Feasibility of a hydraulic powered anthropomorphic prosthetic hand

# Summary

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# Introduction – Overview

There are over one million people worldwide who have had some measure of upper limb amputation (Mata Amritanandamayi et al., 2018), with a projected one million upper—limb amputees to be living in the United States alone by the year 2050 (Perry et al., 2018). As a result, there is a continually increasing need for functional prosthetic limbs to assist amputees with activities of daily living, as well as physically demanding work.

Being able to perform activities of daily living and aesthetic design are most often seen as the two major decision-making factors when choosing whether or not to use a prosthetic (Piazza et al., 2017). However, studies have found that of these two deciding factors, high grip power, grasp versatility, resilience and power autonomy, or, functionality, is generally the dominant design parameter (Piazza et al., 2017, Resnik and Klinger, 2017). This is due to the important part practicality and functionality play in not only being able to perform specific activities and restoring normality into a person’s life, but also improving the possibility of being reinserted into a job (Proaño-Guevara et al., 2018). Additionally, a study found that of all adult amputees who were employed prior to the loss of an upper limb, of the percentage that returned to work, the lowest returning percentage were those who worked in physically demanding environments where either the prosthetic solution they were provided with was either unsuitable or too difficult to operate given their circumstances (Millstein et al., 1985).

The demand for a highly functional prosthesis is supported by the adoption and rejection rates of current prosthesis. Studies have found that between 17% to 80% of people with major upper limb amputation reject the use of a prosthesis entirely because the functional advantage or cosmesis did not outweigh the inconvenience of the prosthesis (Proaño-Guevara et al., 2018, Resnik and Klinger, 2017). A recurring theme presented by amputees is the desire for enhanced strength or grasp force for both myo-electric devices (Hashim et al., 2018, Proaño-Guevara et al., 2018, Piazza et al., 2017) and body powered devices (Ayub et al., 2017, Hichert et al., 2017). For example, for the voluntary closing body powered prosthesis known as the Hosmer Soft Hand, patients had to exert over 131N of cable force in order to achieve a mere 15N pinch force (Hichert et al., 2018). A prosthesis powered by dielectric actuators could only achieve 35-97N output force (El-Hamad et al., 2017), and a novel pneumatically powered soft actuator could only achieve 0.46N at 5 bar of pressure (Mata Amritanandamayi et al., 2018). To illustrate the issue, a typical anatomically intact bicep can exert 40N-116N worth of force during flexion (El-Hamad et al., 2017). Thus, the need for stronger, more powerful actuators are necessary, such as those that can be offered by hydraulics.

Fluid power has the potential to generate extremely large forces with smaller and more flexible configurations. Durfee, Xia and Hsiao-Wecksler modelled micro hydraulic cylinders, and at a nominal pressure of 6.9MPa (1000psi), a single hydraulic cylinder with a mere 4mm bore can output up to 87N worth of force (Durfee et al., 2011). Furthermore, the system output is infinitely variable based on the requirements of the user. For example, if more working force is required, either the pressure of the system can be increased, or the size of the cylinders increased and vice versa. If these cylinders were to be implemented, a considerable number of them would be able to fit in the space that would otherwise be taken up by a servo array, allowing far more precise control and freedom of control over the degrees of freedom of the upper limb. If the upper limb was made anatomically correct, there would be three cylinders used for flexion of a single finger which would result in a previously unseen output force per finger than a lot of currently developing prosthetic hands.

Furthermore, Resnik and Hashim have found that weight is a significant contributor to prosthesis adoption (Resnik and Klinger, 2017, Hashim et al., 2018). Significant musculoskeletal issues can be incurred with the use of heavy and unwieldy prostheses, such as excessive discomfort on the stump and noticeable shoulder strain, and if used for extended periods of time may transition into injuries (Schweitzer et al., 2018, Abayasiri et al., 2017). A majority of externally powered prostheses make use of electrical servo motors in order to actuate the appendages. These prostheses are generally very complex and heavy due to the need of extensive gear trains or drive train mechanisms, and in some cases the placement of a servo motor at every rotational joint (Pai et al., 2016). For example, the Modular Prosthetic Limb developed by DEKA weighs approximately 4.8kg with its battery attached (Leal-Naranjo et al., 2017). In comparison, an upper limb of a 75kg person typically weighs 3kg (Abayasiri et al., 2017).

