A Hybrid Powered Prosthetic Hand: Design, Prototyping and Evaluation

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Abstract— **The hand is possibly the most functional part of the human body. Therefore, it is experienced as a big shortcoming by people who miss theirs due to illness or accidents. Replacements in the form of upper limb prostheses do not yet meet the requirements, rejection rates due to discomfort are high (39-53%). Previous research at Delft University of Technology has focused on reduction of mass, since high mass is one of the major reasons for amputees to reject their prostheses. As a result the Delft Cylinder Hand was developed: a lightweight, body powered, hydraulic hand prosthesis. However, the input force of this purely body powered prosthesis is still too high compared to the output force, making it uncomfortable for daily use. This study presents an electrically powered add-on for the Delft Cylinder Hand. The add-on creates a hybrid system that maintains the positive features of body-powered prostheses, such as intuitive control and proprioceptive feedback, but has a better ratio between user input and output force. This is done by integrating a pump into the system. When the user actuates the hand, the pump assists the user, thus lowering the required input force for the same output force. By using the electrically powered add-on, the same input forces can result to output forces approximately twice as high as the purely body-powered prosthetic hand.**

I. Introduction

In the Netherlands, around 3750 people miss a part of their arm due to a disease or an accident. Most of them own a prosthesis [1]. There are three main types of hand prostheses: cosmetic, myo-electric and body-powered [2], the last of which is shown in Figure 1. Cosmetic hand prostheses are passive prostheses and serve as an aesthetic replacement. They can sometimes be opened and closed, but are not actively controlled. Myo-electric prostheses are moved by electric motors which are powered by batteries. The electromyographic (EMG) signals from the muscles are measured on the skin and transmitted to the controller, to open or close the hand. The hand of a body-powered prosthesis is operated by the use of other body parts with the use of harnesses and cables. Both the myo-electric and body-powered prostheses are available with either a hook or a hand. Most of these prostheses use mechanical transmissions, but there are also prostheses based on hydraulics, for example the Delft Cylinder Hand, which have an increased mechanical efficiency [3].

Myo-eletric prostheses reach higher pinch forces and have a better appearance than body-powered prostheses. However, body-powered prostheses have a lower mass, intuitive control, higher reliability and better proprioceptive feedback for force and position [1]. Additionally, the costs for a body-powered prosthesis are lower than for a myo-electric prosthesis, €2000,- and €30000,- respectively [4].

The rejection rates of upper limb prostheses are high. 14% of the amputees have never worn a prosthesis. 28% of the amputees that have worn a prosthetic hand, have used it less than once a year, whereas 64% are frequent users [5]. Per type - cosmetic, myo-electric and body-powered - the rejection rates are 39%, 53% and 50% respectively [6]. The rejection of the body-powered prostheses is mainly due to low transmission ratio between the input and output force. Because of the arduous use, half of the users can not operate the prosthesis for a whole day [4].

An electrically powered add-on for body-powered hand prostheses can reduce the input force. This combines the high power of myo-electric prostheses and the high proprioceptive feedback of body-powered prostheses. This hybrid system offers a way to increase the comfort of the user by decreasing the input force, keeping low mass in mind.

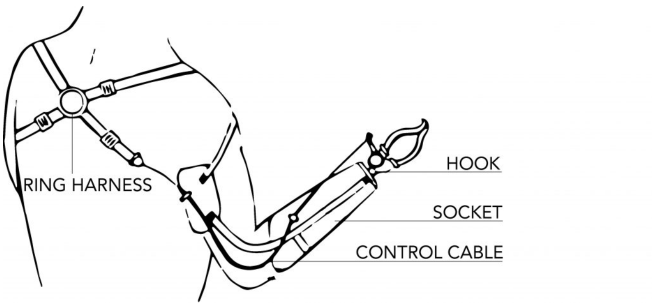

Fig. 1: A schematic of a body-powered upper limb prosthesis [7]

II. Problem

Current body-powered hand prostheses need a high input force due to low transmission ratios. This makes it arduous to use, which is why the rejection rate is high. There is no add-on for hydraulic hand prostheses available which can lower the input force by providing power from an external source, to make it comfortable for daily use.

III. Goal

The goal is to develop an electrically powered add-on for a later iteration of the Delft Cylinder Hand, henceforth referred to as DCH, which should make it less arduous for everyday

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use. This hybrid system should have the advantages of a body-powered prosthesis concerning intuition, proprioceptive feedback and reliability, but with a lower input force while maintaining the same output force. The design will focus on transradial amputees. The space normally covered by the forearm will be used to store the extra components that the hybrid system needs.

