Quotebank

# Issue definition

1. Robotic or artificial hands, those with four fingers and a thumb, have demanding responsibilities that will improve the efficiency and usefulness of the robot if they can establish a power grasp and precision grip. {Mata Amritanandamayi, 2018 #24}
2. There are about 1,000,000 people who had an amputation of a hand or a complete arm worldwide. {Mata Amritanandamayi, 2018 #24}
3. Adoption and rejection is a particularly important outcome for studies of upper limb prosthetic devices, given that many persons with upper limb amputation refuse to use, or stop using, devices that have been prescribed to them. Studies have found that between 17% to 80% of persons with major upper limb amputation reject the use of a prosthesis entirely, with rejection rates typically the lowest for persons with transradial (TR) level amputation, and highest for those with transhumeral (TH) level or shoulder level amputations. {Resnik, 2017 #26}
4. However, various reports have documented consumers’ desire for upper limb prosthesis with greater functionality, lighter weight and more durability. {Resnik, 2017 #26}
5. By the year 2050, an estimated 3.6 million persons will be living with amputations within the United States. Military operation in Iraq and Afghanistan have led to 1716 United States Military Service members sustaining major limb loss as of September 2017, with 297 (17.3%) losing an upper limb. {Perry, 2018 #31}
6. Replacing a lost limb for an amputee is quite a challenge; an intuitive approach would be to mimic the function of the natural lost limb. {El-Hamad, 2017 #34}
7. The hand is considered one of the final actuators of greater complexity in the human body, and this gives its importance given the amount of degrees of freedom and consequent movements that can perform. {Proaño-Guevara, 2018 #36}
8. The possibility of recovering the entire member would give the patient a multipurpose tool, which is not limited to the hand, but to a whole system that would not only allow the patient to perform specific activities but also to live his life with normality and possibly reinserted into a job. {Proaño-Guevara, 2018 #36}
9. The development of an anthropomorphic and anatomically correct system based on musculoskeletal systems has proven to be a very complicated challenge, but once it is completed, it completely changes the range of movements and favours a greater acceptance of the patients that will use it, since, as they resemble a human hand, they feel more comfortable with it and their movements are much more natural and those designs that can be used in other areas of biomechanics. {Proaño-Guevara, 2018 #36}
10. All amputation is a great challenge, but when they are above the elbow they become even more complicated, since it requires not only replacing the functional part of the elbow but also the hand. So, the transhumeral prosthesis proves to be a great design challenge, but at the same time it will be possible to make the person perform practically natural movements. {Proaño-Guevara, 2018 #36}
11. Some reports claim that 50% of upper limb amputees chose not to wear a prosthesis because the functional advantage or cosmesis did not outweigh the inconvenience of the prosthesis. Primary indicators of prostheses rejection include a lack of perceived functional gain, prosthesis weight and socket discomfort. {Hashim, 2018 #38}
12. An increased grasp force is also one of the special desires of body-powered prosthesis users. {Hashim, 2018 #38}
13. Thus many amputees opt for an externally powered prosthesis, and the gap of usage is large between the two types. {Hashim, 2018 #38}
14. The limits that prevent the advent of next generation prostheses, are well knokwn and pertain to both the human machine interface, and to the physical features of the device. Among the latter ones, the most crucial is probably the lack of compact and reliable actuators with power densities similar to the human muscles. {Montagnani, 2017 #39}
15. Using a prosthesis on a daily basis implies that the user should not feel tired after a number of manipulations and should also not experience any pain (e.g. sore muscles and pinching) during or after use. {Hichert, 2018 #40}
16. Among the amputations that involved the upper extremity, approximately 92% of the cases were partial hand amputations. {Imbinto, 2018 #41}
17. Activities of daily living (ADL) and, in particular, some important objectives such as doing work, performing home chores, and participating in hobbies have specific requirements, such as high grip power; grasp versatility; ruggedness; resilience; resistance to water, dust and temperature; durability; power autonomy; and low cost. Alternatively, factors like the multiplicity of gestures or aesthetics are less dominant. {Piazza, 2017 #42}
18. The aesthetic appearance and quietness of the device are usually among the most important characteristics that a prosthetic system should ideally exhibit. However, a robust prosthetic aid that supports the user not only in ADL (an area of fundamental importance) but also in work activities, home chores, and hobbies can play a critical role in psychological wellbeing as well as social acceptance. For these reasons, we can essentially divide the driving force behind technological advancements of upper-limb prosthetic aids into two goals: 1) the attainment of a realistic aesthetic appearance and 2) the restoration of lost functionality and ability. {Piazza, 2017 #42}
19. Among the many requirements needed by these applications, we can cite high grip power, grasp versatility, resilience and power autonomy as the main design parameters, whereas factors like aesthetics or silent operations are less dominant. {Piazza, 2017 #42}
20. Anthropomorphism is sought for a number of reasons and at various levels, from the possibility of imitating how humans approach fine manipulation problems, where dexterity is necessary, to the employment as prosthetic devices, where aesthetics is an important issue. {Borghesan, 2010 #49}
21. Currently, upper limb amputation involves approximately 41,000 persons in the United States. {Gailey, 2017 #54}

