An Overview and Comparison of Upper Limb Prosthetics

Drew van der Riet[1], Riaan Stopforth[2], Glen Bright[3]
School of Mechanical Engineering,
University of KwaZulu-Natal, Howard College,
Durban, South Africa
e-mail: [1]213569879@stu.ukzn.ac.za, [2]stopforth@ukzn.ac.za, [3]brightg@ukzn.ac.za

Olaf Diegel
Massey University,
Auckland, New Zealand
e-mail: o.diegel@massey.ac.nz

Abstract—**This paper looks at various existing upper limb prostheses both from the commercial and research area. It assesses what has been achieved in the commercial field as well as its shortcomings. State-of-the-art research on upper limb prosthetics is reviewed and the progress over the last decade is touched on briefly. The paper then considers haptic feedback and myoelectric control, two cutting-edge technological fields within the field of prosthetics. A comparison is made between current and past upper limb prostheses and improvements to these prostheses are discussed. Suggestions for future work are made to incorporate and develop haptic feedback and more advanced control algorithms to further improve the current prosthetics. Myoelectric control is identified as the most limiting factor to the progress of upper limb prosthetics.**

Keywords—upper limb prosthetics; myoelectric control; haptic feedback; comparison between existing prostheses; future work in upper limb prosthetics

I. Introduction

A classic example of upper limb prostheses can be seen worn by Captain Hook in the childhood story of Peter Pan [1]. Prosthetics have come a long way from simple hooks. Advancements have been made too bringing the hook closer and closer towards the ultimate goal of a full and lifelike replacement for the human hand. There are still several large engineering problems to overcome before reaching this goal as well as the practical consideration of keeping the costs low.

A normal human hand has three basic functions; gripping objects, manipulating them and exploring the surrounding environment [2]. Most rudimentary prosthetics restore the ability to grip and manipulate to some degree. If full restoration is to be achieved through prosthetics, the prosthetic hand must restore the ability to explore as well. Full restoration requires the prosthesis to have proprioceptive (a sense of one's body's positioning) and exteroceptive (touch) sensors, and for this information to be communicated back to the amputee.

In order for progress to be made in the field of prosthetics, it is important to review the current state of prosthetics and to identify the areas needed to be focused on to further improve a system. This paper reviews prostheses currently available on the market as well as the latest research being conducted around the world. It highlights the weaknesses in these prostheses and makes suggestions for the direction of future work.

II. An Overview of Current Prostheses

A. Current Commercial Hand Prostheses

The three main competitors in the market of myoelectric prosthetics are OttoBock©, Touch Bionics© and RSLSteeper©. Touch Bionics©'s latest myoelectric hand, the i-limb ultra, can be seen in Fig. 1 [3]. In 2011, comparisons were done between OttoBock©'s DMC plus and older versions of Touch Bionics©'s i-limb ultra, the i-limb pulse and the i-limb [4]. The DMC plus and i-limb pulse were found to be about equal in grip strength, with the i-limb being weaker. The DMC plus was much stronger than either of the i-limbs in tripod grip strength. The pulse had the highest scores for posture and movement. The pulse also had the highest client satisfaction, although it must be mentioned that only one test subject was used.

The BeBionic3 from RSLSteeper© [5] uses a state machine to control the prosthesis, this state machine relies on manually selected thumb position (opposed or non-opposed) as well as a toggle button allowing a second group of positions. The user simply has two degrees of freedom (DOF) in control: open and close commands. Although this is currently advertised as the most advanced commercially available prosthesis, it is still using a very old system of control.

B. Shortcomings of Commercial Hand Prostheses

It has been found that the grip strength of commercial prosthetic hands is much lower than that of an able-bodied individual [6]. Hand control and motion is also very clumsy and requires manual correction of thumb positions. Dexterity of fingers is extremely limited. Previous research [4] emphasized that at least 4 months of daily training was needed to be able to use a multifunctional myoelectric prosthetic hand.

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

Fig. 1. i-limb ultra from Touch Bionics© has multi-fingered grip resulting in more realistic movement and a variety of grips.

One of the major drawbacks in the use of these state-of-the-art prosthetic hands is the high cost involved. An example of this is the Robohand [7], a purely mechanical prosthetic hand that works on a cable/leverage actuated system. It was released in 2013 and costs around $150 US. This device is very simple and has only one grip position (the tripod grip) in comparison to the multigrip commercial prosthetic hands mentioned above. Despite this, the Robohand has received a large amount of popularity due to its cheap design.

C. *Research and Development of Hand Prostheses*

There have been several multigrasp prosthetic hands developed in recent years [8]. These hands range between one and six actuators working independently which control a varying number of fingers from just the index and thumb in a “claw” style to each finger individually. Vanderbilt University’s [8] prosthetic hand can be seen in Fig. 2, demonstrating its 8 different hand positions.

