Chapter 1

Introductory Chapter: Toward Near-Natural Assistive Devices

Martin Burns, Michelle Schumacher and
Ramana Vinjamuri

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.73637

1. Introduction

For thousands of years, the state-of-the-art prosthetics were very primitive. This is not due to lack of effort or expertise. Rather, the technological capabilities of these eras restricted the possible advancements in prosthetics, such that the most effective solutions leaned heavily toward the most basic designs. These historic prosthetics were devices made of wood, metal, and leather, crafted by blacksmiths and tradesmen, which served more as esthetic pieces than functional tools. Technology today has progressed to the point where biomimetic and anthropomorphic prosthetics are a reality and are beginning to rival their organic counterparts in form and function. Biomimetics, as coined by Otto Schmitt, is the concept in which an artificial device effectively mimics the structural, functional, and biological properties of the natural entity in which it is modeled after [39]. Alternatively, devices that are anthropomorphic in nature mimic the physical characteristics of the limb including its look and feel, integrating aspects such as a textured skin-like material onto the device. These concepts in prosthetic design are enabled by control systems, actuator designs, sensor and biosignal innovations, biomechanical insights, and battery technology, among others. These advances have also led to wearable robotic exoskeletons, allowing functional assistance for individuals with paralysis whose affected limb remains intact. Properly leveraging these technologies requires one to examine the device qualities desired by the user and learn about recent progress in research and development. In this book, we will discuss these issues in the context of assistive limb prosthetics and recent advances in the field.

INTECH
open science | open minds

2. Background

An estimated 185,000 people undergo an amputation every year in America [32]. In the United States, 1.6 million people were living with the loss of a limb in 2005, a number which is expected to more than double by the year 2050 [42]. There are numerous causes for limb loss, which can range from congenital-related instances to trauma [1]. The most common causes are dysvascular and trauma related, making up 82 and 16% of all amputations, respectively [18]. Of all trauma-related amputations, upper limb amputations specifically account for 69%, as well as 58% of all congenital-related amputations [3]. The economic cost to amputees comes primarily from the procedure itself, additional hospital bills, prosthetic devices, and lost wages. A traumatic lower limb amputation, as tracked in the NIH LEAP study, is expected to cost the amputee $350,465 over 40 years, with $91,105 incurred within the first 2 years of the injury. Of this total, an individual will spend $181,500 on prosthetics at approximately $10,232 per unit [13]. These costs are also corroborated in several unrelated studies on civilian and veteran lower limb amputation costs [5, 19]. Similar estimates for upper limb amputations are not readily available in the literature. Considering that children, along with veterans, are one of the leading recipients of prosthetics [3], an additional economic burden comes with the necessity of device abandonment. As most prosthetics are unable to change with a growing child, a new prosthetic must be purchased to match the size of the child [3, 43]. Device rejection rates in adolescents averaged approximately 45 and 35% for body-powered and electric prosthetics, while adult amputees saw significantly lower rejection rates of 26 and 23% for body-powered and electric prosthetics, respectively [5].

Spinal cord injury, traumatic brain injury, and stroke are other major causes of functional impairment. Traumatic brain injury alone was estimated to occur 1.74 million times per year in the United States, with 10% of those occurrences being classified as severe with long-term disability. Of those who are hospitalized for acute traumatic brain injury, 43% develop long-term disability and have difficulty completing activities of daily living (ADL). Instances of spinal cord injury occur between 12,000 and 20,000 times per year; 238,000–332,000 survivors are still alive in the United States today, all with varying degrees of impairment. Stroke is the most prevalent of the aforementioned conditions, with 795,000 annual occurrences, 610,000 of which are first-time strokes. One study found 26% of individuals with stroke required assistance for ADL, while half had reduced motor function and 30% required assistance walking. An individual who survives a stroke will see a lifetime cost of $140,000, while an individual with spinal cord injury will see anywhere from $334,170 to $1.02 million in expenses in the first year and $40,589 to $177,808 per year after. The outcomes of traumatic brain injury vary too much to estimate the annual cost per individual, but the overall direct cost in the United States has been estimated to be $9.2 billion per year and $51.2 billion in indirect costs of work and lost productivity [28].