IV. METHODS

A. *Requirements*

The hybrid system was designed to fit on the body-powered DCH. The requirements for the design of the hybrid -powered prosthetic hand are listed below. Firstly the five non-mechanical requirements will be discussed, followed by the four mechanical requirements.

Aesthetic

For the system to be aesthetically pleasing for most people, it should resemble the human body as much as possible. The DCH, which will be used as the hand of the system, already fits inside a standard 7.5 inch glove. This is an anthropomorphic silicone cosmetic glove used for the look of the prosthethic hand to be more natural. Gloves can be made from silicon or PVC (polyvinylchloride). However, a silicon glove has a lower joint stiffness compared to a PVC glove, which allows for a higher mechanical efficiency of the prosthesis, so this material is preferred [8]. The electrical add-on, placed in the forearm of the system, should be designed such that it has the same dimensions as a human forearm.

Hydraulic

The hand prosthesis needs to be actuated with a hydraulic transmission. This way, the system can be added to the DCH [3] or comparable hydraulic hands.

Hybrid

The hand has to be operated by body power, assisted by an external power source. The pressure generated by the pump always needs to add up to the pressure generated by the body-powered input, to a resulting pressure in the hand. The body-powered input should not only be used as an input for the control of the pump.

Intuitive

The hybrid hand has to be intuitive, so no intensive training period is needed to operate the prosthesis. A new user should be able to pick and hold an object in less than one minute after installation. There are two ways to control a prosthetic hand: voluntary closing and voluntary opening. Since voluntary closing gives a direct relationship between pinch and actuation, it is more intuitive [9]. Therefore, the hand used in the hybrid system should be a voluntary closing hand.

Reliable

The user should be able to rely on the system for everyday usage. Objects should not fall undesirably and the hand must be able to withstand the maximum output force without flexing.

Mass

Amputees encounter lots of discomfort by wearing prostheses that are heavier than the replaced human body parts. Because the prosthetic hand is not connected to the musculoskeletal system of the user, the prosthesis is perceived as an external load to the body, which makes it more exhausting to wear. The prosthetic hand therefore needs to be lighter than a regular human hand and forearm. The average mass of a Dutch human hand and forearm is: $\mu = 1723g$ [10] [11], the mass of the standard 7.5 inch cosmetic glove is: $m_{glove} = 90g$ [12] and the mass of the DCH is: $m_{DCH} = 152g$ [3]. This adds up to a maximum weight of $m_{max} = 1723 - 90 - 152 = 1481g$ for the add-on of the hybrid system.

Fast

The whole hybrid system should have no obstructive lag, since this makes the prosthesis unpleasant to use. This also makes the hand easier to control for the user. The closing time should not exceed $250ms$, since this is the time needed to close the DCH [3].

Output force

For the hand to be useful in everyday activities, it should provide a sufficient output gripping force. The DCH can provide a maximum pinch force per finger of $30N$ and a maximum force of $60N$ with a tripod grip (grip with thumb, index and middle finger) [3], before defects in the system occur. As it is not desired for the system to break down while testing, tests will be held up to a maximum tripod grip force of $20N$. The relation between input and output force for a tripod grip of the DCH will be tested with and without the electrically powered add-on. The measured output force of the hybrid system should be higher for the same input force than the measured output with the non-hybrid system.

Operation time

Since most amputees do not wear their prostheses in bed, charging can be done overnight. The hybrid system must be fully functional during the day, without charging. When the system does run out of power by long use, the prosthesis should still be functional with only muscle power. The design of the add-on will be tested with external power sources and after testing, recommendations will be made concerning what batteries to use.

B. *Prototype Evaluation*

Evaluation of the hand will be done by a combination of mechanical tests and an electrical power test. The tests are discussed below:

Mechanical Evaluation

To test the mechanical performances of the hybrid system, the test setup shown in Figure 2 will be used. The test bench will simulate the user's input force on the Body Powered Cylinder (BPC), which will be measured by a load cell. This force is measured with a *(Zemic: FLB3G-C3-50kg-6B)* load cell and the displacement with a *(LCIT Series)* LVDT, wich is actuated by a spindle [13]. A custom-built pinch force load cell with a thickness of $10mm$ will be used to measure the tripod grip force of the hand. This is the same setup that is used in *Efficiency of voluntary closing hand and hook prostheses* [14].

