Bio-Inspired Designs for Robotic Upper-Limb Prosthesis - a Review

Finlo Heath
MSc Robotics
University of the West of England, Bristol University
Bristol, England
finlo.heath.2022@bristol.ac.uk

***Abstract*—Upper-limb prosthesis is a field which has received considerable scientific and media attention in recent years. Due in part to impressive advances in control, design, sensing and haptic feedback and the application of the products for assisting injured soldiers defending Ukraine. This paper collates, presents and discusses developments in control, haptics, components and commercial prosthetics in the context of bio-inspired upper-limb prosthetics. Each study is presented and critiqued independently before the developments of the field are viewed and discussed as a whole. Current commercial devices focus on delivering intuitive but reductive control via electromyography, with compact lightweight designs. For prosthetics to operate comparably to the natural hand, they must maintain their streamlined form whilst integrating sensory information via haptic feedback to the user. Biological level dexterity will be achieved via machine learning to allow the device to interpret user intention across a wider range of tasks and apply this automatically to minimise the cognitive load on the user.**

***Index Terms*—Bio-inspired, Biomimetic, upper-limb, Prosthesis, Robotics.**

I. Introduction

The human hand is the incredibly complex and remarkably dexterous result of many generations of evolution [1]. Therefore it is logical to look to the human hand for inspiration when considering upper-limb prosthetic devices which seek to restore a comparable level of functionality to users with a limb difference.

Biomimetic technology continues to improve with research into new sensor and actuator types and material possibilities. Researchers are keen to apply these to prosthetics as the most recent wave of upper-limb devices appears tantalisingly close to the full function restoration that has been unachievable in the past [2],[3],[4]. With a combination of soft and hard actuators, smaller and more accurate sensors and haptic feedback to substitute for missing sensory input, modern devices can now mimic many parts of the human structural and somatosensory system.

This review seeks to collate and discuss modern research in the field of bio-inspired upper-limb prosthetics, providing the reader with an understanding of the current state of the art. This has utility for researchers entering the field as well as established researchers - providing a guiding resource which summarises the work, draws out themes across multiple studies and speculates upon the direction that research should take for future development.

II. Search & Selection Methodology

To be confident that this report meets the definition of a review of the state of the art, the studies presented must adequately cover the full breadth of the current research at a suitable level of detail. Google scholar [5] is an excellent resource as one can find research published in many different journals, allowing exposure to a wide range of approaches to bio-inspired prosthesis. Given that actuated prostheses lie fundamentally in the field of robotics, direct search on IEEE [6] Was used in addition. Keywords used in the literature search included Bio-inspired, bio-mimetic, upper limb, prosthesis and prosthetic. This yielded 226 results on Scholar and 48 results on IEEE. Of these, 42 studies were deemed promising enough to read in full, resulting in eight studies and three commercial devices being selected for this review.

As a review of the state of the art, papers published in the last twenty years were selected as a priority, with exception being given to older papers where research still holds relevance today. These are presented and discussed in depth in sections III & IV. These papers were chosen for their aim of developing aspects of artificial upper limbs by taking inspiration from the natural arm. In addition, other studies and their results are cited where relevant. Many papers propose bio-inspired prosthesis components but run experiments which are too far abstracted from their real-world use; such as controlling a robotic hand with computer mouse movements [7]. Studies such as this were not chosen due to their lack of applicability for prosthesis users. For a single scientific paper, an entire prosthetic arm is typically too complex a system to cover. Hence, bio-inspired control methods, sensing, feedback and components have been investigated independently, in addition to whole prosthesis.

III. Results: Presenting the Current Literature

A. Control Mechanisms

The control method defines how a user commands their prosthetic device. Emanuel Todorov [8] defines human motor control as an optimisation process with somatosensory feedback integral to adjusting for control errors. This is of course weighted with experience, with our expectations of the result of a given action informing a cost-benefit analysis of each possible motor action. Therefore, for a prosthesis control method to qualify as bio-inspired, it should utilise sensory feedback mechanisms discussed in section III-B. This would be considered a closed-loop system, with the haptic feedback informing the control mechanism which in turn dictates the next action, generating further haptic feedback.