State-of-the-art myoelectric prosthetics are highly complex and challenging to design. This is because they have to be entirely independent, relying on self-actuation, internal power, built-in intelligent control and sensory feedback while also remaining compact and light-weight to resemble a human hand. They need to be highly functional allowing the user a full range of actions as well as sensory feedback and also have a good battery life. This is a difficult task for a device that is the size of a human hand. Researchers have come a long way in obtaining these goals, as can be seen in the MARCUS [9] and Southampton Hand [10], earlier attempts at improving the state of upper limb prosthetics. The progression showed favour to improving the number of degrees of freedom and the control needed to obtain these positions.

A notable research-based prosthetic hand currently being developed is the SmartHand by the ARTS Lab of Scuola Superiore Sant’ Anna, Pontedera, Italy [11, 12]. This research showcases the use of 4 DC motors to control 16 degrees of freedom (DOF), proprioceptive and exteroceptive sensors with 5 vibrotactile feedback displays. The SmartHand’s weight was considered to be a small problem, 520 g in comparison to an

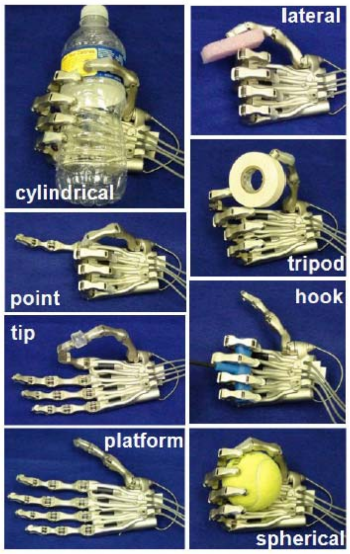


Fig. 2. Eight different grips/hand postures made by a prosthetic hand.

adult male average of 400 g [13]. Its size is 1.3 times larger than the same average adult male statistic. There remains no adequate method of transmitting detailed haptic feedback to the user. It is also stated that the mechanical architecture contains a compromise of mechanical efficiency and the lack of an extension grip, used to grip a book or a plate [14], for adaptive gripping fingers and more strength in power and precision grips. It has also been highlighted that power consumption should be kept to an absolute minimum to extend the battery life of the prosthesis.

III. Haptic Feedback

A. *The Role of Senses in a Hand*

The human body has more than the classically believed 5 senses, the clear 6th sense is the vestibular system, or the sense of balance which is located in the ears. Depending on how one defines senses, touch can be broken down into 4 separate senses; physical touch, temperature, proprioception and pain (which can be separate from touch as humans sense internal pains as well as pains induced through touch). It is suggested that these 9 senses (vision, hearing, smell, taste, touch, balance, temperature, proprioception and pain) should be considered as the fundamental senses [15].

Using the above definition, the classical definition of touch is associated 4 senses, touch/tactile (types of surfaces, i.e. rough, smooth or wet as well as pressure and force), temperature, proprioception and pain (a warning of danger). These four senses are all sensed by ones hand and arm and play a large role in both communicating and exploring one’s environment [16]. It is therefore important to restore not only the motion and physical function of a lost arm or hand through prosthesis but also these 4 senses. Achieving this will create a holistic prosthesis capable of fully restoring the amputee to normal function. It has been found that haptic feedback reduces fatigue in myoelectric prosthetics users. This is because users without haptic feedback tend to use excessive force for excessive periods of time in order to successfully complete tasks [17]. It has also been shown that the use of haptic feedback in prostheses reduces phantom limb pain in amputees [18]. One of the challenges in haptic feedback systems is the fact that touch, which can be classified as a form of communication, hasn't had the rules and symbols to define it explicitly created [16]. Without these rules it is impossible for a computer system to recognize and process this language. A language of communication needs to be established if these senses are to be restored through haptic feedback.

B. *Current Haptic Feedback Systems*

Haptic feedback systems focus on two areas, tactile (touch) and force feedback [19]. Within the tactile feedback area, there are currently two main subdivisions; pressure displays and vibrotactile stimulation [20]. Force feedback systems are found commercially in joysticks and gaming steering wheels, as well as other devices but are not generally implemented in prosthesis as the prosthetic arm itself transfers forces to the amputee's residual limb directly. It has been found that both vibration and pressure feedback systems in additional to visual feedback improved task completion over visual alone [21]. Previous research performed by comparing vibration and pressure feedback systems found that pressure systems are slightly easier to recognize than vibration systems [22]. Haptic feedback is clearly important in the future development of prosthetics in contrast to the high level of dependence on visually aided control in current prosthetic arms.