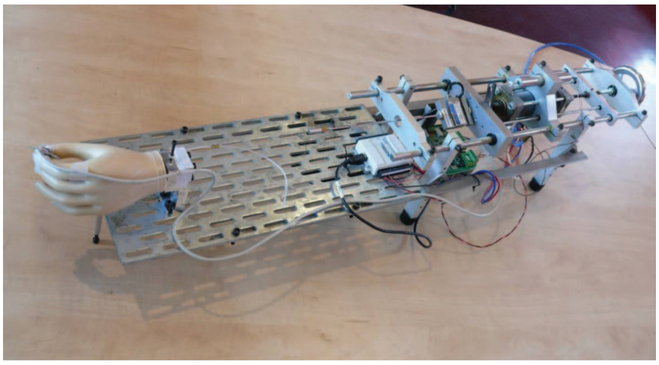

Fig. 2: Test setup that will be used to measure the input force on the BPC and the output force of the prosthesis. [14]

The following three tests will determine the stated properties of the hybrid hand in the mechanical evaluation:

1. *Input Output Relation*
   While executing a tripod grip, the input force on the BPC and the output force will be measured using the test bench showed in Figure 2. These values will be plotted against each other and will then be evaluated. This measurement will be done five times for the hand with and without the hybrid system.
2. *Required Closing Force*
   The measurement results from test 1 will be fitted to be able to determine the force needed to close the hand (during a tripod grip). The point on the fitted line, at which the output force is zero, will then be calculated. The corresponding value for the input force is the force needed to close the hand. This calculation will be done for all the measurements of test 1.
3. *Required Closing Time*
   The hand will be recorded by a high speed camera to determine the time needed to close the hand without pinching an object. This will be done with maximum input force and will be measured five times.

For tests 1 and 2, the results with and without the hybrid system will be compared. The input force at which the hand starts executing an output force (the closing force from test 2) should be lower in the hybrid hand and the transmission ratio should be higher in order to reach high output forces with relatively small input forces. The results from test 3 will be compared to the closing time of the DCH.

Electrical Power Evaluation

Next to the mechanical tests of the hand, an electrical power evaluation test will be executed for a tripod grip of $20N$. The BPC rod will be pulled as powerful as possible during these measurements, to simulate the gripping of a heavy object.

The voltage and current output will be measured directly from the output pins at the back of the external power supply, and will be recorded by *LabView*. These measurements will then be imported in *MATLAB* to calculate the power and then the used energy.

The results from the electrical power test can not be compared to results of other hybrid hand prostheses, since these are not available yet.

With the energy consumption used in one closing movement, an estimation can be made of how much energy would be required for an operation time of one day and recommendations concerning what batteries would suffice, can be made.

V. Results

A. *Conceptual Design*

The hybrid system, schematically shown in Figure 3, will be operated by pulling the piston rod of the BPC. This is done the same way as in current body-powered hydraulic prostheses with a shoulder harness with a BPC attached to it. In this system, the user input is supported by a pressure P_2 on the B side of the BPC (Figure 3), created by a pump. Thereby the pressure in the finger cylinders P_1 will be higher than in the situation without the pump for the same input force.

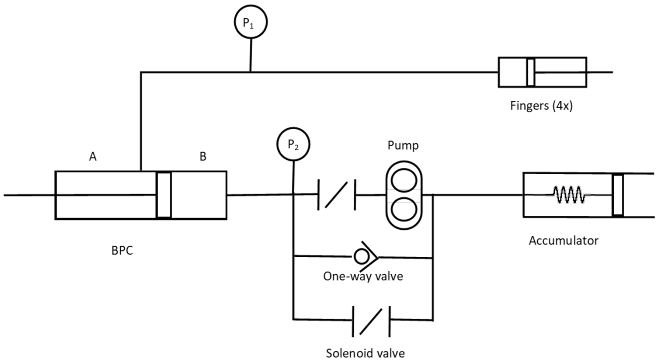

Fig. 3: Schematic model of the hybrid system.

In this system the pressure induced by the pump is also increased by the difference in area on both sides of the piston in the BPC, because the area on side A of the piston is reduced by the cross-section of the piston rod. This difference in area leads to a pressure increase of 12.5% from side B to side A.