Myoelectric Control - the use of electrical signals generated by muscle contractions in the residual limb - is by far the most common control method in actuated upper-limb prosthetics [9]. This can be considered a bio-inspired control method as it typically relies on the corresponding muscles for flexion and extension as the biological human hand (where possible according to the type of limb difference).

Real human upper-limb control has errors [10]. For example, even professional athletes cannot hit the exact same point on a target with a projectile on every throw. *Johnson et al.* [11] used EMG control with amputee and non-amputee participants to observe adaption to random and systematic errors. Participants used various mechanisms (EMG, Torque & Angle) to guide a cursor on a screen in an arc from a start position to a target, antagonistic contractions moving the cursor in opposite directions. There was no significant disparity in the error rates between the intact and residual limbs in amputee participants when using EMG control, including when adapting to random perturbations in the cursor position. 8 amputees (all male) and 8 non-amputees (3 female, 5 male) participated in the study. While this is a reasonable number of amputee participants to acquire given the small population size, the overall sample size of the study is small and weighted toward males, reducing the generalisability of the conclusions made.

Most studies opt for myoelectric control as the most intuitive method for the user and having comparable or superior accuracy to other methods such as ultrasound imaging or Force Sensitive Resistors (FSRs) [1]. Current research now aims to enhance the use of EMGs via the use of machine learning to provide gesture recognition to predict the intended task and therefore required grip for the prosthesis. *Menon et al.* [12] used Brain-inspired Hyper-Dimensional Computing (HDC) in conjunction with myoelectric control, with the aim of reducing the cognitive load on the user during activities of daily living (ADLs). This is a form of shared control, where the user activates the prosthetic via muscle contractions detected by the EMG sensors, and the system predicts the required grip based on the activation pattern in a forearm-based EMG sensor array and FSRs in the fingertips. The study applied the array and FSRs to the intact upper arm of three able-bodied participants and measured the task recognition accuracy of the system when six ADLs were performed. The results showed minimum and maximum task recognition accuracies of 78.5% and 100% respectively, with an average of 91% accuracy across the three subjects each performing 5 repetitions of each ADL. The intention of this research is to train the system to recognise natural human motion for ADLs and then engineer it into commercial prosthetics. The mechanism is designed with user-first functionality but with only three participants and all of them able-bodied, the impressive accuracies recorded have not been verified for real users of prosthetics who have different classifications of amputation.

B. Haptic feedback

Providing users with somatosensory feedback allows for reactive as well as proactive control of their device, which mirrors how natural hands are controlled, as specified in the previous section. The natural hand can sense a range of feedback via shallow and deep mechanoreceptors in the skin and recruits this for dexterous tasks [13]. Bio-inspired Prosthesis feedback must therefore utilise multimodal feedback such as the PneuSleeve by *Zhu et al.* [14], a forearm sleeve which can deliver both vibrotactile and squeeze or shear feedback all via soft actuators. This study demonstrates the delivery of a wide variety of haptic sensations to the user, but is targeted as a social haptic device for able-bodied individuals and would require modification to sit on the upper arm for users with a limb difference.

C. Bio-Inspired Components

Kim et al. [15] designed and tested a lightweight bio-inspired wrist component for prosthetic arms. Here the complex natural structure of the wrist was simplified to two ellipsoidal segments, based on two-carpal-row theory. Where the natural wrist is bound by ligaments with non-linear elasticity here a "ligament tunnel" was developed, which routes through the two ellipsoids in an effort to increase the range of motion without compromising tensile stiffness. A low tensile stiffness results in the components being pulled apart when load is applied. Results showed that using steel wire, the tunnel routing resulted in significantly less displacement when a tensile force of up to $500N$ was applied. In addition, the wrist allowed accurate angular flexion and extension through a range of $40° - 80°$, including when grasping a heavy load.

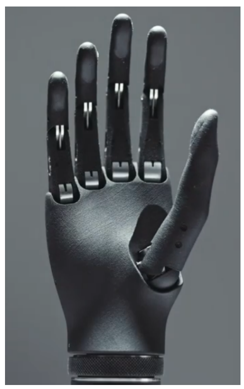
Borisov et al. [16] took inspiration from the multiple grasping options available to the natural hand, designing a prosthetic finger able to perform precision (pinch) and power (enclosing) grasping. This is achieved by having a standard 2 Degree of Freedom (DoF) mode which performs the power grasp, switchable to an under-actuated 1 DoF mode which performs the pinch grasp. Modes are switched using an electromagnet which, when on, creates a rigid joint removing one of the two DoFs. This prototype design has not yet been built and has the drawback of being very aesthetically different to the natural hand, a trait users typically find off-putting [1].