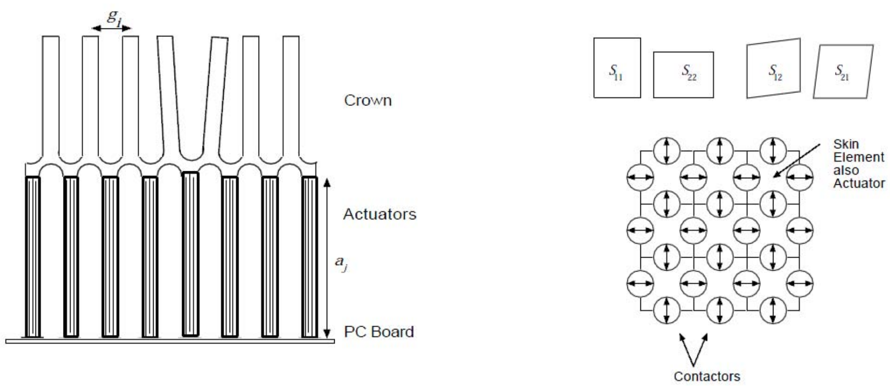
C. *Novel Haptic Feedback Research*

A more recent development in haptic feedback is the use of skin stretching devices. These devices use a mechanical mechanism to stretch the skin of the user in either a lateral [20] or rotational [23] manner in order to display signals. Previous research suggested that the lateral stretch could be used to signal textures [20]. The lateral stretch technique shown in Fig. 3 [20], shows how the vertical actuators move the crown laterally. A rotational stretch device, as shown in Fig. 4 [23], could be used for proprioceptive sensing. Natural proprioceptive sensing uses skin stretch on the joints and so using this rotation skin stretch display is a more natural and thus easily understandable medium for signaling. Tests done using the rotational stretch showed promising results, improving the accuracy of users over no-feedback conditions [24]. This method could be developed further as a proprioceptive feedback device. The proprioceptive sense is significantly more useful than visual positioning when controlling a prosthetic arm. However, there are no current proprioceptive feedback devices commercially available for use in prosthetic arms [25].

One of the major problems found with prosthetic hands is the lack of reliable grip strength. Problems occur with either the grip being too strong and damaging a fragile object or too weak and a heavy object slipping out of the prosthetic hand. There are two possible solutions to this problem; robotic control of grip strength or discernible haptic feedback allowing users to accurately control the grip strength themselves. Experiments have shown successful application of both grip strength and object slip tactile displays [26]. These experiments used a vibrator to indicate grip strength and a stroking belt, as shown in Fig. 5 [26], to indicate slippage. The stroking belt is a new approach to haptic feedback, however, it was found to be both less comfortable and more difficult to interpret than the vibrator. Both displays were stepped into 4 stages and the experiments were done in an individual manner. Further work can be done to examine the combined effect of the sensors in a real-world situation.

A previous research study was done by using three miniature vibrotactile devices placed in different locations on the forearm simultaneously [12]. They concluded that the subjects were able to sense the different locations being stimulated with great accuracy and were also able to discern between 6 unique patterns created by the 3 devices with lesser accuracy but still greater than 75 %. It was suggested that three basic types of information are essential in communicating with the amputee; contact touch, contact position (where on the prosthesis) and contact force.

There are few studies on Neuromuscular Electrical Stimulation (NMES) as a form of haptic feedback. NMES works by providing small stimulating electric shocks to the



(a) (b)

Fig. 3. Lateral stretch idea shown from side (a) and top-down (b) views. The crowns swing laterally when the actuators move up and down.

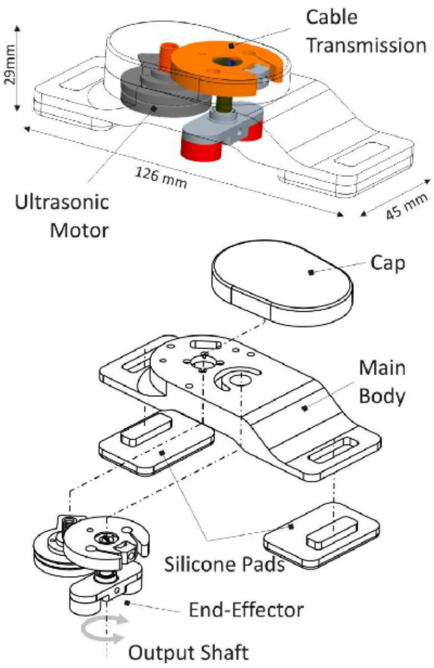
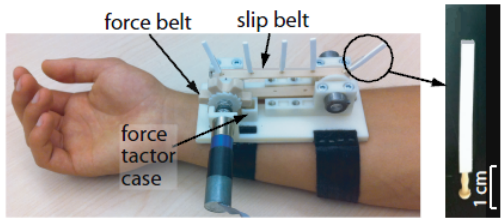


Fig. 4. Rotational skin stretch device.

user. These shocks can vary in amplitude, pulse width and frequency. A study was done on the comfort and effectiveness of using it as haptic feedback for a video game and had mostly positive results [27]. It was found that most subjects thought the stimulation to be informative and exciting (adding to the video game experience) although a few found it uncomfortable and irritating. Previous research analyzed the different types of stimulation that can be induced by NMES [28]. It was found that touch, vibration, pinprick and movement were the most frequently reported stimulations. The type of stimulation felt was controlled to a degree depending on site location of the NMES, type of pulse and number of channels. The magnitude of the sensation was also variable. It is proposed that due to NMES's variety in stimulation it is an appropriate feedback for myoelectric prosthetic hands.