# Problems/notes with current designs

1. About 30 to 50% handicapped persons do not use their conventional prosthetic hands regularly since the hands are heavy in weight, low functionality and limited DOF’s cause inability to adapt to the shape of an object. In order to serve them adequately, it is indispensable for the robots to have soft-moving hands. The various artificial hands that are available are essentially based on linkage-mechanisms or hydraulic and pneumatic elements such as wires, cables and chains, belts, artificial muscles etc. {Mata Amritanandamayi, 2018 #24}
2. Reasons for non-completion by phase of study withdrawal that were related to the DEKA arm were specifically related to the heaviness of the DEKA arm and other reasons other than heaviness. Data coded within this category included statements indicating that the participant didn’t like the appearance, had concerns about reliability; that the arm was too hot; that the arm was a “hindrance” that slowed them down; that the arm needed “significant changes” before being ready for home use; and problems with donning/doffing and the control system (non—IMU set-up) for a lower extremity amputee. {Resnik, 2017 #26}
3. Compared to a body-powered prosthesis, myoelectric control requires significantly less muscle force and can reach a greater range of motion. However, myoelectric prostheses are heavy, lack intuitive control, and provide limited sensory feedback. {Ayub, 2017 #28}
4. Studies have shown that, compared to hooks, non-motorized hands require a larger activation force from the patient and do not yield a grip force sufficient for daily activities. {Ayub, 2017 #28}
5. In a survey of 30 amputees and professionals in the prosthetics field, most agreed that body-powered prostheses are uncomfortable and all agreed that their function requires improvement. {Ayub, 2017 #28}
6. To date, body—powered hooks are equally preferred to myo-electric hands. Stated advantages of body-powered prostheses compared to myo-electric prostheses include mass, robustness and cost-efficiency. However, BPPs are still far from optimal in spite of the advances since the patenting of the Dorrance split hook in 1912. Body powered hands are less preferred than hooks. A user might prefer a prosthetic hand instead of a hook for cosmetic reasons, but then he needs to exert 1.5-8 times more mechanical work and will experience 2-27 times higher hysteresis or energy dissipation. {Hichert, 2017 #29}
7. Additionally, users of body-powered hands also complained about “slowness in movement, insufficient grip strength and high-energy expenditure”. {Hichert, 2017 #29}
8. [On TRS prehensor w/ Bowden cables for shoulder power] These differences are mainly due to friction, a well-known disadvantage of Bowden cables, which increases with the curvature of the cable. In our experiment the friction losses result in efficiencies between 80 and 84% of the exerted forces, despite the Teflon liner in the outer cable housing to improve the efficiency of force transmission. According to Carlson, in a static set up an efficiency of 80% implies a cable curvature of approximately 150 degrees. …This corresponds to recent evidence presented at the ISPO Europe conference 2016: Preliminary results on the dynamic properties of different types of Bowden cables were discussed, that suggest decreasing efficiencies for increasing cable velocities. {Hichert, 2017 #29}
9. [On TRS prehensor w/ Bowden cables for shoulder power] The unpredictable behaviour and the inefficiencies of the Bowden cable during dynamical task execution suggest a need for better solutions in BPPs design. {Hichert, 2017 #29}
10. [On the Modular Prosthetic Limb] He (test subject) was most satisfied by the comfort of the MPL and least satisfied by its weight (1.62kg/3.58lbs plus battery weight of 0.38kg/0.84lb compared to 0.95kg/2.10lbs for conventional prosthesis). His favourite MPL feature was the multi-finger usability. {Perry, 2018 #31}
11. [On the Modular Prosthetic Limb] Its main features are 26 degrees of freedom (including the hand), 17 motors, and a total mass of 4.8kg with battery and a payload of 155N with the static wrist. {Leal-Naranjo, 2017 #32}