The Biotac [17] is an artificial fingertip with multimodal pressure, vibration and temperature sensitivity. This aims to mimic the multimodal sensing of the natural fingertip as well as visually using a hard "fingernail" set on a soft pad.

The Biotac can grasp soft objects without damaging them by measuring their compliance through reaction force. The Tactip [18] uses computer vision to measure deformation. The Tactip structure mimics the natural papillae found in the dermal-epidermal boundary of human skin, the deformation pattern in the papillae array is measured and used to infer object morphology via transduction. Experimentally, this has allowed for precise edge and surface tangent following and slip detection and correction. When integrated into artificial fingertips, the Tactip can be used for grasping tailored to the specific object, rather than selecting from a discrete list of grasp patterns as most commercial prosthetics do. An alternative route has been explored by *Yin et al.* [19] who used liquid metal embedded in artificial skin to measure shear and vibration sensations via variance in resistance across the skin. Resistance is measured at two points of attachment to the fingertip and demonstrated resolution comparable to natural skin at the fingertip, with the capability to detect slippage.

D. Commercial Prosthetics

(a) The Covvi Hand



(b) The Esper Hand

(c) The OpenBionics Hero Arm

Fig. 1. Three leading commercial upper-limb prosthetics. Image (a) was used with permission from Covvi Ltd [2]. Image (b) is publicly available from Esper Bionics [4] and (c) is from the Open Bionics press-approved image gallery [3].

Most leading bio-inspired full upper-limb prosthetics are commercial products and therefore are not published in widely available papers, though technical manuals can give insight into their engineering. Three leading prostheses to consider include the Covvi Hand [2], the Open Bionics Hero Arm [3] and the Esper Hand [4]. Each of these is ergonomically inspired by the natural hand, in particular aiming for a compact and lightweight design to avoid being cumbersome for the user. Comparing the standard size models, the Hero Arm is lightest at $340g$, followed by the Esper hand at $380g$ and Covvi hand at $570g$. However, the Covvi hand can take up to $16kg$ in tensile loading compared to $8kg$ for the Hero Arm. All three devices are EMG controlled, though the Esper hand uses an EMG array compared to the two EMGs used by OpenBionics and Covvi. Still in clinical trials in the US, Esper uses machine learning based on EMG activity to allow the hand to adapt to the user over time. This aims to emulate the natural hand in grasping complexity and speed and is allegedly three times faster to control than other commercial prosthetics; though this claim has not been publicly verified experimentally.

IV. Discussion

Johnson et al. [11] showed that myoelectric control was equally accurate when applied to a residual limb and an intact limb, a useful finding considering that amputee participants are difficult to acquire due to their relatively small population size. Importantly, this study found that error rates with this control method were reduced over each trial despite perturbations, showing that participants can improve their control accuracy through training. This mimics the process of learning control of biological limbs, where error can be reduced with repetition as the neural pathways defining the motor skill are strengthened [20]. They conclude that further reductions in accuracy will require sensory feedback integration with actuated prosthetics; this would align with the biological closed loop process outlined in section III-A.

The study by *Menon et al.* [12] clearly seeks to restore natural low-effort control to the user, by predicting the required grip pattern so that users can perform ADLs without conscious effort, as able-bodied humans can. This would reduce the number of users who do not utilise the grip-changing capabilities of active devices due to the inconvenience of manual switching. With the recent advances in Machine-Learning, particularly imitation learning [21] and generalisability to intra-task variations, this method of increasing prosthetic autonomous functionality appears promising. Further, just as humans can unconsciously adjust grip to avoid object slippage, emerging devices such as the Tactip [18] and even select commercial prosthetic devices like the Covvi Nexus Hand [2] are integrating automatic slip detection and correction. This increases the reliability of the device without increasing the cognitive burden on the user.