IV. Myoelectric Control

The one of the highest priorities when designing prostheses is the ability for it to be controlled by the amputee. Traditionally prostheses were controlled by mechanical cables and levers attached to the amputees body, allowing the amputee to drive the prosthesis. In most modern prostheses, the focus is to restore full function to the amputee. This means that the amputee can control his/her prosthesis simply by using his mind, as he controls any other limb in his body. This approach can be carried out through invasive nerve connectors which read signals directly from the nerves or through an electroencephalography (EEG) headset. Another method is for the signals to be read directly from the muscles through electromyography (EMG). This method is generally a non-invasive technique and is preferred in upper limb prosthetics because of its simplicity to connect the EMG sensors to the



(a) (b)

Fig. 5. (a) Grip strength and object slip display using a vibrator and (b) stroking belt.

patient along with the rest of the prosthesis. It has also had the most success in upper prosthetic control [29].

A. Problems in Electromyography

The main challenge of EMG control is mapping the myoelectric input signals to the output actuators of the prosthetic hand. This is particularly challenging when the number of input channels is significantly less than the number of output channels. There are several other challenges faced with all EMG signal extraction [30]: (1) everybody's arm produces different electrical signals, and so the EMG controller needs to be configured for each user individually, (2) a change in arm position results in a change in EMG signals even if the hand grip did not change, (3) the EMG signal will vary according to the placement of the electrode, and (4) fatigue of the muscles being read reduces the root mean square (RMS) value of the signal.

B. Approaches to Myoelectric Control

Different experiments have been done with the number of EMG sensors ranging from 32 sensors to only 2 [31]. Results have been found to be better with a larger number of sensors, but not drastically, and the large increase in cost in the use of multiple EMG sensors motivates the use of less electrodes. There are two main fields of EMG control, pattern recognition and non-pattern recognition [29]. Pattern recognition is the most common method for EMG signal processing in research literature [31]. Algorithms have been developed to be able to recognize multiple finger movements both individual and paired, with roughly 90 % accuracy.

The problems with current pattern recognition systems are that they are limited in the number of patterns to select from, which means that the prosthesis has limited positions and lacks the freedom of a natural hand [32]. Increasing the number of patterns means that the classification error will worsen and the training time will be extended. Also, only one pattern can be selected at a time further reducing the flexibility and creating a sequential control scheme. There has been recent work done to allow for multiple DOF control simultaneously [32]. Non-pattern recognition is more commonly used in clinical practice as it is more reliable and offers simplified open/close or proportional control [29]. This control method can be simply used to control the grip strength (a high priority in modern prostheses) of a single DOF prosthesis such as ones used clinically like OttoBock©'s DMC plus [33].

The main reasons why pattern recognition hasn't been used in clinical applications yet is due to the lack of an easy user interface, uncertainty that good classification relates to good control of a prosthesis and that muscle patterns change over time making long term accuracy more questionable. One of the reasons for poor control through pattern recognition despite the high accuracy of classification is that there is also a high level of false activation movements (an unintended activation of movement). A method to reduce this is a multiple check classification system that uses all the classes to agree on a decision before activating a movement. A multiple binary classification (MBC) algorithm has been developed in previous research using this method. It was found that the MBC system, compared to a conventional pattern recognition system, had lower false activation and better control of a virtual prosthesis despite an increased classification error [34].

One of the approaches to non-pattern recognition control is an array selection technique [29]. An array consisting of a 5x5 grid was used to represent three grip types; power, precision and lateral and a variety of intermediate positions between an open hand state and the stated closed grip positions. The user could navigate through this 2-dimensional array by either flexing (x-axis) or twisting (y-axis) his wrist. The maximum and minimum myoelectric signals would be collected from the user to calibrate the system before use. The systems major shortcomings are the lack of grip strength control and a relatively long time required to grip objects correctly (approximately 5 seconds). The time taken to grip objects could be improved through prolonged practice with the device. Another non-pattern recognition control technique is the use of an event driven finite-state algorithm [35]. This approach only uses the state of flexion on the wrist as an input, requiring only a single pair of EMG sensors. The sensors read 4 states; flexion, extension, joint flexion-extension (co-contraction) and rest. Using these command inputs it is possible to navigate through a bi-linear map corresponding to all the different grip types in a sequential order. Flexion and extension signals were used to progress forwards and backwards through the different stages of the map and co-contraction as a toggle between linear maps [35]. Power, tip, pinch and hook grips were achieved in this manner as well as a point and open hand position. These grips were achieved faster than the previously mentioned method (the average time taken to select a position was around 2 seconds) and also improved with practice.