12. Even though researches have been carried out to achieve these functions [wrist motions] using parallel manipulators and motors and using hybrid (Electrically powered+body powered) prosthesis, they have failed to achieve the shift between two axes of two wrist motions. {Abayasiri, 2017 #33}
13. [On dielectric elastomer actuators] One design presenta joint driven by two antagonistic DE actuators, but the reported output force does not exceede 5N. While another design employing spring roll DE actuator, reports outputs of 15N. A planar actuator design employing hyperelastic DE material model reports 35N output. These output forces are less than the force an average human bicep can exert during flexion which is estimated to be in the range of 40N to 116N. {El-Hamad, 2017 #34}
14. Researchers have developed a EMG acquisition system with reduced noise and interference effect to acquire the EMG signal through surface electrode, but still they are using motor coupled with linkage mechanism or drivetrain mechanism in the construction of prosthetic arm. The existing 3D printed hands are costly due to use of many parts in the hand such as ball bearings, miniature epicyclic geared motors, stainless steel tendons with nylon coating, bolts and nuts and feedback sensors etc. The recent trends in prosthetic arm industry are fingers actuated by servo motors at each joints where rotation is required which itself makes the design complex and heavy. Hence the elimination of extra servo motors itself made our design lightweight. {Pai, 2016 #35}
15. 3D printed prostheses have been developed, which have 4 DOFs, that are controlled with surface electromyography (EMGs) and use servo motors for their movement. It makes it very low cost, but the main problem with this type of prosthesis is that they are not strong enough to perform properly all the movements of daily activities. {Proaño-Guevara, 2018 #36}
16. Tendon-based hands have the advantage of locating actuators away from the hand with relatively more torque but the relationships at finger joints are really complex and require a specific kinematic study for their functioning, so they use link systems, unions by blocks and springs that transmit movement to achieve the same effects as tendons. {Proaño-Guevara, 2018 #36}
17. In particular, most transradial prostheses are designed to perform a few of the grasping tasks with limited degrees of freedom (DoF), in comparison to the biological wrist and hand that have 27 DoF. {Semasinghe, 2018 #37}
18. Since they [body-powered transradial prostheses] can only perform maximum two grasping actions from a single terminal device, different terminal devices are required to fulfil various activities of daily living (ADL). {Semasinghe, 2018 #37}
19. Ability to miniaturize the end effector is the key advantage of the tendon-based mechanisms used in the most transradial prosthetic devices. This advantage is mainly due to the ability of placing the actuators away from joints of fingers. In addition, the tendon-based mechanism helps in reducing bulkiness of the end effector while reducing the complexity of operation of prosthetic fingers. However this mechanism is known to have some drawbacks as well. The friction between tendon and tendon enclosures or sliding groves results in inefficiencies in power transmission. The durability of tendon is also a major concern. {Semasinghe, 2018 #37}
20. The benefits of body-powered prostheses include silent action, light weight, moderate cost, durability, reliability, rough sensory feedback aboujt the positioning of the terminal device, and simple operational mechanism with certain body movements to operate the voluntary open or voluntary close terminal device. {Hashim, 2018 #38}
21. Body-powered prostheses are rejected by 26%-45% of the users. One of the reasons for rejection is the high operating force required for prosthesis activation, leading to pain or fatigue or in the worst case, nerve and vessel damage. {Hichert, 2018 #40}
22. [On body powered prostheses] The results indicate that 3 of 10 evaluated prosthesis cannot be operated by all subjects even when exerting their MCFs [Maximum Cable Operation Forces]. More than 50% of the subjects will not operate 8 of the 10 evaluated prosthesis in daily life fatigue free. One prosthesis included into the study, the Hosmer Soft Hand, cannot even be operated by a single user without exhaustion. {Hichert, 2018 #40}