Valves are used to further control the hybrid system. The one-way valve enables a fluid flow from the accumulator to the BPC when the pump is turned off or when the user pulls faster than the pump flow can handle. This enables fast closing of the hand.

There are also two solenoid valves used in the hybrid system. The valve next to the pump is closed when the pump is turned off to prevent leakage through the pump. The other valve opens when the hand has to be opened fast. This enables a greater fluid flow than the capacity of the pump, which enables shorter opening times.

A great advantage of this setup, is that the pressure in side A of the BPC is the same as the pressure in the cylinders in the fingers, since the BPC and finger cylinders are directly connected. This enables fast feedback in the case of sudden changes in output force. For example, when an objects falls out of the hand, the sudden pressure difference between P_1 and P_2 causes the piston of the BPC to move to achieve an equilibrium between P_1 and P_2. This movement will be noticed by the user, and will be a form of feedback.

Another advantage is that this concept mainly uses available hydraulic components, which reduces the complexity of manufacturing and assembling the hybrid system for this study.

B. *Detailed Design*

Several design choices were made concerning availability and suitability of components. The design choices are discussed below per part of the system.

Accumulator

A spring type hydraulic accumulator is used to store hydraulic liquid that will be pumped into side B of the BPC in Figure 3. Because there were no accumulators available that met the requirements, a custom accumulator has been made.

The accumulator requires a spring in order to have a resultant force on the piston in the direction of the outlet without having to pump a vacuum. Instead of using a compression spring, which is normally used, the custom made accumulator uses a tension spring. A compression spring would have a great risk of buckling, and thereby damaging the inner surface of the accumulator tube which would lead to leaks. Because the tension spring needs to be mounted in the hydraulic liquid, a stainless steel spring should be used to prevent the formation of rust.

Gear Pump

A gear pump is used to increase pressure P_2 relative to the pressure in the accumulator, which is be slightly higher than atmospheric due to the spring. The *Mini Hydraulic brushless pump* from Magom is chosen for its relative low weight of $83g$ and predictable behaviour. This pump is rated for $20bar$, but has been recorded to go up to $60bar$ [15], which is sufficient for the hybrid system. A brushless motor powers the gear pump. Brushless motors have a higher performance, efficiency and power-to-weight ratio compared to brushed motors, which is all beneficial for the usability of the hand. The brushless motor is controlled by a *Lumenier Razor Pro F3 BLHeli_32 45A 2-6S* Electronic Speed Control (ESC). This ESC is chosen for its low weight of $3g$ and because it can change the direction of the motor. It can be controlled by an Arduino and is powered with a separate power supply to be able to use maximal current to drive the pump without influencing other components by back EMF. The calibration and setup are done using *BLHeli Suite 32*.

Valves

The excitation system uses two different kinds of valves. The solenoid valves are both a *IEPA1211141H*, which have been chosen for their low weight of $4.7g$ and small size. The one in series with the pump is used to reduce leakage when the pump is not in use. The other solenoid valve is used to open the hand quickly, when the pump can not reduce the pressure in the BPC fast enough. These normally closed valves require a $3.8ms$ $12V$ spike voltage to open and a smaller hold voltage of $1.6V$ to keep the solenoid in an energized state.

The one-way valve is mainly used to minimize the closing time of the hand. A *Cambridge Reactor Design 4mm (12130)* has been chosen for its small dimensions and low weight. When the pump is not fast enough to increase pressure P_2, the fluid from the accumulator can flow through the one-way valve and allow the hand to close. All valves use a custom made connector to be fitted to the hoses.

Pressure Sensors

Two ceramic pressure sensors are used to measure pressures P_1 and P_2. Sensors of the type *DS-KE-R60B* are used to measure static and dynamic pressures from $1.6bar$ up to $60bar$, which is sufficient for the hybrid hand. These sensors are fitted into custom made containers to connect to the system. The main advantages of these sensors are their robustness, small size and low weight. The sensor values are transduced by *DS-MOD-10V* transducers. They convert the relative low sensor voltage into a standard signal. Two potentiometers are included on the PCBs to provide a mechanical way to adjust the output value to calibrate the sensors. The DS-MOD is made for the DS-KE series ceramic pressure sensors.

All components are held together with custom 3D-printed brackets. These brackets are mounted to the main support, which is connected to the hand. Figure 4 shows a 3D render of the total add-on.