An individual must undergo rehabilitation in the aftermath of any amputation or paralysis in order to maintain as much function as possible. Many researchers believe rehabilitation outcomes can be improved by using virtual reality-based training. This can be made more effective by tailoring difficulty of training to the user and by encouraging the user to transfer or empathize with the virtual model. Research groups have only recently begun investigating virtual reality as a viable means of improving rehabilitation outcomes. Small-scale pilot studies have shown that individuals with stroke improved functional scores in the Wolf Motor Function Test and Fugl-Meyer Assessment after playing commercial virtual reality video games daily for 10 consecutive days [30]. These findings have been corroborated by numerous small studies. No major study has taken place to examine this effect on a large patient population, however. An individualized virtual reality rehabilitation scheme has been implemented in a case study with a single hemiparetic individual poststroke with positive results [20]. Another group conducted individualized virtual rehabilitation for 21 individuals with stroke, although they did not report standard functional evaluation scores for their subjects [9]. In theory, a subject who empathizes with the virtual model or exhibits transference onto the virtual world could experience greater functional recovery than if they were training on an abstract game. This is not a novel concept: the rubber hand experiment successfully mapped sensations on a rubber hand to the user’s visually occluded hand by matching the sensation to the opposite limb [6]. This technique has been successfully used to reduce phantom limb pain in the form of mirror therapy [11] and virtual visual feedback [29].

Research conducted within the past 30 years has provided insight into the most sought-after qualities of prosthetics. Designing systems, which satisfy these needs, are essential, as upper limb amputees typically use their prosthetic for more than 8 hours a day [24]. The needs of these users vary based on the type of amputation and type of prosthetic used, but several common factors are present among the different groups. Passive prosthetic users tend to focus more on cosmetics, comfort, and basic function, while users of body-powered and myoelectric prosthetics tend to focus more on advanced function. Myoelectric prosthetic users tend to request sensory feedback, along with simpler controls that can provide more dexterous motions. Active or powered prostheses focus on even more advanced motor function by providing external power through actuated motors. The most universally desired characteristics among all groups are reductions in cost and weight. Overall, ADL tasks that people rank as most important include mobility, object handling, and manipulation [14].

The decision to choose a passive or active prosthetic is primarily motivated by the type of disability and the user’s desired level of physical activity. Additional factors include the user’s ability to operate a powered device and personal requirements for cost, weight, and reliability. A passive leg prosthetic would partially restore the user’s mobility, whereas a passive upper limb prosthetic would not restore the user’s ability to interact with objects to the same degree. Therefore, a passive lower limb prosthetic would be more appealing from a functional perspective than an equivalent upper limb prosthetic. Someone who expects minimal or low levels of physical activity would be more likely to choose a passive prosthetic, since the extra functionality of active systems would go unused while incurring additional cost and weight. Furthermore, complex active prosthetics are more likely to break down and need repair, which may not be acceptable for a user who is primarily interested in cosmetics.

There are several options for passive prosthetics. Local prosthetists are skilled in crafting custom-fit cuffs and limb components, while several companies specialize in producing convincing passive limbs. Some of the more prominent companies in upper limbs include Touch

Bionics and Liberating Technologies Inc. (LTI), which provide the Livingskin and FHL line of passive hands, respectively. Livingskin products are custom-made silicon prosthetics that are made to match the user's skin tone and markings and can act as stand-alone prosthetics or skin coverings for robotic systems. The FHL line of hands by LTI is foam endoskeletal hands, which can be posed and mounted onto other products offered by the company, including passive wrist, elbow, and shoulder prosthetics. Ottobock offers a whole-arm endoskeletal prosthetic consisting of a metal articulated skeleton encased in foam and a silicon skin. Ottobock also provides multiple passive lower limb prosthetics such as the Harmony P4, a vacuum-cuffed below knee passive ankle, and the Aqualine, an above-knee endoskeletal prosthetic, which features metals and coatings resistant to water and chlorine corrosion. The Solid Ankle, Cushioned Heel (SACH) foot produced by NZALS is a popular passive foot prosthetic featuring rubber regions that flex and deform through the wearer's gait, replicating how the foot articulates during normal walking. Össur produces several passive lower limb solutions for knee and ankle prosthetics for both low-activity and athletic populations. The Flex-Run and Flex-Foot Cheetah foot prosthetics by Össur are famous for providing unprecedented athletic capability for transtibial amputees.