23. The majority of subjects cannot use most body-powered prostheses fatigue free on a daily basis. {Hichert, 2018 #40}
24. The results show that the required cable forces of available prostheses are, generally speaking, not befitted to the user’s strength when corrected for fatigue-free operation.
25. Thus the development of low operation force prehensors, especially of more efficient hand prostheses, is greatly desired. Current body powered hand prosthesis show inferior mechanical behaviour compared to hook prostheses but might be preferred by users for cosmetic reasons. {Hichert, 2018 #40}
26. Additionally, a myo-electric prosthesis does not offer the user proprioceptive feedback of prehensor activation like a body-powered prosthesis. {Hichert, 2018 #40}
27. In many cases, the user’s strength is insufficient to operate body-powered prostheses fatigue free on a daily basis. {Hichert, 2018 #40}
28. MPs (myoelectric prostheses) tend to be more accepted for low-intensity work, while BPPs are well suited for high-intensity work. As a result, today, many prosthesis users prefer to have two prostheses, one with a predominantly aesthetic role and one with a mainly functional role. {Piazza, 2017 #42}
29. One limitation of the current solution is the overall weight of the SHPH, between 73% and 82% heavier than the other two solutions [Ottobock Hook and Hosmer Soft Hand]. {Piazza, 2017 #42}
30. Wrists with passive flexion/extension and/or radial/ulnar deviation that can be fitted in upper limb prostheses also exist. These wrists enhance the dexterity of the prosthesis and reduce the need by the individuals to compensate for the missing DoFs by means of unnatural movements of the elbow, shoulder and trunk. The latter, namely compensatory movements, induce excessive stresses on the joints and the muscle-skeletal system, which cause discomfort and secondary injuries in the long run. {Kanitz, 2018 #51}
31. In prosthetic hand designs, increases in the number of actuators usually lead to multiple grip patterns and decreased grip force. This is due to the nature of limited space and weight requirements of prosthetics. A study has shown that a pinch force of 68N is enough to be used in ADLs, but many commercial hands with multiple actuators could achieve less than the mentioned value, varying from 10.8N to 29.5N. {Wattanasiri, 2018 #58}
32. Tendon friction coefficient is a function of joints angles, so any control strategy, as the one described in [10], must consider it. {Borghesan, 2010 #49}
33. Joint friction coefficient depends on the sum of the tendon forces, as expressed by (17). High forces or friction coefficient can cause a grip on a phalanx; this can also happen if reference torques are too high. By these consideration emerges that reducing friction is an obvious advantage, but joint friction is more crucial than tendon friction; moreover control strategies must consider that excessive tendon tensions have to be avoided. {Borghesan, 2010 #49}
34. In a meta-analysis of prosthesis use and abandonment literature, Biddis and Chau found the adult rejection rate for body-powered and electrically-powered prostheses to be 26% and 23%, respectively. Major reasons for rejection include heavy weight, lack of function and durability, discomfort, and poor cosmetic appearance. {Gailey, 2017 #54}
35. Furthermore, users often complain about the effort required to control upper extremity prostheses. In addition, current prostheses do not provide sensory feedback, which has been shown to affect the usage of prosthetic hands and sense of embodiment. Thus, research efforts have focused on improving prostheses appearance, function, control, comfort, durability, and quality of feedback. {Gailey, 2017 #54}
36. However, such transmissions (wrt. Pulleys, sliders and intermediate bodies) must be carefully designed in order to avoid introducing unwanted friction, which can significantly reduce the effectiveness of the hand and lead to poor performances. For example, sliders with linear guiding rails should be avoided since they introduce friction and are prone to jamming. {Mottard, 2017 #53}
37. A combination of some of these arrangements (pulleys, sliders and intermediate bodies) has been used with good results. One limitation noted by the authors was the lack of grasping force for a given actuation force. {Mottard, 2017 #53}

