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# Demonstrator of a Low-Cost Hand Prosthesis

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**Abstract:** Upper limb absence has an impact on both physical and mental health of a human being. Nowadays, the costs of commercial, externally powered prosthetic hands range between 25.000 € and 70.000 €. A first demonstrator of a lightweight low-cost prosthetic hand is produced with 3D-printing technology (Fused Deposition Modeling). Due to integration of single-axis solid-state joints the five fingers can be printed in one piece. Thermoplastic polyurethane is used for this purpose. The flexion of all fingers is achieved by moving cords which are positioned on the palmar side of each finger. Two twisted string actuators are integrated to allow the movement of the thumb and the remaining four fingers. These actuators consist of two polyethylene strands which are twisted along their main axis by a DC motor, providing a tensile force to bend the fingers. In order to achieve simultaneous but differential actuation of the four fingers (small finger, ring finger, middle finger and index finger), a differential mechanism is used. The thumb is driven by a separate unit. In order to open the hand, the elasticity of the joints' material is taken advantage of. With the developed mechanics it is possible to perform precision and cylindrical grasps with an opposed thumb. Weights up to 260 g can be held according to the shape and size of an object. To increase the adaption to different sizes and weights of objects, the design should be modified. It can be concluded, that the presented device is a promising basis for a lightweight, low-cost prosthetic hand in the future.

Keywords: Twisted String Actuation, Hand prosthesis, 3D printing, solid-state joints, precision and cylindrical grasp

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## 1. INTRODUCTION

In the evolution of mankind, the hand plays an essential role. It assures important gripping and tactile functions. With the help of the hand, both powerful and precise tasks can be performed. As a cultural organ, the hand is an important component of non-verbal communication, either accompanied by the spoken word or as part of the silent body language (Aumüller, Aust, Engele, Kirsch, Maio, Mayerhofer, et al., 2014).

The need for hand prostheses arises from people with dysmelia − congenital malformations of one or more limbs − and people who have had to have part of their upper extremities removed unilaterally or bilaterally. Amputations not only represent the functional loss of the limb, they also have an impact on the mental health and social life of the affected person (Maduri & Akhondi, 2019). Thus, the degree of independence and the ability to do a job as well as social and everyday tasks are influenced (Cordella, Ciancio, Sacchetti, Davalli, Cutti, Guglielmelli, et al., 2016).

A good prosthetic restoration/care can help to reduce the limitations caused by the absence of a body part. It is particularly important to satisfy the needs of the user. Cordella et al. have conducted seven studies on the needs of upper limb prosthesis users regarding their prosthetic care (Cordella et al., 2016). For this purpose, users of passive and active prostheses for different residual limb lengths were interviewed. Depending on the type of prosthetic fitting, the needs may be weighted differently. Individual requirements are also added (Cordella et al., 2016). Table 1 summarizes the identified users' needs for a prosthetic hand.

Table 1. Identified users' needs for a prosthetic hand (Cordella et al., 2016)

| **Design** | **Kinematics** | **Electrical** | **Application** |
|---|---|---|---|
| Anthropomorphic in size, mass, shape, and colour<br>Natural appearance<br>Variety of prosthetic gloves | Independent finger movement<br>Precise and efficient motion execution<br>(At least) passive flexion / extension of the wrist | Sensory feedback<br>Reliability of power supply and electrodes | Suitability for everyday tasks<br>Fine motor skills<br>High forces can be applied<br>Low noise<br>Minimal heat dissipation<br>Long life |

While in Germany prosthetic care can be part of health insurance, there are many regions in the world where this medical care has to be paid for privately. The price spectrum of commercially available hand prostheses is large, as the costs vary greatly depending on the type of care and individual characteristics.

A purely cosmetic silicone hand can be obtained in Germany for approx. 1.700 €, while a myoelectrically controlled upper arm prosthesis can cost up to 140.000 € (Sanitätshaus Glotz, 15. August). Other suppliers sell myoelectric hand prostheses in a price range between 25.000 € and 70.000 € (Sanitätshaus Nusser & Schaal, 2019).

At the same time, (online) communities are emerging and growing, offering free access to models for 3D printable hand prostheses. The global network e-NABLE offers an online platform where everyone can download files of developed prostheses free of charge (Enabling The Future, 2019). This movement is particularly enriching for the prosthetic care of children. In their growth phase, they require new prostheses at short intervals. Commercially available hand prostheses represent a major financial burden. It is important to wear prostheses already in childhood in order to train the handling and adaption to the artificial limb. All models currently offered on e-NABLE are operated by a (lever) mechanism by the user (Enabling The Future, 2019). Power-driven low-cost hand prostheses are generally a minority, which is why research on and development of these are relevant.