V. Comparative Results

It is necessary to compare the various available prostheses in order to fully understand the scope of work that has been achieved and what can be implemented in the future to further improve this area. The comparison was done by using available information. Comparisons were done with 3 commercially available dexterous prosthetic hands and a state-of-the-art researched based prosthetic hand, which can be seen in Table I. Only relevant and comparable data was used in the tables.

TABLE I. CONTEMPORARY UPPER LIMB PROSTHESES

	i-limb ultra [3]	**BeBionic3 [5]**	**Michelangelo [36]**	**SmartHand [13]**
Grip Strength (N):				
Power Grip**	136	140	70	36
Lateral Grip***	34	27	60	8
Passive Load (kg) - Hook Grip (Suitcase Hold)	90	45	-*	10
Closing Speed - Power Grip (sec)	1.2	1.0	-*	1.5
Grip and Hand Positions	11	14	7	-*
Control	2 Channel Myoelectric	2 Channel Myoelectric	2 Channel Myoelectric	Myoelectric
Actuators	DC Motors	DC Motors	DC Motors	DC Motors
Touch Sensors	No	No	No	pressure
Feedback Displays	No	No	No	5 vibrotactile displays
Weight (g)	479	598	600	530
Cost (US$)****	40'000	35'000	75'000	-*

*data unavailable **this grip uses all the fingers and the palm with the thumb in the opposed position and is used to grip objects such as a bottle
***this grip is between the thumb and the side of the finger with the thumb in the non-opposed position and its used to grip objects such as a key
****cost is approximate and varies greatly according to the amputation

TABLE II. RESEARCH BASED UPPER LIMB PROSTHESES

	SmartHand [13]	Vanderbilt University Hand [8]	Southamption Hand [10]	MARCUS [9]
Grip Strength – Power Grip ** **(N)**	36	50	-*	-*
Degrees of Freedom	16	-*	6	2
Closing Speed - Power Grip (sec)	1.5	0.3	-*	-*
Grip and Hand Positions	-*	8	6	3
Control	Myoelectric	Myoelectric	Myoelectric	Myoelectric
Actuators	DC Motors	DC Motors	DC Motors	DC Motors
Touch Sensors	pressure	No	pressure, slip, temperature	pressure, slip
Feedback Displays	5 vibrotactile displays	No	No	No

*data unavailable **this grip uses all the fingers and the palm with the thumb in the opposed position and is used to grip objects such as a bottle

The second table compares the prosthetic hands developed through research based institutions. Some of the more notable hands have been compared here and Table II also shows the development of the upper limb prostheses over time with older versions also included.

From these tables, graphs have been drawn up to compare various aspects. Fig. 6, shows a comparison of grip strength of the prostheses in power and lateral grip positions. It was found that power and lateral grips were the best for comparison as they were the most commonly measured grip strengths. The passive load limit of the prostheses is shown in Fig. 7 using the hook grip.

Most of the prostheses compared in this study had a high DOF, allowing for a large combination of grip types. The limiting factor in grip types is the control algorithm used. The MARCUS [9] and Southampton Hand [10] both used state machine control methodologies. Generally the prostheses developed in research are capable of a high level of dexterity and are limited only by the current technology available to control the prosthesis as discussed in section IV. The possible grip and hand positions are shown in Fig. 8. The total weight of the complete prostheses including the wrist is shown in Fig. 9.

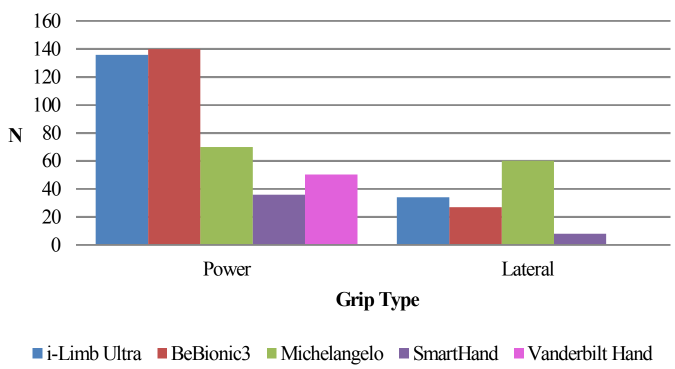


Fig. 6. Grip strength (in Newtons) of prosthesis in power and lateral grip types.