An alternative to passive limbs is body-powered prosthetics, which is controlled through a series of cables that link the movement of the body to the movement of the prosthetic. These devices are built to perform specific tasks and have terminal devices such as hooks to perform gripping. However, these devices often require the user to exert large cable operation forces. A study performed by Hichert et al. found that the force required to activate multiple body-powered prosthetics elicited fatigue, discomfort, and even pain in the user [22]. One way to control the prosthetic without fatiguing the user is to use an active prosthetic, which is powered by external power sources and is capable of more precise movements through the use of actuators. Many active prosthetics adapt biosignal-based control, in which signals generated by the user's own body are utilized to control the actuation of the device. Translating these initial signals into precise control of the prosthetic device can vary depending on the individual needs of the particular prosthetic but generally includes three major stages: signal acquisition, signal processing, and prosthetic interfacing and actuation. Signal acquisition is dependent on the type of biosignal being measured and is subsequently converted from an analog to digital signal. From here, the signal can undergo processing, which consists of feature extraction (filtering and isolation of the targeted signal) and translation (determining the intended movement). The prosthetic interface then takes this information and signals the prosthetic to physically carry out the intended movement.

There are a few different biosignal inputs that can be used in active prosthetic control. Many current active prosthetics are myoelectric, which are controlled through the use of electromyography (EMG) signals, allowing the device to better reflect the intention of the user [21]. EMG signals have been utilized to successfully control prosthetic hands [37]. Some myoelectric devices have even been noted as commercially available and reimbursed by the French health-care system [27] The I-Limb Quantum from Touch Bionics by Össur is a current commercial model of a prosthetic hand that features 36 different available grip postures and can be controlled through three methods in addition to muscle-based control. The LUKE arm by Mobius Bionics is the first bionic arm to received market approval by the FDA. This arm is controlled through a variety of methods including EMG electrodes and features 10 degrees of freedom. A few drawbacks to muscle-based control technology, however, are its generally high cost [7] as well as repeatability and reliability issues in surface EMG signals [36], making this input method difficult to use in prosthetic control. Implanted EMG sensors are a promising technology that can provide high-quality signals; however, they are costly, invasive, and only in the primary stages of human use [33]. Myoelectric control also relies on undamaged neuromuscular pathways being accessible to present the EMG signal [7]. Although strides are being taken in targeted muscle reinnervation (TMR) to allow for greater EMG accessibility [21], this may not be possible in all cases. Electroencephalogram (EEG)-based control of prosthetics attempts to bypass this problem [21]. EEG-controlled prosthetics employ the user's brain signals in conjunction with brain-computer interface (BCI) systems for control. Brain signals have been successfully detected through the use of an EEG to effectively control prosthetics including that of bionic arms. Current bionic hands have been able to demonstrate two degrees of freedom in the fingers [4, 7]. Additionally, Vidaurre et al. demonstrated EEG-based control of an exoskeleton [38]. Invasive brain-computer interfaces have demonstrated accurate and real-time control of advanced prosthetics such as modular prosthetic limb [15, 23, 40, 41].