# Design concerns/constraints

1. The lack of wrist degree of freedom (DoF) increases unnecessary motions of whole body. The wrist DoF affects to body motions more largely than hand DoF in several tasks of daily livings. {Kim, 2017 #25}
2. The hand is the most complex part of the upper limb and presents 22 DOFs distributed in the fingers to perform many gestures and grasps. {Leal-Naranjo, 2017 #32}

|  |  |  |
| --- | --- | --- |
| Articulation | Movement | Range of Motion |
| Shoulder | Extension – Flexion | 50-180 |
|  | Abduction – Adduction | 180-30 |
|  | Internal – external rotation | 100-80 |
| Elbow | Extension – Flexion | 0-145 |
|  | Pronation – Supination | 85-90 |
| Wrist | Flexion – Extension | 85-85 |
|  | Adduction – Abduction | 45-15 |

1. The lack of dexterity of the prosthetic arm yields to compensatory movements that could cause injuries in the long term. {Leal-Naranjo, 2017 #32}
2. Prosthesis with over weight limit the ranges of motions of the prosthesis and cause musculo-skeletal disorders. {Abayasiri, 2017 #33}
3. Emulating the level of functionality of the human hand has proved to be extremely complicated, from a mechanical perspective it is very difficult to integrate a large number of degrees of freedom and their corresponding actuators within a dimensioned structure for a purpose. {Proaño-Guevara, 2018 #36}
4. A very important objective in the development of the prosthesis is that it should be as light as possible, cosmetically pleasing, comfortable for daily use and providing sufficient functions for ADLs. {Proaño-Guevara, 2018 #36}
5. Regarding the design of the wrist, it is important to take into consideration the degrees of freedom that it can perform, since in the development of daily activities these have a greater impact than the degrees of freedom present in the hand. {Proaño-Guevara, 2018 #36}
6. A recent clinical study showed that a hand with 22 DOF with a wrist of 1 DOF is functionally equivalent to a hand of 1 DOF and a wrist of 2 DOF when performing daily activities. {Proaño-Guevara, 2018 #36}
7. The hand design features found after reviewing previous designs are (1) the entire structure has a weight less than 500g so the actuators do not see compromised its efficiency and there are no overexertion (2) Make a highly functional design that minimises the actuators needed to perform the movements and (3) focus on a mechanical design that allows to meet the points previously described. {Proaño-Guevara, 2018 #36}
8. Recent research has debated whether enhancing prosthetic wrist serves better amputees than a highly skilled hand. {Proaño-Guevara, 2018 #36}
9. Range of motions of wrist: {Semasinghe, 2018 #37}

|  |  |
| --- | --- |
| Motion | Range |
| Flexion-extension | 0° -75° /0° -(-70° ) |
| Radial deviation-ulnar deviation | 0° -20° /0° -(-35° ) |
| Supination-pronation | 0° -90° /0° -(-90° ) |

1. Users express their interest in improved wrist movement and control, overall manoeuvrability, coordination, and sensory feedback when considering functionality. {Hashim, 2018 #38}
2. A number of studies compared the performance of stiff versus compliant wrists, during ADLs. All of them revealed improved functionality for most of the ADLs (in particular: bimanual tasks and tool manipulation) when using the compliant wrist, with the exception of those tasks which involved the manipulation of heavy objects; these tasks were better performed with a stiff wrist. {Montagnani, 2017 #39}
3. Humans can conduct isometric contractions without fatigue effects at a critical force level of 15%--20% of their maximum voluntary contraction. Hence taking the conservative value and maintaining 20% of users’ maximum cable operation force as an upper boundary for daily use will enable users to operate their body powered prosthesis fatigue free. {Hichert, 2018 #40}
4. In prosthetics, non-back drivability is required to maintain a certain grip force without consuming battery power. {Imbinto, 2018 #41}
5. Mean and Standard Deviation and Hand Grip Strength in kilograms, for men and women, presented in ascending age groups {Massy-Westropp, 2011 #59}

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Men | | | | Women | | | |
| Age | Right | Left | BMI | Age | Right | Left | BMI |
| 20 to 29 | 47(9.5) | 45(8.8) | 26.4(5.1) | 20 to 29 | 30(7) | 28(6.1) | 25.1(5.8) |
| 30 to 39 | 47(9.7) | 47(9.8) | 28.3(5.2) | 30 to 39 | 31(6.4) | 29(6) | 27.3(6.8) |
| 40 to 49 | 47(9.5) | 45(9.3) | 28.4(4.6) | 40 to 49 | 29(5.7) | 28(5.7) | 27.7(7.7) |
| 50 to 59 | 45(8.4) | 43(8.3) | 28.7(4.3) | 50 to 59 | 28(6.3) | 26(5.7) | 29.1(6.4) |
| 60 to 69 | 40(8.3) | 38(8) | 28.6(4.4) | 60 to 69 | 24(5.3) | 23(5) | 28.1(5.1) |
| 70+ | 33(7.8) | 32(7.5) | 27.2(3.9) | 70+ | 20(5.8) | 19(5.5) | 27(4.7) |