VI. DISCUSSION

A. Grip and Load Force

Grip strength, although improving, is still considerably lower than that of an unaffected hand. Only the i-limb ultra and the BeBionic3 have considerable grip strength, and this is still 4 times less than an unaffected hand. The motor size is the limiting factor in this area. Most prostheses are designed with 4-5 motors which are all situated in the hand itself, thus the space is very small. Since a motors power is related to its size, this proves a difficult challenge that has yet to be properly solved. Possibly redesigning the entire system would be needed to improve the grip strength as a cable/tendon system has high loses due to force angels. Further work should be done into mechanical designs of the finger as well as consideration into alternative actuators to improve this problem. The passive force limit ranges greatly between the 3 prostheses compared in Fig. 7. i-limb ultra's performance in this area is remarkable and definitely adequate for daily life, even BeBionic3's passive force limit would be sufficient to lift daily items.

B. Weight

As a normal adult male's hand weighs around 400 g, the weights of the prostheses seen in Fig. 9, are still too heavy. Weight is a trade-off criteria and this area will improve slowly as the development of micro-electronics continues. The major

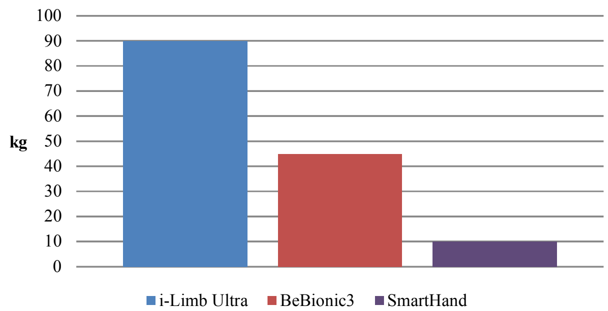


Fig. 7. Passive load (in kilograms) of prosthesis in the hook grip position.

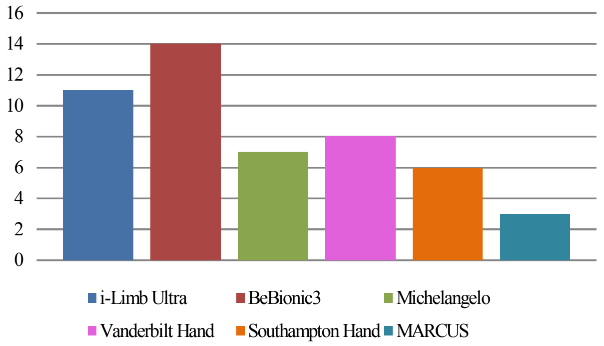


Fig. 8. The number of available grip and hand positions the prosthesis is able to form.

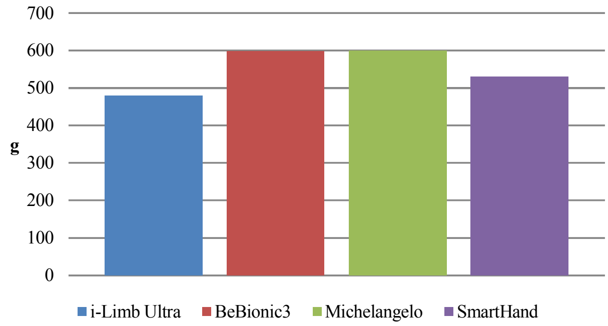


Fig. 9. Complete system weight (in grams) of prosthesis including the wrist.

contributors to weight are the motors. This is a difficult balance to find as it was also stated that the grip strength was lower than that of a normal hand. Thus it can be seen that the designers have taken both these factors into consideration and probably placed more importance on keeping the weight down, as the weights are only 25 – 50 % heavier than a human hand. It is notable that an overly heavy prosthesis would be unusable but an underpowered prosthesis is merely limiting. Future work needs to be done in the use of lighter materials and using alternative actuators to reduce the weight of the system.

C. *Hand Positions and Myoelectric Control*

The number of grip types available to the prosthesis is very important. This plays a big role in how useful a prosthetic hand is practically. One must consider the number of daily tasks that can be achieved with the prosthesis and which tasks cannot. The first versions of the myoelectric upper limb prosthetic would have only 1 grip type, a precision grip, similar to that of the hand of a manufacturing robot. MARCUS was one of the first adaptations to introduce a second DOF to allow for both precision and power grips. A progression of grip types is seen in Fig. 8 from MARCUS [9] to the Southampton Hand [10] and then the Vanderbilt Hand [8] showing the progress research has made in fifteen years. The number of grips these prostheses are able to perform is limited by the myoelectric control algorithm. As mentioned in section IV, there are several different methods of control divided into two main fields; pattern recognition and non-pattern recognition. It is interesting to note also that all the commercial prostheses use very simple non-pattern recognition control. This is probably because of the lower level of training needed to learn how to use these state driven control algorithms, the prosthesis doesn’t need to be trained or personally configured. However the drawback of such systems is the time taken to select the required grip. As the number of grips increases this method will become cumbersome and slow.

Current state-of-the-art myoelectric control algorithms such as pattern recognition have flaws too, and won’t be a long term solution. Future work needs to be done to develop a different type control algorithm that successfully allows the user to control all fingers of the prosthesis separately, proportionately and simultaneously.