It is conceivable that a decentralized production of hand prostheses will be established in the future. The transfer of CAD or STL files via the Internet is uncomplicated and fast. Users could purchase a self-assembly kit or individual components and, with access to a 3D printer, produce the printable components of their own prosthesis. Spare parts could also be reprinted with little effort.

### *1.1 Goal of this work*

The user requirements listed in Table 1 and the limited space available for the actuators pose many challenges for the development of hand prostheses. In the context of this work, a demonstrator of a low-cost hand prosthesis is developed and assembled, which can initially perform a simple gripping function.

The key note of this work is the low-cost approach and the high availability of all components. The aim is to find a solution for structurally weak and low-income regions.

3D printing technology should be used for the fabrication of the hand prosthesis. This offers the possibility to realize cost-effective products that can be adjusted to personal needs. The so-called Twisted String Actuation (TSA) should be used as drive unit. TSA has the advantage of working quickly and quietly. It enables translational movements by twisting cords. In addition, the TSA itself acts as a gearbox, saving mass and cost (see 1.2 Twisted String Actuation). It is hypothesised that the 3D printing technology and the implementation of TSA meet the defined requirements.

In addition to sensory feedback, the aim is to reduce the amount of attention required of the user during operation. This can be done by the prosthesis itself selecting the appropriate grip pattern for the object to be handled. For this reason, a camera should be integrated into the palm of the hand. Artificial intelligence can be used to work on automatic grip pattern selection.

### *1.2 Twisted String Actuation*

The TSA is a small, lightweight, and low-cost drive unit creating a tensile force. The TSA principle consists of (at least) two cords that are twisted by an electric motor along the TSA main axis (Gaponov, Popov, & Ryu, 2014). The twisting reduces the initial length of the string by creating a helix and – given a non-elastic behaviour of the material – generates a tensile force against the load. An axial bearing to compensate the load force and a linear guide that counteracts the motor torque, complete the general construction. Due to the high transmission ratio of the string, no motor gearing is required (Palli, Natale, May, Melchiorri, & Wurtz, 2013).

## 2. STATE OF THE ART

### *2.1 Active hand prostheses*

Kate et al. analysed a total of 51 prostheses for upper extremities from Internet sources and seven prostheses from scientific literature (Kate, Smit, & Breedveld, 2017). A total of four commercially available hand prostheses is given in Table 2. These are the Michelangelo hand and the bebionic hand by Otto Bock HealthCare Deutschland GmbH (Duderstadt, Germany) (Otto Bock HealthCare Deutschland GmbH, 2019) as well as the i-limb quantum by Össur Deutschland GmbH (Frechen, Germany) (Össur Deutschland GmbH, 2019) and the VINCENT-evolution 3 by Vincent Systems GmbH (Karlsruhe, Germany) (Vincent Systems GmbH).

Table 2. Identified properties/characteristics of the analysed hand prosthesis

| | Number of actuators | Thumb opposition | Number of grip pattern | Automated grip function |
|---|---|---|---|---|
| Michelangelo hand | 2 | Active | 7 | Not specified |
| bebionic hand | 5 | Passive | 14 | Yes |
| i-limb quantum | Not specified | Active | 36 | Yes |
| VINCENT-evolution 3 | 6 | Active | 14 | Not specified |