Restoring hand function is one of the top priorities for individuals with paralysis and other motor disabilities. Normal hand movement is dependent on both visual and tactile feedbacks to assist the brain in determining the proper hand grasp, grip strength, movement speed, etc. required to successfully perform the intended task. This feedback creates a closed-loop system between the limb and the brain. Most current prostheses, however, operate through open-loop control by which the flow of information is unidirectional, from the user to the prosthetic. It is believed that the implementation of feedback to create a closed-loop system will improve the performance of the prosthetic. In active prosthetics, three of the major ways to provide sensor feedback to the user include substitution, modality-matched, and somatically matched feedback mechanisms [35]. In general, substitution feedback is the application of an indirect stimulus that is intended to substitute another form of stimulus, i.e., substituting a touch stimulus with an auditory one. There are different types of feedback including vibrotactile and electrotactile sensory substitution, which utilize vibration and electrical current stimuli, respectively. Alternatively, modality-matched feedback applies an identical sensation to the one being detected but on a different part of the body. For instance, the user may feel a prosthetic hand's grip force through a force generated on the abdomen or chest. Somatotopically matched feedback causes the user to perceive the correct sensation from the correct location, as if the prosthetic was their natural limb. In order to create a prosthetic that most accurately performs sensory feedback, both modality-matched and somatotopically matched feedbacks should be employed [2, 35].

Somatotopically matched feedback may be made possible as an added benefit of afferent TMR [36]; however, damage to the peripheral nerves from amputation may have altered their ability to elicit the correct sensory response in thus altering the effects of the feedback [17]. In light of this, new strides are being taken to directly stimulate the human somatosensory cortex. A study conducted by Cronin et al. [16] demonstrated a subject's ability to modulate hand motor behavior in response to cortical sensory stimulation delivered by ECoG electrodes. It is believed that this same technology may be used in the tactile feedback of a prosthetic hand

[16]. Another very important factor to take into account, in addition to the type of feedback present, is the time delay of the stimulus. At a distance of approximately 1 meter, the conduction times of afferent nerves range between approximately 14 and 28 ms [25]; therefore a short latency of the additional feedback is important to create real-time reactions. Short latencies, similar to that of a normal human hand, are also believed to help promote user ownership of the prosthetic [35].

Prosthetic devices are traditionally viewed as systems intended to replace a missing limb. However, a prosthetic can also be seen as a device that restores a missing bodily function. Taking this definition introduces assistive robots such as exoskeletons, which promise to restore missing function in those who are partially or completely paralyzed in one or more parts of their body. Several companies offer exoskeletons for assistance and rehabilitation of individuals with stroke, including Myomo's MyoPro hand/arm system, Bioservo's SEM Glove, Hocoma's ArmeoPower and ManovoPower upper limb systems, and Rehab-Robotics' Hand of Hope. Cyberdyne's HAL Lower Limb, Rewalk's Rewalk Personal and Rewalk Rehabilitation, and Rex Bionics' Rex P among many others provide lower limb rehabilitation and walking platforms for those with paralysis. Exoskeletons also exist in the academic research field, including ExoGlove Poly [26], the Wyss Institute's Soft Robotic Glove [34], HandSOME [12], Pisa/IIT SoftHand [10], and several others [8, 31], which serve as platforms to research novel control algorithms.

The above discussion provides a brief background and establishes relevance to the topics discussed in this book. This discussion is in no way completely exhaustive. There are numerous research studies in many of these research areas that could not be discussed due to time and space constraints. In fact, there are many manuscripts in preparation and press while we are reading or writing this chapter. We believe that biomimetic prosthetics will play a major role in revolutionizing the form and function of assistive devices in the near future.

Author details

Martin Burns, Michelle Schumacher and Ramana Vinjamuri*

*Address all correspondence to: ramana.vinjamuri@gmail.com

Department of Biomedical Engineering, Stevens Institute of Technology, NJ, USA

References

[1] Limb Loss Task Force/Amputee Coalition. Roadmap for Preventing Limb Loss in America: Recommendations From the 2012 Limb Loss Task Force. Knoxville, Tennessee; 2012

[2] Antfolk C, D'Alonzo M, Rosén B, Lundborg G, Sebelius F, Cipriani C. Sensory feedback in upper limb prosthetics. Expert Review of Medical Devices. 2013;**10**(1):45-54. DOI: https://doi.org/10.1586/erd.12.68