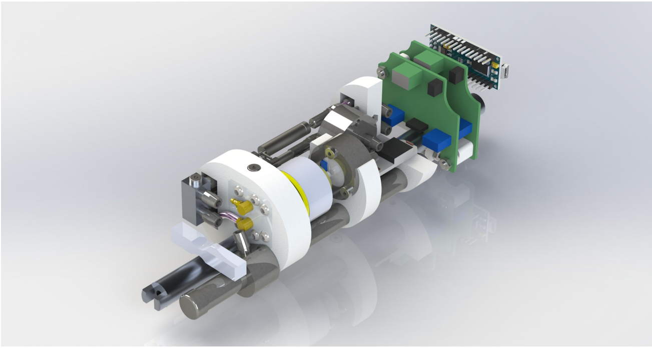

Fig. 4: 3D render of spatial layout of the hybrid system in the wrist and forearm of the hand prosthesis.

C. *Prototype*

The prototype consists of three parts: the prosthetic hand, the electrically powered add-on and the control system. All parts are discussed below.

Hand

The hand that is used, is shown in Figure 5. This is a later version of the DCH [3] with only 4 cylinders ($D = 8mm$) in the hand instead of 7. It is closed by pulling the rod of the BPC ($D = 9mm$), which has only one degree of freedom (DoF). Because this one DoF causes the movement of the four fingers (4 DoFs), the hand is underactuated. The thumb of this hand is passively adjustable, and can be moved by the sound hand of the user. Due to the passive adjustable thumb and the underactuated fingers, the hand can adapt to a lot of different shapes and sizes of objects that need to be picked up. This hand was originally designed as a purely body powered hand prosthesis, and only the BPC will be slightly modified for the hybrid system.

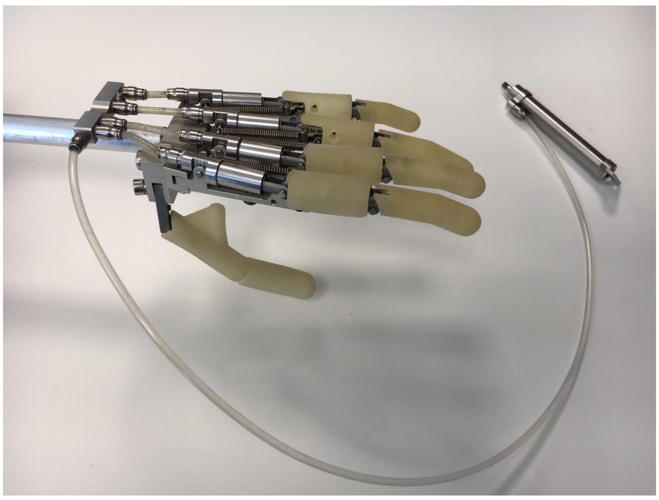

Fig. 5: The used version of the DCH. The four finger cylinders are connected to a different body powered cylinder via a hose to distribute the hydraulic fluid.

Electrically powered add-on

The add-on is made in order to match the dimensions of a lower arm. This is done with the use of 3D-printed brackets to support the components of the system. Closest to the hand are all hydraulic components, such as the gear pump, valves and pressure sensors. Distal to the hand are the motherboards with the transducers for the pressure sensors, the ESC, Arduino and DC/DC converter. This is done to prevent oil leakage on these components. The BPC will be placed at the same position as in the DCH; along the elbow of the impaired arm. Figure 6 shows the total hybrid system, consisting of the DCH and the add-on.

Power Supply

For the power provision, two external power supplies are used. One of them supplies the motor and ESC with power and the other is used for the rest of the electrical components, being the solenoid valves and the pressure sensors and its transducers. The decision to use two different power supplies was made to prevent the back EMF of the motor from influencing the other components.