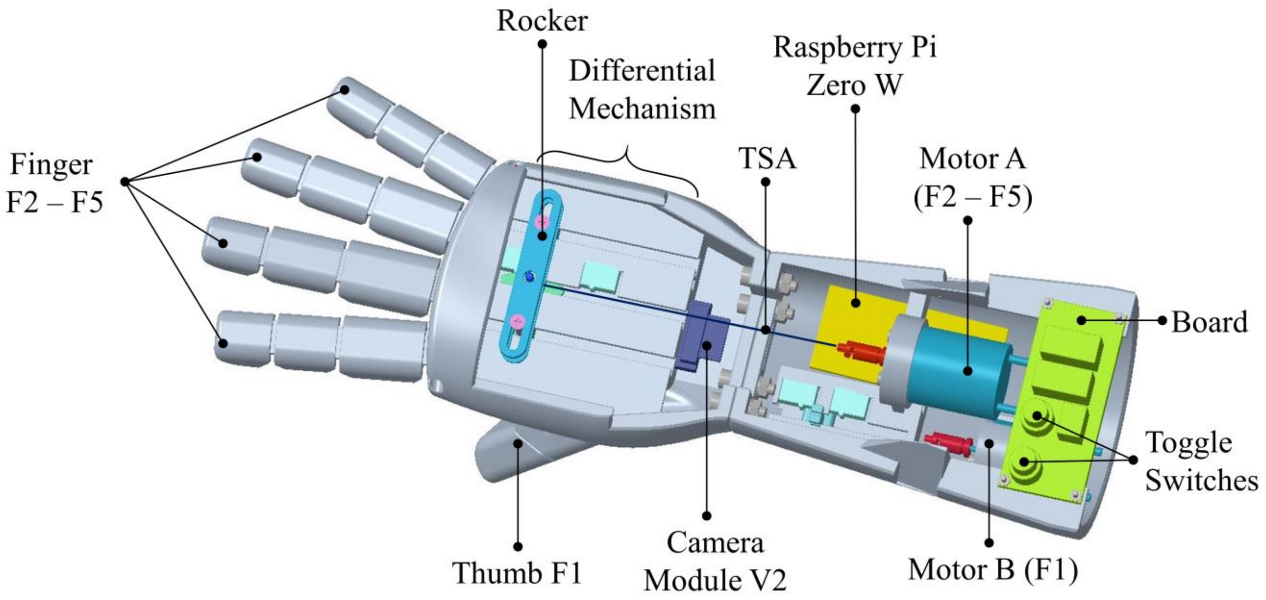

Fig. 1. CAD rendering of the 3D printed hand prosthesis. Motor A drives the four fingers while Motor B is driving the thumb. The device is controlled though the PCB board depicted on the right. The differential mechanism assures smooth gripping of non-cylindrical objects. The camera module allows identification of objects in reach.

## 3. SYSTEM DESIGN

### *3.1 Requirements*

The main function of the developing prosthesis is a functional replacement of the anatomical structure of the (right) hand. The first goal of the prosthesis is to perform two grip patterns. A precision grasp should be possible with thumb (F1) and index finger (F2) as well as a cylindrical grasp with all five fingers is required (Palaniswami, 2007). The anatomical dimensions of the upper extremity determine the geometry of the hand prosthesis. It is based on the right hand of a 50-percentile man according to standard DIN 33402-2.

The prosthesis should be able to hold a load of at least 100 g with a cylindrical grip. Furthermore, the dimensions of the drive unit should be as small as possible and compatible with the standardized hand dimensions. The mass of the hand prosthesis should be a maximum of 600 g. A flexion of the fingers should be completely possible over an angle of 90° (Aumüller, Aust, Engele, Kirsch, Maio, Mayerhofer, et al., 2014).

### *3.2 Material, Mechanism and Control*

Figure 1 shows a schematic of the first prototype. The fingers are actuated through Dyneema® cords with a diameter of 0.24 mm (Whiplash Crystal, Berkley, Pure Fishing Deutschland GmbH, Gelnhausen, Germany) that run through each finger. Under a tensile force generated by the TSA, the finger bends over the solid-state joints between the phalanges. The TSA consists of an electric motor (2738-125-GC-5, Igarashi Motoren GmbH, Burgthann Germany) connected via a motor coupling to two Dyneema® cords (diameter of 0.24 mm). The TSA moves the four finger (F2-F5) via a mechanical differential mechanism (Weiner, Starke, Hundhausen, Beil, & Asfour, 2018 - 2018). It enables the fingers to adapt to different object shapes as an under-actuated system within the given power and space constraints. A second TSA actuates the thumb directly using a second DC motor (RK-370CA-081050, MABUCHI MOTOR CO., LTD, Chiba, Japan).

The differential mechanism consists of a rocker, which is guided via bolts in three T-profile rails. The twisted string is attached to the central bolt and pulls it towards the motor. The bolts of the two outer guides serve as deflection of the cord, which connects the fingers F2 and F3 as well as F4 and F5. The individual fingers bend by pulling the rocker back by the TSA until one finger encounters a resistance. The mechanism tilts, allowing a single finger to stop while the remaining, unblocked fingers continue to enclose the object. Two toggle switches are integrated at the upper and lower reversal point of the mechanism.