# Alternative design mentions

1. Several kinds of pneumatic rubber actuators have been developed and reported with two or more internal chambers having symmetric cross section or attached to a joint to create bending motion. … Examples of them are rubber gas actuator driven by hydrogen storage alloy, Flexible micro actuator (FMA), pneumatic wobble motor, pneumatic soft actuator, flexible fluidic actuator (FFA) and flexible pneumatic actuator (FPA). {Mata Amritanandamayi, 2018 #24}
2. Also many research groups have developed artificial hands with a fluidic actuator that is called McKibben artificial muscle or Pneumatic Muscle Actuator (PMA) {Mata Amritanandamayi, 2018 #24}
3. However, grippers having flexible tube like pneumatic fingers constrained by the supporting member such as thin plate or rod along one side have been proposed. This may be called as composite material flexible pneumatic actuator (CMFPA). An attempt has been made with dual compartment, differential pressure flexible pneumatic actuators (DPFA) in the construction of robotic grippers for soft fruit packing but not for the investigation on the multi-jointed multi-fingered prosthetic hand based on asymmetric bellow flexible rubber actuators. The main disadvantage with the above type of grippers is the fingers inability to grasp both soft and hard objects of different shapes, sizes and weights. {Mata Amritanandamayi, 2018 #24}
4. Actuators made of bellows or tubes with asymmetric cross section has been investigated to overcome the disadvantages of FMA and FPAs or FFAs and applied for the robotic soft gripper construction and the same technique is proposed for the development of a dexterous hand. {Mata Amritanandamayi, 2018 #24}
5. The above research groups use embedded PneuNets (pneumatic networks) channels in elastomers of square shaped tubes and these channels inflate when pressurised, creating motion either by varying the thickness of the walls of the tube or by changing the material of the active and passive layers of the square shaped tube, or square shaped moulded silicone actuator with rounding on one side. {Mata Amritanandamayi, 2018 #24}
6. A complex construction of fibre-reinforced tubular soft prosthetic hand with stretchable optical waveguides for strain sensing has been developed using external control devices and air supply. {Mata Amritanandamayi, 2018 #24}
7. A hybrid actuation principle combining both pneumatic and tendon-driven actuators for a soft robotic manipulator has been constructed which needs both external motors and compressor. {Mata Amritanandamayi, 2018 #24}
8. Recently research on bellows to generate bending motion using symmetric thickness actuator and polymer Bi-bellows have been carried out. {Mata Amritanandamayi, 2018 #24}
9. Contemporary Upper Limb Prostheses Comparative Results {Riet, 2013 #60}

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | i-limb ultra | BeBionic3 | Michelangelo | SmartHand | Vanderbilt University Hand | Southhampton Hand | MARCUS |
| Grip Strength – Power Grip (N) | 136 | 140 | 70 | 36 | 50 | - | - |
| Closing Speed – Power Grip (sec) | 1.2 | 1 | - | 1.5 | 0.3 | - | - |
| Grip and Hand Positions | 11 | 14 | 7 | - | 8 | 6 | 3 |
| Control | 2 Channel Myoelectric | 2 Channel Myoelectric | 2 Channel Myoelectric | Myoelectric | Myoelectric | Myoelectric | Myoelectric |
| Actuators | DC Motors | DC Motors | DC Motors | DC Motors | DC Motors | DC Motors | DC Motors |
| Touch Sensors | No | No | No | Pressure | No | Pressure, slip, temperature | Pressure, slip |
| Cost | 40,000 | 35,000 | 75,000 |  |  |  |  |

