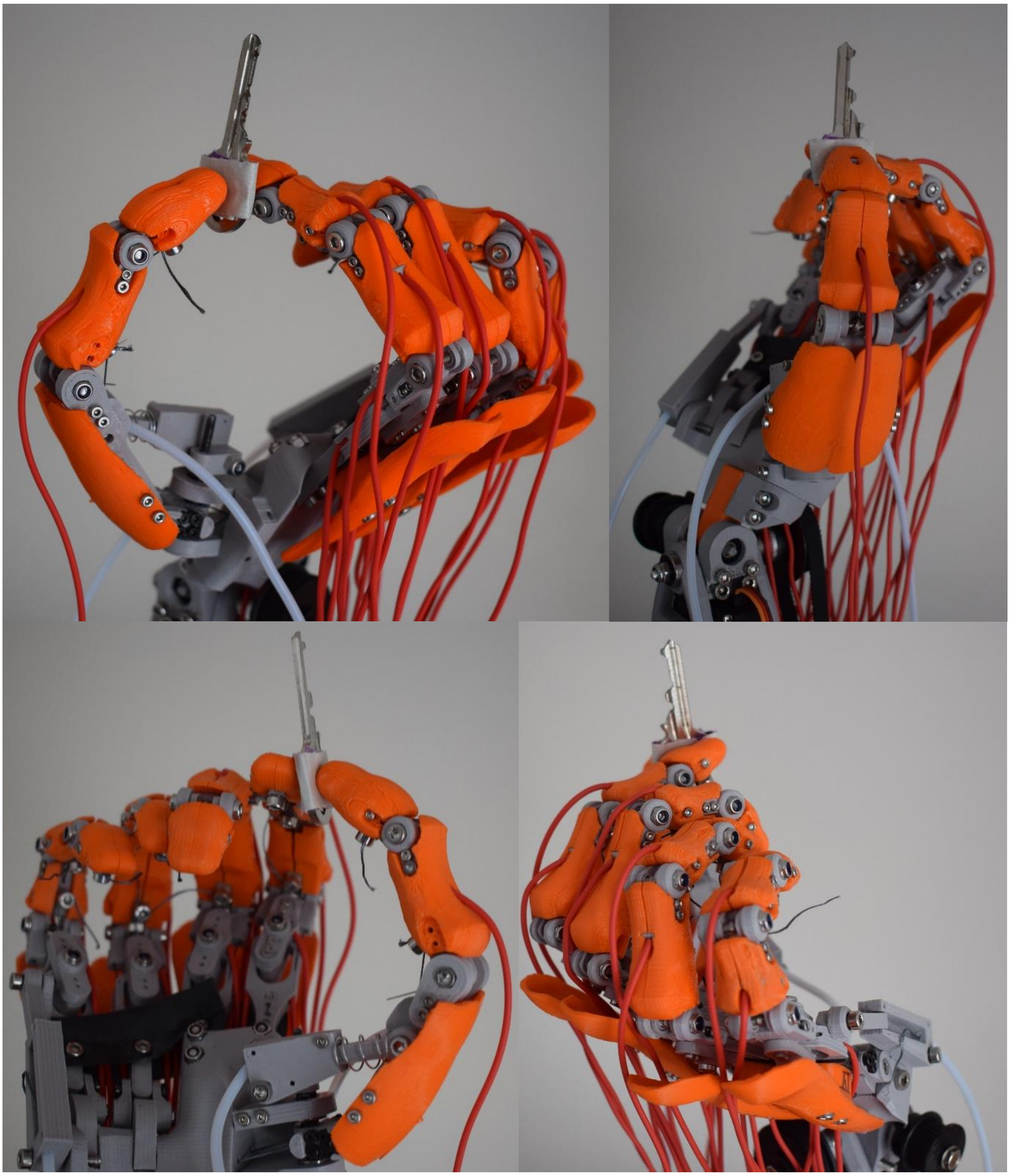

Figure 21.68 - Lateral grip type views

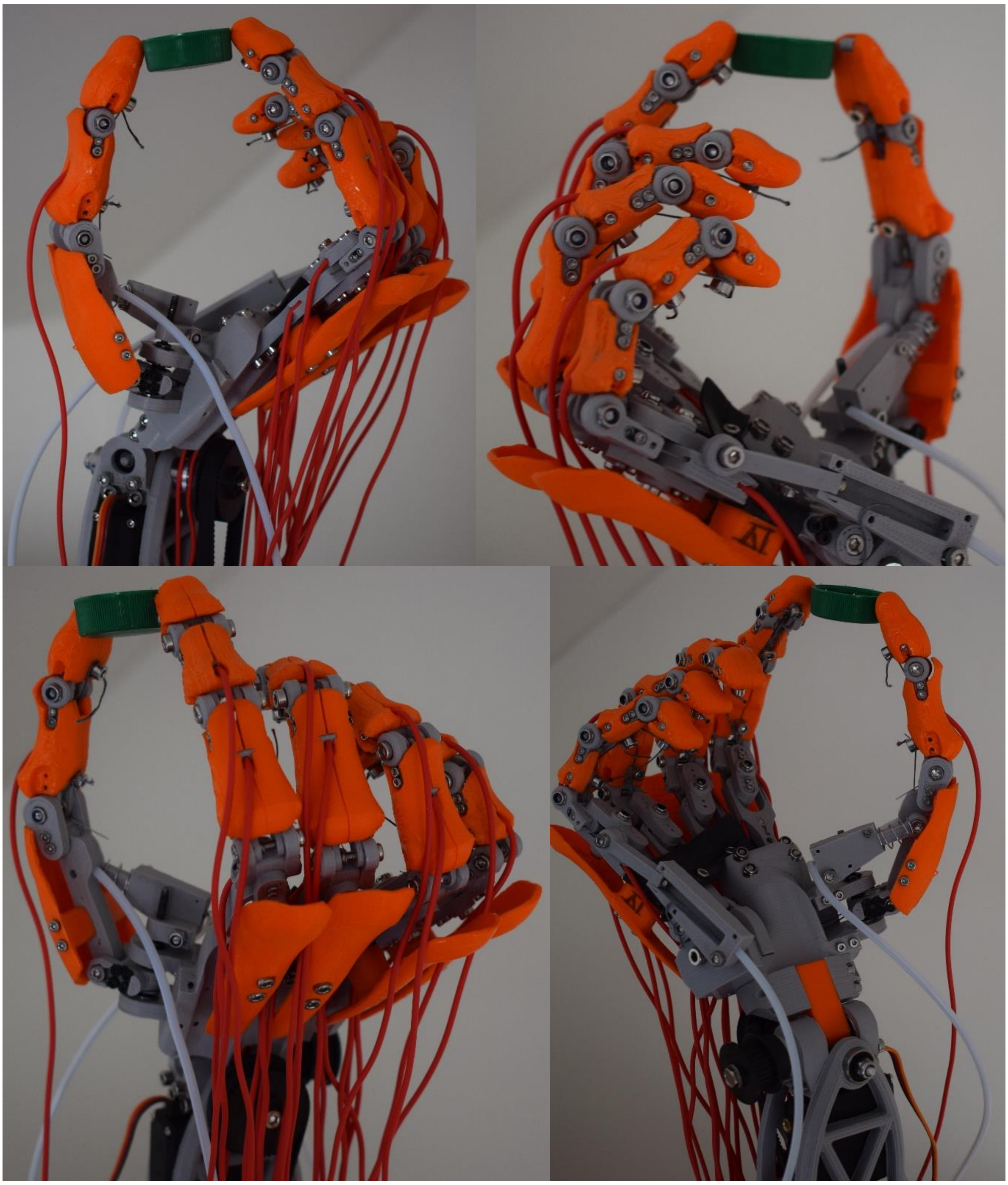

Figure 21.69 - Tip grip type views

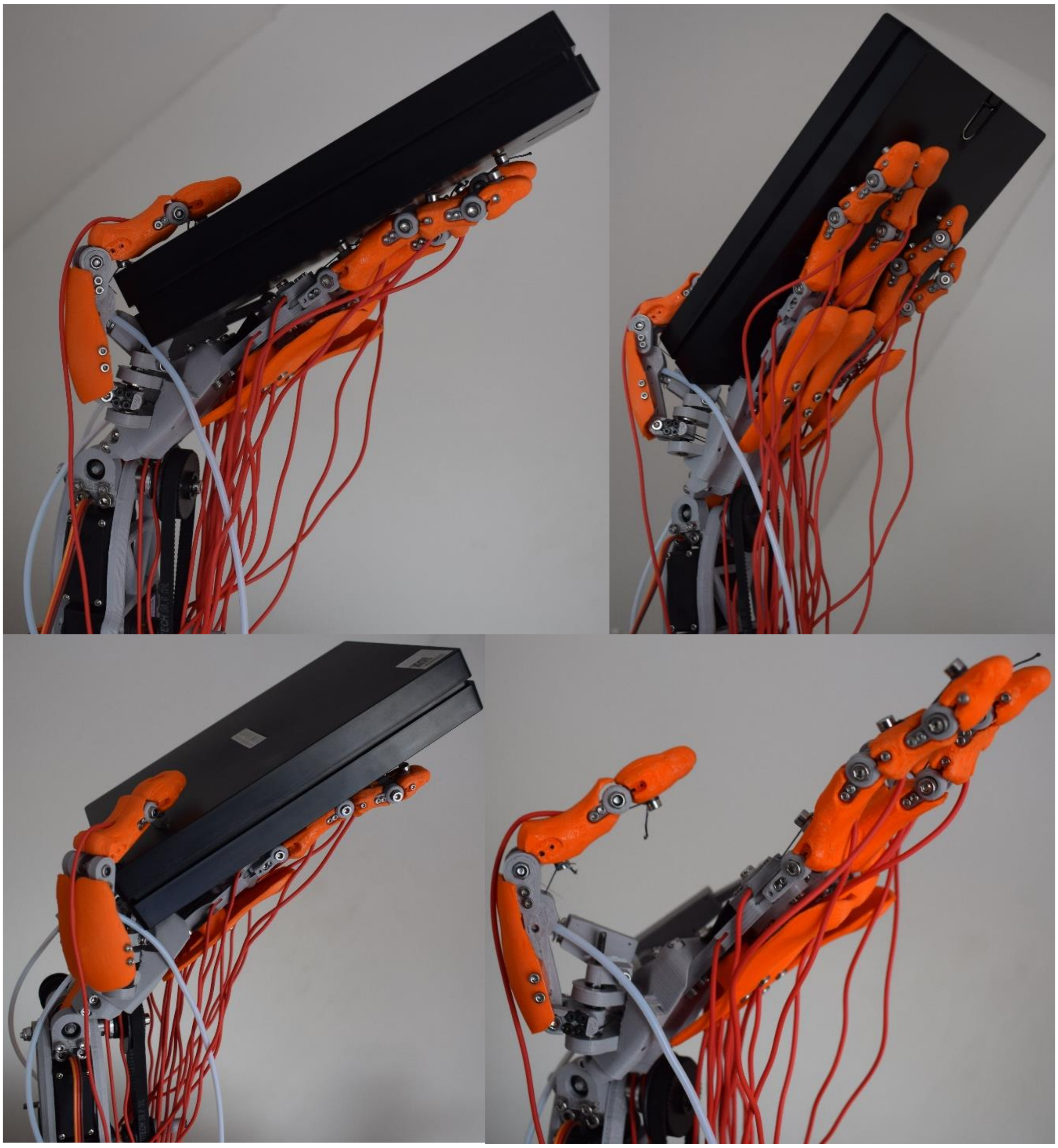

Figure 21.70 - Extension grip type views

Sub-System	Issue	Improvement
Fingers	Unwanted friction in joints	Use smooth, unthreaded pivots
		Reduce area of 3D printed material in contact with other parts
	Long assembly time	Reduce component count by combining some simple components
	Limited ROM	Use small pulley at each joint to ensure cable always has mechanical advantage on phalanx
		Reduce size of components to avoid collisions
	Finger width thicker than intended	Use longer bolts or (preferably) reduce width of fingers
		Use higher quality 3D printer or 3D printing settings
		More in depth post-processing such as sanding all components to a desired thickness
	Ring and little finger MCP poor lateral movement ability	Offset fingers away from palm
	Poor grip friction	Use higher friction material at finger tips and inner fingers such as TPU
	Obstructive cable clamping bolts	Use smaller bolts
		Make cable clamping position closer to centre of finger