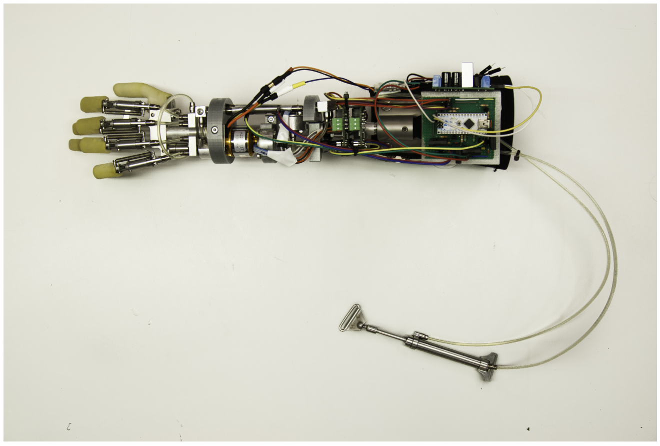

Fig. 6: Hand with hybrid add-on prototype

Control System

In the system, the output pressure is the pressure inside the cylinders in the hand as stated in Equation 1. The input pressure is the pressure induced by pulling on the piston rod of the BPC. This pressure is equal to the difference in pressures on both sides of the BPC, with a correction f for the difference in area (Equation 2) as stated in section Conceptual Design. The gain K is determined to be the ratio between the input and the output pressure, as showed in Equation 3. By rewriting the equation, the setpoint for P_2 follows from Equation 4. P_2 will be controlled to reach $P_{2,setpoint}$ in order to power the hybrid prosthesis.

$$P_{out} = P_1 \quad (1)$$

$$P_{in} = P_1 - f \cdot P_2 \quad (2)$$

$$\frac{P_{out}}{P_{in}} = \frac{P_1}{P_1 - f \cdot P_2} = K \quad (3)$$

$$P_{2,setpoint} = P_1 \cdot \frac{K-1}{K \cdot f} \quad (4)$$

For controlling the system to reach the setpoint, a proportional control strategy will be used on an *Arduino Nano*. Every loop, the setpoint is calculated from the measured pressures. Then, the difference between the measured P_2 and the setpoint will be mapped to match a specific pump speed. Large differences will lead to high pump speeds, and vice-versa.

D. *Experimental Evaluation*

Mass

The masses of different parts of the system have been measured with a simple kitchen scale. The add-on has a total mass of $508g \pm 1$ and the BPC's mass is $42g \pm 1$. The mass of the hand is unchanged, since there were no changes made to it. In addition to these masses, the mass of a battery should also be considered, however since this depends on the chosen capacity, it is not included in the evaluation. The results are shown in Table I.

Part	Mass (g)
Hand (without glove)	152 ± 1
Add-on	508 ± 1
Double acting Body Powered Cylinder	42 ± 1
Total weight	702 $\pm \sqrt{3}$

TABLE I: The masses of the parts of the hybrid hand.

Mechanical Evaluation

1. *Input Output Relation*
   In test 1, the relation between the user's input (pull) force and the output (tripod grip) force is determined. The deviations of all five measurements were small for both the tests with and without the hybrid system, so only one plot is shown for both tests in Figure 7. The line for the hybrid system has a higher slope than the line for the hand without the hybrid system. Both tests were done with an ungloved hand.
2. *Required Closing Force*
   In the second test the force that is needed to close the hand was determined. For the hand without the hybrid system, this force is $29 \pm 1N$ and for the hand with the hybrid system, this force is $23 \pm 3N$. The standard deviation was calculated using the polyfitn toolbox in *MATLAB*.
3. *Required Closing Time*
   In the third test the closing time of the ungloved hand with hybrid system is measured with a camera which records with $240fps$. The hand closes in 49 frames, so the maximum closing time does not exceed $204ms$ when closed as fast as possible.

Electrical Power Evaluation

The energy that is used by the electrical components of the hybrid hand was measured. This energy is $(1.1 \pm 0.1) \cdot 10^2 J$. This result was acquired from 9 measurements, and then the mean and standard deviation were calculated.

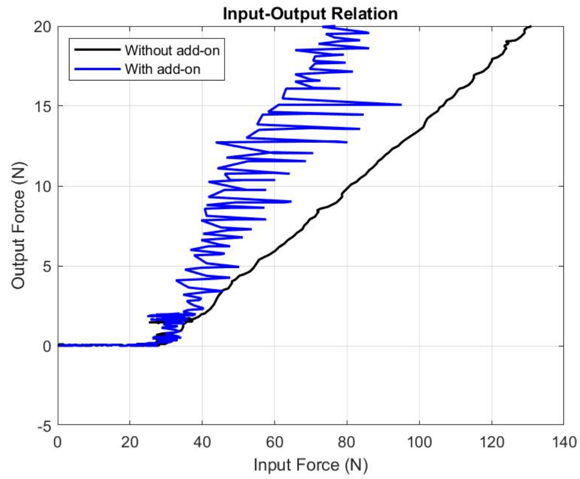

Fig. 7: Relation between input and output force for the tests with and without the add-on