D. *Haptic Feedback*

Haptic feedback has been almost completely been left out of current prostheses. The only prosthesis out of the comparison using haptic feedback is the SmartHand. This research could be incorporated into current commercial prostheses to improve grip control and create a more realistic feel of the prosthesis for the amputee. Haptic feedback technology still remains very rudimentary. Pressure and vibration are the only two well-developed feedback systems. More attention needs to be paid in future work to improve the haptic display of information allowing for multiple dimensions to be displayed simultaneously such as pressure and proprioception. Site location identification of vibration devices has potential to be developed further. The haptic feedback system could be extended to incorporate multiple dimensions of sensory information, such as temperature, grip force, slippage and touch. Vibration devices have the additional strength in the fact that they are inexpensive. Pressure displays could also be used in the same system. Existing devices such as the rotational stretch and the NMES should also be investigated in actual prosthesis application. These devices can also add additional dimensions of sensory information if used with the vibration or pressure devices.

E. *Cost*

The commercially available prostheses are all very expensive. The Michelangelo is significantly more expensive than the other devices, however this large price difference doesn’t reflect in any performance improvements over the other hands. The large cost associated with all the myoelectric prosthetic limbs is one of the main reasons stopping these devices becoming common place in the prosthetic community. Future work should focus on the development of cheaper myoelectric controlled upper limb prostheses.

VII. Conclusion

Upper limb prosthetics has improved greatly over the last 10 years. This paper has reviewed the state of current prostheses as well as the progress made to get there. Current work on haptic feedback systems for use with prosthetic hands was examined and it was found that although haptic feedback devices haven't been used in commercially available upper limb prostheses, the implementation of such devices can improve the prosthetic experience. Myoelectric control is the most common and most practical use of extracting signals from the amputee. There are currently a variety of different control techniques but all with many limitations. The design of more versatile control algorithms would greatly improve the functionality and realism of current prosthetics. Reducing the cost of myoelectric upper limb prostheses will improve the accessibility and interest in the field, thus accelerating the rate of development.

REFERENCES

[1] J. Barrie, Peter Pan: The Complete and Unabridged Text. Viking Press, October 1991.

[2] M. Carrozza, F. Vecchi, F. Sebastiani, G. Cappiello, S. Roccella, M. Zecca, R. Lazzarini, and P. Dario, "Experimental analysis of an innovative prosthetic hand with proprioceptive sensors," IEEE International Conference on Robotics & Automation Taipei, Taiwan, September 2003.

[3] Touch Bionics, [Online]. Available: www.touchbionics.com, date viewed: 25 February 2013.

[4] O. van der Niet, H. Reinders-Messelink, H. Bouwsema, R. Bongers, and C. van der Sluis, "The i-limb pulse hand compared to the i-limb and DMC plus hand," MyoElectric Controls/Powered Prosthetics Symposium Fredericton, New Brunswick, Canada, August 2011.

[5] RSLSteeper, [Online]. Available: www.bebionic.com, date viewed: 25 February 2013.

[6] O. van der Niet, H. Reinders-Messelink, R. Bongers, H. Bouwsema, and C. van der Sluis, "The i-limb hand and the DMC plus hand compared: a case report," Prosthetics and Orthotics International, Vol. 34, pp. 216–220, June 2010.

[7] R. Van As, and I. Owen, "Coming up short handed (the Robohand blog)," [Online]. Available: www.comingupshorthanded.com, date viewed: 13 February 2013.

[8] S. Dalley, T. Wiste, H. Varol, and M. Goldfarb, "A multigrasp hand prosthesis for transradial amputees," International Conference of the IEEE EMBS Buenos Aires, Argentina, 2010.

[9] P. Kyberd, O. Holland, P. Chappell, S. Smith, R. Tregidgo, P. Bagwell, and M. Snaith, "MARCUS: a two degree of freedom hand prosthesis with hierarchical grip control," IEEE Transactions on Rehabilitation Engineering, Vol. 3, No. 1, March 1995.

[10] D. Cotton, A. Cranny, P. Chappell, N. White, and S. Beeby, "Control strategies for a multiple degree of freedom prosthetic hand," UKACC Control, Mini Symposia, pp. 211-218, August 2006.

[11] C. Cipriani, M. Controzzi, and M. Carrozza, "Progress towards the development of the SmartHand transradial prosthesis," IEEE International Conference on Rehabilitation Robotics Kyoto International Conference Center, Japan, June 2009.

[12] C. Cipriani, M. D'Alonzo, and M. Carrozza, "A miniature virbotactile sensory substitution device for multifingered hand prosthetics," IEEE Transactions on Biomedical Engineering, Vol. 59, No. 2, February 2012.

[13] C. Cipriani, M. Controzzi, and M. Carrozza, "The SmartHand transradial prosthesis," Journal of Neuroengineering and Rehabilitation, 2011.