Considering haptic feedback, while the researchers did not propose the PneuSleeve [14] as a prosthetic haptics device, it is one of the only devices claiming multi-modality that could be worn by prosthetic users in addition to their device. Soft actuators can minimise sensory substitution by delivering pressure feedback as a fingertip would, including transient and persistent feedback. This has been shown to provide better discrimination for stimulation location than vibration [22], likely due to the larger surface area of skin which can stimulate deep mechanoreceptors responsible for detection of vibration. With adaption for use on the upper arm to allow space for the prosthetic, the PneuSleeve could provide integral substitution for lost sensory information in the hand, helping the user achieve more dexterous operation of their device.

A contributing factor in prosthetic abandonment is the weight of carrying the prosthetic, an issue addressed by *Kim et al.* [15] through their bio-inspired wrist component. By emulating the natural wrist, in addition to novel cable routing for the artificial tendons, both high tensile strength and wrist mobility were achieved. Acquiring this functionality while retaining a lightweight structure is essential to allow modern prosthetics to emulate the natural wrist. The current prosthetic universal wrist connection allows for minimal wrist flexion or extension. This is a fundamentally unnatural design which limits the angle of approach for many ADLs, making them more cumbersome to complete. However, *Kim et al.*'s wrist does not provide internal routing for the connection of control sensors such as EMGs, this modification will be essential before it can be integrated with commercial devices.

Intelligent Morphological design can provide functional benefits to the prosthetic, without increasing weight or power consumption. The *Borisov et al.* [16] design aims to build multiple grasping patterns into the digit structure. However using an electromagnet to restrict the DoFs in each digit is an unnecessary power sink, especially when commercial hands can already achieve many grasping patterns with a more natural appearance [2]. In comparison, prosthetic fingertip sensing is still an emerging field. Both the Biotac[17] and Tactip [18] take a soft-robotic approach to artificial fingertip sensing, mimicking the natural finger. The Biotac's multimodal sensing brings it closer to the natural finger, being able to distinguish both pressure and temperature. This functionality could potentially be achieved in the Tactip. Given it is an optical system, a thermosensitive coating of paint on the internal papillae could turn them different colours as the temperature changes, which then indicates the temperature in a measurable way for the system. Thermal sensing in commercial prosthetics could allow automatic recoil of the fingertip if it senses a dangerously hot object, preventing damage to the device. *Yin et al.*'s [19] artificial skin mimics natural skin in flexibility and durability and in that it is applied as a deformable sensory layer over a rigid skeleton. It is advantageous since it could be affixed to any commercial prosthetic device as an exterior sensing layer. However, control methods would be required to react to the sensory information detected and the prosthetic must have the DoFs required to perform novel grasp patterns. Both the Biotac and Tactip have demonstrated improved control experimentally with the Tactip integrating control into its design, thereby establishing these two components as the forerunners in practical artificial haptic sensing.

Regarding the leading commercial upper-limb prosthetics [2], [3], [4], Only EMG control has been utilised out of all the bio-inspired developments considered in this review. Compromise is required, as devices must be lightweight so as not to be fatiguing, but all are lacking in haptic feedback, wrist range of motion comparable to the natural hand and sensory capabilities. While these advances could increase the functionality of commercial devices, they would also add to the already substantial cost [1], making them less accessible to potential users; this is likely a critical reason for their current lack of commercial integration.

Integration of additional sensors in the fingertips would require an increase in size, taking away from the sleek design of these devices; an important factor for users, who will be less likely to wear a device that is not visually appealing. The Covvi Hand contains FSRs used in automatic slip detection and correction, but this information is not delivered to the user. The Hero Arm does not contain any slip detection and the Esper Bionics make no mention of it, thus we must assume the hand does not have this capability. Though useful as an automatic mechanism, it could also be desirable for users to receive this information via haptic feedback. For example, allowing the user to locate the points of contact between hand and object, either via vibrotactile or pressure feedback, as demonstrated by *Antfolk et al.* [22]. Humans are able to operate natural body parts without visual confirmation due to proprioception [23] and sensory feedback when they come into contact with an object. Ultimately, some form of sensory feedback is required to enable future devices to be operated without constant visual confirmation, restoring this ability to prosthesis users. Reliable and intuitive haptic feedback may lessen the cognitive load of using these devices to perform dexterous tasks, as grasp corrections with the natural hand are made based on both somatosensory and visual feedback, whereas prosthesis users must currently rely on visual feedback alone.