[3] Baker C, Brent D, Wilson C, Xu J, Thompson LA. Additive Manufacturing for Economical, User-Accessible Upper-Limb Prosthetics. Prosthetics and Orthotics Open Journal. 2017;**1**(1,8):1-5 Available from: http://www.imedpub.com/articles/additive-manufacturing-for-economical-useraccessible-upperlimb-prosthetics.pdf

[4] Beyrouthy T, Al Kork SK, Akl Korbane J, Abdulmonem A. EEG mind controlled smart prosthetic arm. In: 2016 IEEE International Conference on Emerging Technologies and Innovative Business Practices for the Transformation of Societies. Mauritius: EmergiTech; 2016. pp. 404-409. DOI: https://doi.org/10.1109/EmergiTech.2016.7737375

[5] Biddiss E, Chau T. Upper limb prosthesis use and abandonment: A survey of the last 25 years. Prosthetics and Orthotics International. 2007;**31**(3):236-257. DOI: https://doi.org/10.1080/03093640600994581

[6] Botvinick M, Cohen J. Rubber hands 'feel' touch that eyes see. Nature. 1998;**391**(6669):756. DOI: https://doi.org/10.1038/35784

[7] Bright D, Nair A, Salvekar D, Bhisikar S. EEG-based brain controlled prosthetic arm. In: Conference on Advances in Signal Processing. Pune, India: CASP 2016; 2016. pp. 479-483. DOI: https://doi.org/10.1109/CASP.2016.7746219

[8] Burns MK, Van Orden K, Patel V, Vinjamuri R. Towards a wearable hand exoskeleton with embedded synergies. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society. Jeju Island, Korea: EMBS; 2017. pp. 213-216. DOI: https://doi.org/10.1109/EMBC.2017.8036800

[9] Cameirao MS, Badia SB i, Oller ED, Verschure PFMJ. Neurorehabilitation using the virtual reality based rehabilitation gaming system: Methodology, design, psychometrics, usability and validation. Journal of Neuroengineering and Rehabilitation. 2010;**7**(1):48. DOI: https://doi.org/10.1186/1743-0003-7-48

[10] Catalano MG, Grioli G, Farnioli E, Serio A, Piazza C, Bicchi A. Adaptive synergies for the design and control of the Pisa/IIT SoftHand. The International Journal of Robotics Research. 2014;**33**(5):768-782

[11] Chan BL, Witt R, Charrow AP, Magee A, Howard R, Pasquina PF, Heilman KM, Tsao JW. Mirror therapy for phantom limb pain. New England Journal of Medicine. 2007;**357**(21):2206-2207. DOI: https://doi.org/10.1056/NEJMc071927

[12] Chen J, Nichols D, Brokaw EB, Lum PS. Home-based therapy after stroke using the hand spring operated movement enhancer (HandSOME). IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2017;**25**(12):1-1. DOI: https://doi.org/10.1109/TNSRE.2017.2695379

[13] Chung KC, Saddawi-Konefka D, Haase SC, Kaul G. A cost-utility analysis of amputation versus salvage for Gustilo type IIIB and IIIC open Tibial fractures. Plastic and Reconstructive Surgery. 2009;**124**(6):1965-1973. DOI: https://doi.org/10.1097/PRS.0b013e3181bcf156

[14] Cordella F, Ciancio AL, Sacchetti R, Davalli A, Cutti AG, Guglielmelli E, Zollo L. Literature review on needs of upper limb prosthesis users. Frontiers in Neuroscience. 2016;**10**(May):1-14. DOI: https://doi.org/10.3389/fnins.2016.00209

[15] Collinger JL, Wodlinger B, Downey JE, Wang W, Tyler-Kabara EC, Weber DJ, McMorland AJC, Velliste M, Boninger ML, Schwartz AB. High-performance neuroprosthetic control by an individual with tetraplegia. The Lancet. 2013;**381**(9866):557-564

[16] Cronin JA, Jing W, Collins KL, Sarma D, Rao RPN, Ojemann JG, Olson JD. Task-specific somatosensory feedback via cortical stimulation in humans. IEEE Transactions on Haptics. 2016;**9**(4):515-522. DOI: https://doi.org/10.1109/TOH.2016.2591952