[14] C. Cipriani, M. Controzzi, and M. Carrozza, "Objectives, criteria and methods for the design of the SmartHand transradial prosthesis," Robotica, Vol. 28, Iss: 6, pp. 919-927, October 2010.

[15] J. Henshaw, "Tour of the senses," The John Hopkins University Press, 2012.

[16] K. MacLean, "Designing with haptic feedback," IEEE International Conference on Robotics & Automation San Francisco, CA, April 2000.

[17] K. Kim, and J. Colgate, "Haptic feedback enhances grip force control of sEMG-controlled prosthetic hands in targeted reinnervation amputees," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 20, No. 6, November 2012.

[18] C. Dietrich, K. Walter-Walsh, S. PreiBler, G. Hofmann, O. Witte, W. Miltner, and T. Weiss, "Sensory feedback prosthesis reduces phantom limb pain: proof of a principle," Neuroscience Letters, Vol. 507, pp. 97-100, 2012.

[19] A. Okamura, "Methods for haptic feedback in teleoperated robot-assisted surgery," Industrial Robot: An International Journal, Vol. 31 Iss: 6, pp. 499 – 508, 2004.

[20] V. Hayward, and J. Cruz-Hernandez, "Tactile display device using distributed lateral skin stretch," Symposium on Haptic interfaces for Virtual Environment and Teleoperator Systems, IMECE Conference, November 2000.

[21] C. Tejeiro, C. Stepp, M. Malhotra, E. Rombokas, and Y. Matsuoka, "Comparison of remote pressure and vobrotactile feedback for prosthetic hand control," IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics Roma, Italy, June 2012.

[22] C. Antfolk, M. Alomzo, M. Controzzi, G. Lundborg, B. Rosén, F. Sebelius, and C. Cipriani, "Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: vibrotactile versus mechanotactile sensory feedback," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 21, No. 1, January 2013.

[23] K. Bark, J. Wheeler, G. Lee, J. Savall, and M. Cutkosky, "A wearable skin stretch device for haptic feedback," Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Salt Lake City, UT, USA, March 2009.

[24] J. Wheeler, K. Bark, J. Savall, and M. Cutkosky, "Investigation of rotational skin stretch for proprioceptive feedback with application to myoelectric systems," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 18, No. 1, February 2010.

[25] N. Gurari, K. Kuchenbecker, and A. Okamura, "Perception of springs with visual and proprioceptive motion cues: implications for prosthetics," IEEE Transactions on Human-Machine Systems, Vol. 43, No. 1, January 2013.

[26] D. Damian, M. Ludersdorfer, Y. Kim, A. Arieta, R. Pfeifer, and A. Okamura, "Wearable haptic device for cutaneous force and slip speed display," IEEE International Conference on Robotics & Automation RiverCentre, Saint Paul, Minnesota, May 2012.

[27] E. Kruijff, D. Schmalstieg, and S. Beckhaus, "Using neuromuscular electrical stimulation for pseudo-haptic feedback," Proceedings of the ACM Symposium on Virtual Reality Software and Technology, pp. 316-319, New York, NY, USA, 2006.

[28] B. Geng, K. Yoshida, L. Petrini, and W. Jensen, "Evaluation of sensation evoked by electrocutaneous stimulation on forearm in nondisabled subjects," Journal of Rehabilitation Research & Development, Vol. 49, No. 2, pp. 297-308, 2012.

[29] G. Matrone, C. Cipriani, M. Carrozza, and G. Magenes, "Real-time myoelectric control of a multi-fingered hand prosthesis using principle components analysis," Journal of NeuroEngineering and Rehabilitation, 2012.

[30] C. Castellini, and P. van der Smagt, "Surface EMG inadvanced hand prosthetics," Biological Cybernetics, pp. 35-47, 2009.

[31] R. Khushaba, S. Kodagoda, M. Takruri, and G. Dissanayake, "Toward improved control of prosthetic fingers using surface electromyogram (EMG) signals," Expert Systems with Applications, Vol. 39, pp. 10731-10738, 2012.

[32] N. Jiang, K. Englehart, and P. Parker, "Extracting simultaneous and proportional neural control information for multiple-DOF prostheses from the surface electromyographic signal," IEEE Transactions on Biomedical Engineering, Vol. 56, No. 4, April 2009.

[33] OttoBock[a], [Online]. Available: www.ottobock.com, date viewed: 18 Febraury 2013.

[34] L. Hargrove, E. Scheme, K. Englehart, and B. Hudgins, "Multiple binary classifications via linear discriminant analysis for improved controllability of a powered prosthesis," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 18, No. 1, February 2010.

[35] S. Dalley, H. Varol, and M. Goldfarb, "A method for the control of multigrasp myoelectric prosthetic hands," IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 20, No. 1, January 2012.

[36] OttoBock[b], [Online]. Available: www.living-with-michelangelo.com, date viewed: 25 Febraury 2013.