# Alternative design papers

1. **[Asymmetric Bellow Flexible Pneumatic Actuator (ABFPA)] On ‘A novel underactuated multi-fingered soft robotic hand for prosthetic application’{Mata Amritanandamayi, 2018 #24}:**
   1. The manufactured hand can carry a payload of about 220g at 5 bar pressure without slipping. The strength and weight carrying capacity of the hand can be increased by providing thin steel wire or fibre reinforcement at the thicker side of the rubber bellow actuator.
   2. The pressure range is from 0 to 5 bar. The force characteristics are non-linear. The maximum measured force is 0.46N for rubber at 5 bar pressure.
   3. Since the fingers are fabricated using nitrile rubber material without fibre reinforcement, each finger weighs less than 15g.
   4. The total mass of the full prosthetic arm including mini compressor, valves and battery is just about half the mass of the conventional prosthetic hand. However the conventional hand carries weights up to 6kg as compared to the current hand which carries up to 220g.
   5. The time for a complete flexion and extension of fingers is less than 100ms. Therefore it is possible to open and close the hand with frequency of about 10Hz. This is 5 to 8 times faster than conventional prosthesis as the complete flexion and extension takes 0.5s to 0.8s.
2. **[F-hand] On ‘Development of Humanoid Hand with Cover Integrated Link Mechanism for Daily Life Work’ {Fukaya, 2017 #27}**
   1. Everything was easy to carry out, but it was not possible to manipulate tools such as pliers or kitchen knife. This is due to the fact that it was impossible to build a complicated and flexible structure of human hand such as a soft palm, plica interdigitalis (first web space of hand) and thenar eminence like conventional hand with 3D printer.
   2. However, as this model was constructed with a 3D printer, the palm was hard and because it was poor in flexibility, it was not able to stably hold the knife handle.
3. **[SoftHand-Pro (SHP)] On ‘Improving Fine Control of Grasping Force during Hand-Object Interactions for a Soft Synergy-Inspired Myoelectric Prosthetic Hand’ {Fu, 2018 #30}**
   1. This design is combined with an elastic recoil force implemented as elastic ligaments in all joints to help the fingers conform to arbitrary object shapes, and bring the fingers back to their starting position.
   2. For a Large Object Pick and Place test, there were two object weights: Medium (420g) and Heavy (820g).
   3. Issues were found with fine force control with goals for picking and placing both heavy and fragile items.
4. **On ‘Mechanical Design of a Prosthetic Human Arm and its Dynamic Simulation’ {Leal-Naranjo, 2017 #32}**
   1. The elbow is described as a cardan joint, despite in reality the flexion-extension and pronation-supination axes are not perpendicular.
   2. In order to represent the two axes of movement of the wrist joint a cardan joint is again considered.
   3. The simulation results show the feasibility of the operation with a mechanical design with light human-like structure.
5. **[MoBio] On ‘MoBio: A 5 DOF Trans-humeral Robotic Prosthesis’ {Abayasiri, 2017 #33}**
   1. It has a novel 2 DOF wrist which has 20mm axes shift between two wrist motions.
   2. Fabricated prosthesis: MoBio weighs 3.2kg which is same as the weight of actual human arm. Actual human arm’s weight of 75kg human is 3kg.
6. **On ‘Modelling of High Output Force Dielectric Elastomer Actuator’ {El-Hamad, 2017 #34}**
   1. The mechanical design of the DE actuator produces compressive stress on the DE membrane that ranges from 73N to 97N according to the angular position.
7. **On ‘Design and Manufacture of 3D printed Myoelectric Multi-Fingered Hand for Prosthetic Application’**
   1. The material chosen for printing was ABS plastic keeping in mind the finish that needs to be achieved for multi-fingered or anthropomorphism and also the cost and availability in the local market.
   2. The model is made with ABS plastic due to the following reasons:
      1. Good strength to weight ratio.
      2. Easy to manufacture since the design is quite complex
      3. Economical compared to other molding and forming process
      4. Satisfactory aesthetic finish
8. **On ‘A passive wrist with switchable stiffness for a body-powered hydraulically actuated hand prosthesis’ {Montagnani, 2017 #39}**
   1. Although hydraulic transmissions are an efficient and reliable solution, and they have been frequently investigated to develop externally powered hand prostheses, this is the first example of a body powered prosthetic wrist with hydraulic actuation.
   2. The choice of exploiting a spherical joint in order to enable the flexion/extension and radial/ulnar deviation movements was deemed as the most effective for limiting the dimensions in both the radial and axial directions. This solution, already demonstrated in both research and commercial/clinical domains, was preferred over other solutions like universal joints and differential mechanism, already investigated by the authors.
9. **On ‘Wrist-powered partial hand prosthesis using a continuum whiffle tree mechanism: a case study’ {Imbinto, 2018 #41}**
   1. Average forces of 15.5N and 8.69N for the power grasp and pinch respectively are considered well acceptable for most daily life activities.
10. **On ‘Grasp performance of a soft synergy-based prosthetic hand: a pilot study’ {Gailey, 2017 #54}**
    1. The SHP design combines two design strategies, soft synergies and under-actuation, to simplify the mechanics and control of robotic hands. The idea underlying soft synergies is to encode a movement pattern (here the first principal component extracted from hand postures) into hardware design while allowing flexibility. Under actuation, or having fewer motors than degrees of freedom, enables an elegant implementation of the above design strategy, leading.

# Modelling Issues

1. One of the most important problems in robot kinematics and control is finding the solution of inverse kinematics. Traditional solution methods such as geometric, iterative, and algebraic are inadequate if the joint structure of the manipulator is complex. {Kumar, 2017 #23}

# Control methods

1. ANFIS is a neural network with hybrid learning rules based on sugeno fuzzy interface system, which maps the input and output data. ANFIS architecture is developed to control each link of arm. {Kumar, 2017 #23}
2. Another approach is to use a force-position hybrid control scheme to handle motion and force automatically within the hand based on feedback from force/position sensing. {Fu, 2018 #30}