VI. Discussion

A. *Experimental Evaluation*

Mechanical Evaluation

1. *Input Output Relation*
   In Figure 7, it is shown that the graph of the hybrid hand has a steeper slope than the purely body-powered prosthetic hand. This implies that the transmission ratio of the hybrid hand is higher than the transmission ratio of the DCH. This allows for high output forces at relatively low input forces. This transmission ratio could be even increased by increasing the controller gain K.
   However, the hybrid hand shows large fluctuations in the required input force for a tripod grip output force. This can be ascribed to the diminishing of the user's input at the moment that the pump increases the pressure at the B side of the BPC. When the piston rod of the BPC is pulled, the pump increases the pressure on the B side of the BPC, thereby moving the piston and decreasing the input force on the BPC. Because the test bench does not react to this displacement, the input force decreases and this induces the fluctuations in figure 7. Because a person would react to the displacement, the fluctuations could be smaller when used by a person.
2. *Required Closing Force*
   Figure 7 also shows the input force at which the output force is initiated. This is the input force required for closing the hand, which is comparable for both the hybrid and non-hybrid system. This was expected to be lower for the hybrid system. An explanation for this could be that the hybrid system adds extra internal friction to the system, due to the extra tubes, valves and the piston of the accumulator. The extra pressure generated by the pump needs to overcome this friction first, before it can positively

influence the relation between in- and output.

The controller determines the input force by comparing P_1 and P_2. The pressure in the system during the closing movement of the hand only consists due to friction in the system. The friction in the BPC has to be overcome by user input, before P_1 and P_2 start to differ significantly. Since the controller is proportional, a small pressure difference between P_2 and $P_{2,\ \text{setpoint}}$ results in a low power delivery of the pump, and thereby a small pressure increase. Thus a lower threshold value does not increase the closing force significantly. With a higher gain, the pump power could also be higher at low input forces but the pump would require significantly more power at high input forces.

A different sensor for the input force, like a load cell at the pulling rod of the BPC, could be used to detect low user inputs because it measures the input force without the friction in of the system. The controller needs to be changed to have the pump provide extra power when the hand is closing, this should lower the closing force.

3. *Required Closing Time*

   The minimum time needed to close the hand from a fully open position with the add-on is around $204ms$. This is comparable to the closing speed of the DCH [3]. A human hand can close in around $100ms$. Thus the system does not imitate the speed of a human hand. However, it is much faster than other hand prostheses, the myo-electric *i-limb* prostheses closes in $800ms$ for example [16]. A closing time of $204ms$ is sufficient for accurate control which gives it an advantage over myo-electric prostheses.

Electrical Power Evaluation

The result of the electrical power evaluation, gives the energy used to close the hand and reach an output force of $20N$. It consists of the sum of the power of two external power supplies, integrated over the operation time. Both power supplies were set on $15V$. While closing and pinching, the power supply used for the motor uses a current up to $5A$, restricted by the maximum current of the power supply, and the other supply uses a almost constant current of $120mA$, mainly used to hold the valves open.

When the hand is not operated, only the pressure sensors require power. They use a current of only $5mA$ and therefore, their contribution to the total energy consumption is negligible.

With the known energy consumption, recommendations can be made concerning what battery to use. A lithium polymer battery is preferable, due to its high energy density. A 4S Lipo pack supplies $14.8V$, which comes close to the $15V$ of the power supply. The measured energy consumption from an open position to a tripod grip of $20N$ is $110J$. The capacity for one closing can be calculated as follows.

$$C = \frac{E}{U} = \frac{110J}{14.8V} = 7.432mAh \tag{5}$$

An example for a suitable battery pack is the *Gens ace bashing series* $5500mAh$ *14.8V 50C 4S1P HardCase 14 car Lipo Battery Pack with XT90*. This battery weighs $466g$ and therefore would fit into the mass requirement of the prosthesis. With this capacity, the user would be able to close the hand once a minute for a whole day (12 hours), which is more than sufficient.

B. Evaluation of Non-Mechanical Requirements

The requirements concerning the mechanical performance of the hybrid hand are already discussed before in the discussion. Therefore, only the requirements that are not specifically tested are discussed below:

Aesthetic

The used hand is not changed, so it still fits inside a 7.5 inch glove. The add-on is placed in the dimensions of a human forearm (a frustum of a oval with maximum radii of 50mm to 60mm). A central axis is used to connect the hydraulic parts to the hand and sleeve. An upper limb clove can be used to cover the hydraulics. The electronics can also be placed on the socket, to keep the length of the forearm as short as possible, which makes the system adjustable for different amputation lengths.
The system is tested with external power supplies, so the size of possible batteries has not been taken into account.