The mechanism is located in the hand chamber. The Twisted String leads from the rocker back to the forearm where the motors and other electronic components are located. The motor rotation is controlled manually via two relays, which are connected to two switches on the forearm. If the "close switch" is triggered by the user, the motor is energized and rotates until the switch is released again – closing the hand. The rotation is stopped on contact with one of the two toggle switches. In this case, only the second switch can be triggered reversing the motor rotation and open the hand again.

A Raspberry Pi Zero W (Raspberry Pi Foundation, Caldecote, United Kingdom) is integrated into the design of the forearm. Allowing the recognition of objects in the reach of the hands by using the Raspberry Pi Camera Module (V2, Raspberry Pi Foundation) integrated in the palm. In the forearm there is space for two 9 V batteries for power supply. For the first lab test, external power supply is used.

### *3.3 Experimental Design*

To validate the hand prosthesis, objects of different shapes are gripped. The required handles will be verified by holding corresponding objects. Image and video recordings of the hand prosthesis including the objects held, are used for this purpose. In the first step, the construction of the hand prosthesis was validated. Therefore, the strings were pulled manually to flex the fingers. A spring force gauge was used to measure the tensile force needed to close the fingers.

## 4. RESULTS

A demonstrator of a hand prosthesis has been set up. The assembly of the hand prosthesis is shown in Figure 2. The forearm and the hand chamber are printed with PLA. The fingers are 3D-printed in one piece from TPU 92A. The thumb saddle joint of the opposing F1 is rigid. All other joints of the five fingers have one degree of freedom: flexion/extension. The mobility of the fingers is realised by solid-state joints. The under actuated flexion of a finger is achieved by a linear cord movement. When the tensile force on the cord decreases, the solid-state joints extend due to the elasticity of the material.

To allow access to the drive unit, the hand chamber and forearm are separated into two parts. The connection is made using a tongue-and-groove principle on the hand chamber and a snap-fit connection on the forearm.

The cylindrical grasp (see Figure 3 (a)) and the precision grasp (see Figure 3 (b)) can be performed manually. However small and light objects need an additional weight so they can be held.

Fig. 2. Assembly. Demonstrator of the hand prosthesis.

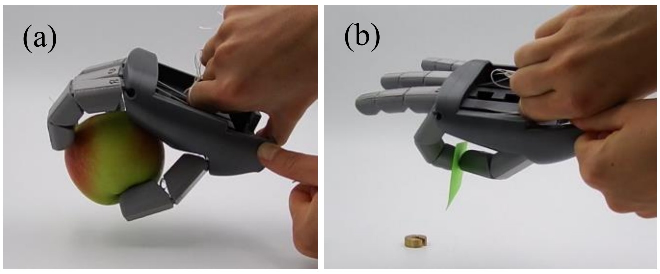

Fig. 3. Manually gripping. (a) Cylindrical grasp holding an apple, (b) tip grasp holding a piece of paper during manual experiments.

The cylindrical grasp is suitable for objects with a diameter of 22 mm or more. A tensile force of 12 N for each finger is needed to close the fingers and hold the object. The maximal achievable size is measured with an apple (Ø 56 mm at the gripping point and 127 g). A full beverage aluminium can with a diameter of 53 mm and a mass of 274 g slowly slips out of the handle.

To verify the gripping function with the TSA, a screwdriver is gripped and held in a cylindrical grasp, see Figure 4 and 5. The rocker tilts because the screwdriver blocks the fingers.

Fig. 4. Cylindrical grasp. Holding a screwdriver with TSA. Forearm and hand chamber are opened.

Fig. 5. Cylindrical grasp (side view). Holding a screwdriver with TSA. Forearm and hand chamber are opened.

The precision grasp cannot be executed for small objects because thumb and index finger do not meet correctly. Complete flexion of the fingers is not possible, as the phalanges of the individual fingers collide before the finger is fully flexed. Figure 6 shows two possible positions of the rocker with the corresponding position of the fingers.