[17] D'Anna E, Petrini FM, Artoni F, Popovic I, Simanić I, Raspopovic S, Micera S. A Somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback. Scientific Reports. 2017;**7**(1). DOI: https://doi.org/10.1038/s41598-017-11306-w

[18] Dillingham TR, Pezzin LE, Mackenzie EJ. Limb amputation and limb deficiency: Epidemiology and recent trends in the United States. Southern Medical Journal. 2002;**95**(8):875-884. DOI: https://doi.org/10.1097/00007611-200208000-00018

[19] Edwards DS, Phillip RD, Bosanquet N, Bull AMJ, Clasper JC. What is the magnitude and long-term economic cost of care of the British Military Afghanistan Amputee Cohort? Clinical Orthopaedics and Related Research. Springer US. 2015;**473**(9):2848-2855. DOI: https://doi.org/10.1007/s11999-015-4250-9

[20] Fluet GG, Merians AS, Qiu Q, Saleh S, Ruano V, Delmonico AR, Adamovich SV. Robotic/virtual reality intervention program individualized to meet the specific sensorimotor impairments of an individual patient: A case study. International Journal on Disability and Human Development. 2014;**13**(3):401-407. DOI: https://doi.org/10.1515/ijdhd-2014-0334

[21] Geethanjali P. Myoelectric control of prosthetic hands: State-of-the-art review. Medical Devices: Evidence and Research. 2016;**9**:247-255. DOI: https://doi.org/10.2147/MDER.S91102

[22] Hichert M, Vardy AN, Plettenburg D. Fatigue-free operation of most body-powered prostheses not feasible for majority of users with trans-radial deficiency. Prosthetics and Orthotics International. 2017;**0**(0):309364617708651. DOI: https://doi.org/10.1177/0309364617708651

[23] Hotson G, McMullen DP, Fifer MS, Johannes MS, Katyal KD, Para MP, Armiger R, et al. Individual finger control of a modular prosthetic limb using high-density electrocorticography in a human subject. Journal of Neural Engineering. 2016;**13**(2):026017

[24] Jang CH, Yang HS, Yang HE, Lee SY, Kwon JW, Yun BD, Choi JY, Kim SN, Jeong HW. A survey on activities of daily living and occupations of upper extremity amputees. Annals of Rehabilitation Medicine. 2011;**35**:907. DOI: https://doi.org/10.5535/arm.2011.35.6.907

[25] Johansson RS, Flanagan JR. Coding and use of tactile signals from the fingertips in object manipulation tasks. Nature Reviews Neuroscience. 2009;**10**(5):345-359. DOI: https://doi.org/10.1038/nrn2621

[26] Kang BB, Lee H, In H, Jeong U, Chung J, Cho KJ. Development of a polymer-based tendon-driven wearable robotic hand. In: Proceedings – IEEE International Conference on Robotics and Automation, June 2016. 2016. pp. 3750-3755. DOI: https://doi.org/10.1109/ICRA.2016.7487562

[27] Loiret I, Sanamane V, Touillet A, Martinet N, Paysant J, Fournier-Farley C, François A-G. Assessment of multigrip prosthetic hand by a crossover longitudinal study. Annals of Physical and Rehabilitation Medicine. 2017;**60**(Suppl):e34. DOI: https://doi.org/https://doi.org/10.1016/j.rehab.2017.07.005

[28] Ma VY, Chan L, Carruthers KJ. The incidence, prevalence, costs and impact on disability of common conditions requiring rehabilitation in the US: Stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, osteoarthritis, rheumatoid arthritis, limb loss, and back pain. Archives of Physical Medicine and Rehabilitation. 2014;**95**(5):986-995. DOI: https://doi.org/10.1016/j.apmr.2013.10.032

[29] Mercier C, Sirigu A. Training with virtual visual feedback to alleviate phantom limb pain. Neurorehabilitation and Neural Repair. 2009;**23**(6):587-594. DOI: https://doi.org/10.1177/1545968308328717