Hydraulic

The original DCH uses water for the hydraulics, because of the availability and the convenient refillment. By making it a hybrid system a pump was introduced. This pump works on hydraulic oil. This decreases the ease of refilling, since the user will need to have the oil in stock in order to refill it. The oil used is from the same manufacturer, Magom, as the gear pump.

Hybrid

As shown in Figure 3, the designed system adds electrical power, converted into hydraulic power, to the input of the user. The add-on can be used on any hydraulic body powered hand prosthesis. The combination of intuitive muscle power with high forces provided by the gear pump shows potential to increase the usability of hand prostheses.

Intuitive

Operating the prosthesis with or without the add-on is comparable, so no intense training is needed to pick and hold objects for regular body powered prostheses users. New users can use the prosthesis after a short instruction.

Reliable

Some parts of the system are not sufficiently reliable to be used for a whole day. The accumulator is prone to leaks, since the piston vibrates radially when it is pulled or pushed inside the tube. This could be solved with a sliding bearing attached to the piston. Other parts leak less, but need to be refilled regularly. Several vent valves have been installed to refill, however a cylinder with a one-way valve on the vent could make this process easier.

While the maximum pressure of the pump is known to go up to $60bar$. It can only hold this pressure for short periods, otherwise it will start overheating. The software closes the valves to hold a pressure, so the motor has time to cool down. This also lowers the power consumption for a stationary position of the hand. A thermometer can be used to detect overheating, which can increase the reliability.

The hand does not flex visually by large output forces. Since the valves close to retain the pressure in the hand, it can be used to hold objects firmly without supplying an input force.

C. Design improvements

Accumulator

The accumulator was expected to experience solely axial forces, being the force from the tension spring and pressure from the hydraulic fluid. Therefore, the piston was expected to move linearly through the cylinder. However, this was not the case, possibly due to the inside of the cylinder not being perfectly smooth. This resulted in shocking movement through the cylinder, leading to more friction and leaks. To prevent this from happening in a next design, a bearing could be added to the piston. However, this would be at the cost of more friction than with a smooth movement without a bearing.

Electronics

The electronics used for testing consisted of an ESC, two *DS-MOD-10V* transducers, one *Arduino Nano*, one DC/DC converter, and one prototyping soldering board. These components can be integrated on a PCB and the off the shelf components can be replaced by surface mount devices, which would decrease the size significantly. This would also result in fewer cables throughout the system.

Furthermore, two external power supplies are used to prevent the motor's back EMF to influence the other electrical components. However, all electrical components can be powered by a single battery, as discussed previously, on the condition that the back EMF is filtered out.

Motor and pump

A more powerful pump would increase the power of the system. The used gear pump can overheat, which causes the O-rings to leak onto the motor. The used brushless motor makes a high pitched noise when in use, this can be annoying to hear. A quieter or insulated motor in combination with a cooled and/or more powerful pump would increase the usability.

D. Study strengths and limitations

This study showed that it is possible to increase output forces while maintaining low input forces through the use of a hybrid powered system. A big limitation to this study was the available time for tuning the controller. With some more time, other control strategies could be explored and parameters could be tuned to smooth the output force of the hybrid hand. This could also decrease the closing force and thereby decrease the needed input power for the entire closing movement.

VII. Conclusion

This study presents an electrically powered add-on for hydraulic upper limb prostheses. This makes the system hybrid; it decreases input forces, while maintaining high output forces. The output forces can go up to twice as high as the output forces in the Delft Cylinder Hand for the same input force, depending on the the gain set in the control system. The mass of the hybrid system is $702 \pm \sqrt{3}g$, which is less than the mass of an average human forearm and hand ($1723g$). The add-on fits in the dimensions of the human forearm, making it suitable for transradial amputees. The closing speed of the hand is only $204ms$. This is faster than current myo-electric upper limb prostheses and comparable to the Delft Cylinder Hand. $110J$ is used by the hybrid system for closing the hand and grabbing with an output force of $20N$. Accordingly, regular battery packs contain enough energy for the hybrid system to be used for a sufficiently long operating time. The hybrid hand prosthesis combines high output forces with the intuitive control of a body powered prosthesis, showing great perspective for the usability of hand prostheses.

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