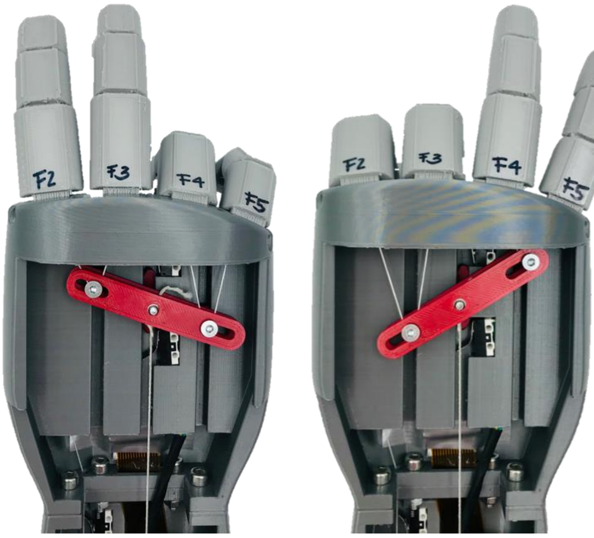

Fig. 6. Rocker (red bar) of the differential mechanism. Different positions of the rocker according to the resistance on the finger.

The mass of the developed prosthesis is 448 g. The length of the hand prosthesis is 326 mm, of which 130 mm is required for the forearm. The diameter at the widest point of the forearm is 89 mm.

## 5. DISCUSSION

With the developed hand prosthesis, the TSA has been successfully implemented in a first demonstrator. The weight of the prosthesis was well below the required value of 600 g and thus also lighter than the mass of the human hand of a 50-percentile man (480 g) (Leva, 1996). The anthropomorphic dimensions of a 50-percentile man hand are adhered to. The choice of materials for the 3D-printed components as well as the purchased parts satisfies the low-cost requirement. During the development of the hand prosthesis, attention has always been paid to a low number of purchased parts and types in order to guarantee high availability. A compact, aesthetic appearance was achieved, with only a few interface elements breaking through the outer contours (see Figure 2).

The design of the cylindrical grasp is satisfactory. The load capacity of at least 100 g is fulfilled with the cylindrical grasp. The suitability for larger objects and higher loads can be worked on by enhancing friction properties of the fingertips and stronger TSA. Small objects cannot be gripped with the precision grasp, since the phalanges collide, and index finger and thumb do not meet correctly. Further flexion is possible due to the material properties, but requires high forces. However, this cannot be achieved with the implemented motors. A revision of the finger design regarding the bending angle of the phalanges must take place to reduce the necessary forces for a complete flexion of the fingers. It must be noted that the grip area of the individual phalanges remains wide enough to hold an object.

Concepts for friction reduction in the mechanism should be developed. One possible approach is a modification of the cord guide in the distal hand chamber reducing the friction due to contact with the chamber wall. Another point of high friction is the differential mechanism. The TSA is not attached at the same level as the guidance of the mechanism causing the rocker to tilt and producing additional friction. Dedicated bearing of the mechanism could reduce friction.

A further point to be improved is the slip resistance. This became clear when trying to hold a full beverage can. The material of the phalanges and its flexibility suggests that an initial point contact is widened to a slight line or surface contact. However, the friction force created by the finger is not yet sufficient. A variation of the surface in its geometry and material is conceivable.

Due to the length of the forearm, a specific user group with a short residual limb length only could use the hand prosthesis. When using TSA, the unidirectional function must be considered, which results in the length of the forearm. A size reduction, especially of the differential mechanism, is desirable. Positioning the drive unit outside the forearm would also increase the adaption of the prosthesis to different residual limb lengths.

Furthermore, the mechanical solution with relays and micro switches is to be discussed. Relays have been used because they are reliable, cope well with the high motor currents, and easy to integrate. However, with very large objects, complete twisting of the TSA is not achieved, and the toggle switch is not contacted. Also, during flexion, the twisting of the cords causes a load to be pulled. During untwisting, the fingers are stretched through the solid-state joints. It is noticed that when untwisting the cords, fewer revolutions are converted than when twisting the cords, i.e. when pulling the load. The remaining twists are added up by repeated execution of the gripping movement. The traverse path is restricted with each further opening and closing of the fingers until the toggle switch can no longer be reached. In this case the motor is not reversed. As a result, the starting position is not always reached with stretched fingers. Motor control via an encoder and motor current measurement will be implemented in the future. From the motor current, the resistance to the finger can be inferred by the object. Controlling the motor current prevents the cords from tearing due to overloading or the destruction of fragile objects, such as an egg. In the future, the gripping force will be adjusted by detecting objects using the integrated camera module.

## 6. CONCLUSIONS

A device has been developed that replaces gripping functionality of the right hand and replicates its anatomical structure. The cylindrical grasp is executable, the precision grasp is only possible to a limited extent. Future modifications to the design of the prosthesis will increase reliability, reproducibility, and adaptability of the precision grasp to different object sizes and dimensions.

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