	Fingers have trouble opposing each other	Find a way to integrate the inwards twisting at MCP joints
		Increase ROM of lateral motion at MCP joints
	Finger return springs too weak	Use stronger springs
		Reduce friction
Thumb	Thumb cannot touch index finger intermediate phalanx	Experiment with angle of hinge mounted on carpal block
		Design alternative hinge using inwards twisting as with finger MCP joints
	Thumb cannot flex far enough into palm	Offset thumb CMC joint such that range is shifted closer to palm
Wrist	Poor quality axels	Use more careful machining strategy for better quality axels
Palm	Elastic return mechanism too stiff and not enough force in desired direction	Use better material such as spring steel or nylon to apply force more towards neutral position than simply pulling metacarpals towards each other
	Palm is too large	Reduce size of carpal block, possibly also metacarpals
Shell Components	Friction too low	Use higher friction material at finger tips and inner fingers such as TPU
	Shell obstructing other components	More in-depth motion analysis in SOLIDWORKS to design better fitting components
Actuation System	Guide cable is compressible	Use incompressible material such as PTFE tubing or spring wire housing
	Cables are messy and may obstruct motion	Integrate wire-routing components to guide cables more neatly through the mechanism
	Inefficient use of space around motors	Cable mounting posts could be placed on top of servos to conserve space

Figure 21.71 – Summary of bionic hand issues and improvements

Section 16

21.11

Components	number	cost
Potentiometers	40.00	£ 23.20
M1.6 Bolts	200.00	£ 50.00
M2 Bolts	20	£ 1.20
M3 Bolts	80.00	£ 2.40
Torsion Springs	30.00	£ 36.00
MG90s	20.00	£ 146.00
MG996R	5.00	£ 62.50
Arduino Due	1.00	£ 25.00
Adafruit Driver	2.00	£ 37.80
Arduino Uno	1.00	£ 15.00
Total		**£ 384.10**

Figure 21.72 - Rough cost caluclation for ideal scenario

Components	number	cost
Potentiometers	40.00	£ 23.20
M1.6 Bolts	200.00	£ 50.00
M2 Bolts	20	£ 1.20
M3 Bolts	80.00	£ 2.40
Torsion Springs	30.00	£ 36.00
Small High T Servo	20.00	£ 400.00
High Torque Servo	5.00	£ 150.00
Arduino Due	0.00	£ 25.00
Adafruit Driver	1.00	£ 18.90
High Torque Stepper	3.00	£150.00
Arduino Uno	1.00	£ 15.00
Total		**£ 856.70**

Figure 21.73 - Best case scenario rough cost calculation