# Design recommendations

1. The appropriate materials considered for developing the model are plastic polymer, carbon fibre, and aluminium. {Kumar, 2017 #23}
2. The designed robotic arm should be manufactured using 3D printer; remodelling the design by adding 1dof between the shoulder and elbow which is analogous to the human arm; show the device to prosthetics and amputees and get their feedback on the current system; redesign mechanical packaging to further reduce the size and weight of the system; orientation-based control algorithms can be developed. {Kumar, 2017 #23}
3. We also believe that if we can build a structure for converting the MP joint of the thumb to 2 degrees of freedom with a 3D printer, we can further improve the grasping ability. For people who dislike appearance like a robot, if this robot hand attaches a cosmetic glove like human, the size looks unnatural because it is too large. When using the robot hand for such use, it is necessary to develop a slim structure. {Fukaya, 2017 #27}
4. To reduce friction in the cable A Teflon liner for heavy duty cable housing (CH100-HD) was placed inside of the cable housing. {Hichert, 2017 #29}
5. Placing the weight closer to the shoulder reduces the rotational inertia. {Leal-Naranjo, 2017 #32}
6. As for the movement of the fingers, Kontoudis recommends using elastomeric materials to perform the digital extension while for flexion cables are used, attached to actuators suitable for this movement. {Proaño-Guevara, 2018 #36}
7. Sekine proposes the use not only of motors and metal parts for the construction of the prosthesis but also the integration of different materials and systems in order to make the design of the prosthesis more suitable for daily use. In fact, current prostheses should be designed to provide sufficient torque, velocity, and range of motion to develop the person’s daily activities. {Proaño-Guevara, 2018 #36}
8. With this design [musculoskeletal design of the arm] the actuators over a DOF could be more than one, maybe a small group could control the fine motor and when strength is required other actuators, stronger but slower could act to develop the activity with property. {Proaño-Guevara, 2018 #36}
9. It is important to have independently controlled actuators in developing a dexterous hand with individual finger movements. {Semasinghe, 2018 #37}
10. Additionally, the use of a pulley to double the force transmitted to the fingers for a given input force provides a significant advantage over direct drive designs. {Mottard, 2017 #53}

# Other recommendations

1. Our findings suggest that better rates of adoption might result if patients had the opportunity to fully train with and evaluate a device before finalising a prescription for them. {Resnik, 2017 #26}
2. The quantification of daily usage patterns is an important aspect in prosthesis development, and more research attention is greatly desired. This knowledge would allow an optimised transmission system design, matching user capacities (cable operation forces or “input”) with demands (pinch forces or “output”) for body-powered prosthesis. Also, it would quantify technical specifications to allow minimisation of motors and battery packs in myo-electric prostheses and therefore, reduce the prosthesis’ weight. {Hichert, 2018 #40}

# Actuation methods

1. Dynamixel servo motors were chosen, since they include positional feedback in real time to the motors and adjust the position according to the requirements.
2. The advantage of electrical motors is being environment friendly and noise less unlike usual hydraulic cylinders. {Kumar, 2017 #23}

# Design mentions

**On the subject of under actuation**

1. The approach of UA hands offers many advantages to the designer: saving of space, weight and cost, all derive from using a lower number of motors. {Grioli, 2012 #50}
2. One particularly investigated aspect of robotic and prosthetic UA hands is adaptivity. Hands, as those proposed in [10] and [11], and grippers, such as in [12], are characterized by many DOFs but just one degree of actuation. They are designed to allow passive movements which are used to adapt the hand shape to the grasped object. These passive movements are determined by the equilibrium of the contact forces with passive elements as springs or, less often, clutches or brakes. {Grioli, 2012 #50}
3. One of the strong motivations behind hand under-actuation is the inherent gain of space and weight derived by the smaller number of motors. This comes at the cost of a slight loss in terms of mechanism complication, which is usually welly balanced. Nevertheless the introduction of synergies in a robotic hand could imply an excessive complication of the mechanism due to the potentially high number of differential systems needed to mechanically implement a synergic motion. {Grioli, 2012 #50}
4. Under actuation, or having fewer motors than degrees of freedom, enables an elegant implementation of the above design strategy, leading (encoding a movement pattern whilst allowing flexibility. {Gailey, 2017 #54}
5. Independent actuation of all joints leads to a very large number of actuators and is not a realistic approach. In fact, even biological systems do not generally allow independent motion of all the joints. {Baril, 2010 #47}
6. In robotics, the large number of degrees of freedom in a multi-fingured hand poses a great challenge in terms of design (large number of actuators, complex transmissions) and control (coordination of the degrees of freedom in the performance of a task). This has motivated the use of underactuation, i.e. the introduction of mechanisms that distribute the action of a certain number of actuators to a large number of degrees of freedom.