Hydraulic powered actuators however do not require the typical power transfer systems in order to operate (Foglyano et al., 2015). It was found that for a 100W mechanical system, an electromechanical system is predicted to weigh 428g. A hydraulic system with equivalent mechanical output weight will change significantly with the pressure of the system. For example, at 0.69MPa (100psi) a 100W mechanical output system is estimated to weigh 625g, at 3.45MPa (500psi) it is estimated to weigh 125g and only 63g at 6.9MPa (1000psi) (Durfee et al., 2011). This gives significant flexibility in the design to maximise the desired weight to power ratio whilst also providing a significant weight reduction which can aid heavily in the comfort and usability of the device.

Whilst the weight of the arm is extremely important, the distribution of the weight along the arm is equally as important. Additional weight from heavy servo motors and other additional components, especially towards the extremities of the body impacts negatively to the usability of the device. Waters and Mulroy found that an additional weight of 2kg on each foot of a healthy adult results in a 30% increase in oxygen uptake, whilst over ten times that amount on the torso has little impact (Waters and Mulroy, 1999). Extending this to the upper limb demonstrates that a poor weight distribution often provided by externally powered prostheses is often hugely detrimental to the benefits that the prostheses strive to provide. For example, the TRS i-Limb (a commercially available prosthetic hand) weighs 0.63kg with a centre of gravity that is fairly distal in comparison to an anatomically intact hand due to the location of the actuators (2015). It was found that this caused significant discomfort on the stump and noticeable shoulder strain during extended use (Schweitzer et al., 2018).

A key advantage of fluid power is the ability of power to be transported through flexible hosing which can be snaked over moving joints and placed in locations that would otherwise be impractical for electrical motors. This characteristic provides great flexibility in component placement such as placing the hydraulic cylinders on the proximal joints (Durfee et al., 2011), and the other heavier components such as the pump, valves and battery may be kept on the torso where they cause a considerably lesser strain on the body (Foglyano et al., 2015). Furthermore, this flexibility can be leveraged for numerous additional benefits. By being able to choose the location of the actuators, they can be optimised for maximum benefit. Placing the actuators away from the joints of the fingers and closer to the shoulder aids in reducing the rotational inertia (Leal-Naranjo et al., 2017) which allows greater control over the arm and reduced power requirements in order to operate it. This also allows the end effector or the hand to be minimised to further reduce the weight (Semasinghe et al., 2018), as a prosthetic hand weighing 0.5kg or more tends to lead to overexertion (Proaño-Guevara et al., 2018). Power then can be transmitted to the distal joints via tendon or cables – a technique used often in prosthetics to gain similar benefits (Love et al., 2009).

There is a clear need for stronger and more powerful, yet lighter and more robust prosthetic devices, which can be catered to by hydraulics. These benefits combined with its flexible component configuration as well as its force-to-weight ratio have the potential to develop a revolutionary prosthetic design. It will be another step in the direction to allow amputees and similarly disadvantaged persons to mitigate the adverse effects of upper limb loss and enable them to retain or regain their standard of living.

The aim of this project is to explore the use of hydraulics in upper limb prostheses - to identify its practicality and feasibility in the field. The goal is to rapidly prototype an anthropomorphic prosthetic arm with a high and demonstrable degree of freedom using readily available and off-the-shelf components.

## Background – Types of prosthetics

## Motivation & Aims – Research gap (general)

# Evaluation of current 3D printed prostheses

# Concept development of a full hand prosthesis

# Final design

# Functional evaluation

## Precision

## Grip force

# Discussion

# Acknowledgement

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# Appendices

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