Further, only the Covvi Hand has any flexion or extension at the wrist, $30°$ in either direction controlled by a manual switch on the hand. The natural hand boasts near $90°$ flexion and extension, crucially allowing the approach of ADLs from different directions, so that tasks can be completed easily without having to reorient your position to suit the task. Each of these hands could benefit from a lightweight joint such as *Kim et al.*'s [15] two-part wrist. If actuated, the routed cables could provide variable stiffness at the wrist. Sensing the desired user flexion or extension would be more successful with the machine-learning approach of the Esper hand. More EMG data will help to distinguish between user intention to grasp only, compared to flexing the wrist before grasping. The natural arm has seven DoF [24], in order to restore natural levels of dexterity, modern devices must aim to match the DoF in the artificial limb to the DoF in the segment of the natural limb which the device replaces.

V. Conclusions

The literature largely agrees that EMG control is most intuitive, particularly with pattern over direct proportional control [1]. In addition to reducing the cognitive load, pattern control allows a single DoF contraction to activate multiple DoFs in the artificial hand, so more complicated grasping can be achieved. EMG control of actuated hands alone has led to commercial hands that have impressed users and the media.

The greatest strides in upper-limb prosthesis technology are currently being made in sensing, where the Tactip and Biotac have proven the possibility of precise, multimodal sensation in artificial hands. Once integrated into prosthetics, the device will receive much more interaction information. Research into delivery of haptic feedback must continue in order to provide users with an intuitive mechanism to receive this information from the device, in turn. This will most likely be in the form of a haptic band on the upper limb, such as the vibrotactile sleeve developed by *Smith et al.* [25]. It remains to be seen whether haptic delivery of sensory information will increase or decrease the cognitive load of dexterous prosthesis use.

To truly serve as a replacement for the natural hand, future devices must integrate sensory detection, haptic feedback and DoFs comparable to the natural hand and wrist. In addition, machine learning should be utilised to provide automatic reactivity in these devices, such as slip detection and correction, to reduce the cognitive load on users. These improvements are required for devices to feel intuitive and functional, which will result in lower rates of abandonment.

Besides the already considerable cost of commercial actuated prosthetics, the challenge of integrating sensing and feedback into these devices comes from the requirement to maintain a sleek, natural appearance and low mass. To combat weight increases, artificial arms could be leveraged from the shoulder, rather than the elbow. This idea takes inspiration from the natural arm and would reduce the torque acting on the user, allowing them to manipulate a heavier device without being overburdened. The counterargument to this suggestion is that already bespoke sockets would become even more complicated to cast and fit along with the large increase in device size. This would cause significant cost increases. However, a larger overall device could provide space for additional sensors, haptic feedback actuators and more powerful onboard computing.

Many users place high importance on having a prosthetic which closely resembles the natural hand [1]. However, Open Bionics has taken a different approach in providing changeable colour pallets for users as shown in Fig. 1, though the form of the Hero Arm still closely resembles the natural arm. Indeed, all three commercial devices use unnatural colour choices; true black for the Covvi and Esper hands. It is possible that making it clear the hand is artificial is a sensible design choice as in a social situation people around the user will be able to anticipate that they may have less dexterity or functionality with the artificial limb, without the user having to declare this. The aesthetically pleasing design still allows these devices to be an encouraging example of the cutting edge, whilst making it clear that it is not a perfect replacement for the natural hand. This may give confidence to users that they can use their devices in social situations and allowing users to personalise the design will increase their desire to wear it regularly.

To summarise, the natural human hand and arm is a highly dexterous limb which uses multi-modal somatosensory information to respond to changes in grasp with little or no cognitive burden on the person. In addition, the arm has seven DoF, the redundancy allowing for multiple configurations to approach a given task. This allows for automatic changes in grip and corrections to avoid object slippage as well as the flexibility to operate in confined areas or specific workspaces. The ideal future bio-inspired prosthetic upper-limb will integrate multi-modal sensory information into on-board intelligent processing to automatically adjust grasping. It will have the same DoF redundancy as the natural hand and deliver modality-matching haptic feedback to the user such as pressure or temperature fluctuations. While all of this technology exists separately, the engineering challenge is to bring all of them together in a prosthetic which is lightweight, compact, mobile and visually similar to the natural arm. Considering the achievements in this field over the previous two decades, this daunting task appears increasingly close to being realised.

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