[30] Mouawad MR, Doust CG, Max MD, McNulty PA. Wii-based movement therapy to promote improved upper extremity function post-stroke: A pilot study. Journal of Rehabilitation Medicine. 2011;**43**(6):527-533. DOI: https://doi.org/10.2340/16501977-0816

[31] Nycz CJ, Butzer T, Lambercy O, Arata J, Fischer GS, Gassert R. Design and characterization of a lightweight and fully portable remote actuation system for use with a hand exoskeleton. IEEE Robotics and Automation Letters. 2016;**1**(2):976-983. DOI: https://doi.org/10.1109/LRA.2016.2528296

[32] Owings MF, Kozak LJ, Ambulatory and inpatient procedures in the United States, 1996. In: Vital and Health Statistics, Series 13, Data from the National Health Survey, No. 139. 1998. pp. 1-119

[33] Pasquina PF, Evangelista M, Carvalho AJ, Lockhart J, Griffin S, Nanos G, McKay P, et al. First-in-man demonstration of a fully implanted myoelectric sensors system to control an advanced electromechanical prosthetic hand. Journal of Neuroscience Methods. 2015;**244**:85-93. DOI: https://doi.org/10.1016/j.jneumeth.2014.07.016

[34] Polygerinos P, Wang Z, Galloway KC, Wood RJ, Walsh CJ. Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems. Elsevier BV. 2015;**73**:135-143. DOI: https://doi.org/10.1016/j.robot.2014.08.014

[35] Schofield JS, Evans KR, Carey JP, Hebert JS. Applications of sensory feedback in motorized upper extremity prosthesis: A review. Expert Review of Medical Devices. 2014;**11**(5):499-511. DOI: https://doi.org/10.1586/17434440.2014.929496

[36] Schultz AE, Kuiken TA. Neural interfaces for control of upper limb prostheses: The state of the art and future possibilities. PM & R: The Journal of Injury, Function, and Rehabilitation. 2011;**3**(1):55-67. DOI: https://doi.org/10.1016/j.pmrj.2010.06.016

[37] Tavakoli M, Benussi C, Lourenco JL. Single channel surface EMG control of advanced prosthetic hands: A simple, low cost and efficient approach. Expert Systems with Applications. 2017;**79**:322-332. DOI: https://doi.org/10.1016/j.eswa.2017.03.012

[38] Vidaurre C, Klauer C, Schauer T, Ramos-Murguialday A, Müller KR. EEG-based BCI for the linear control of an upper-limb neuroprosthesis. Medical Engineering and Physics. 2016;**38**(11):1195-1204. DOI: https://doi.org/10.1016/j.medengphy.2016.06.010

[39] Vincent JFV, Bogatyreva OA, Bogatyrev NR, Bowyer A, Pahl A-K. Biomimetics: Its practice and theory. Journal of the Royal Society Interface. 2006;**3**(9):471-482. DOI: https://doi.org/10.1098/rsif.2006.0127

[40] Vinjamuri R, Weber DJ, Mao Z-H, Collinger JL, Degenhart AD, Kelly JW, Boninger ML, Tyler-Kabara EC, Wang W. Toward synergy-based brain-machine interfaces. IEEE Transactions on Information Technology in Biomedicine. 2011;**15**(5):726-736

[41] Wang W, Collinger JL, Degenhart AD, Tyler-Kabara EC, Schwartz AB, Moran DW, Weber DJ, et al. An electrocorticographic brain interface in an individual with tetraplegia. PLoS One. 2013;**8**(2):e55344

[42] Ziegler-Graham K, MacKenzie EJ, Ephraim PL, Travison TG, Brookmeyer R. Estimating the prevalence of limb loss in the United States: 2005 to 2050. Archives of Physical Medicine and Rehabilitation. 2008;**89**(3):422-429. DOI: https://doi.org/10.1016/j.apmr.2007.11.005

[43] Zuniga J, Katsavelis D, Peck J, Stollberg J, Petrykowski M, Carson A, Fernandez C. Cyborg beast: A low-cost 3D-printed prosthetic hand for children with upper-limb differences. BMC Research Notes. 2015;**8**(1):10. DOI: https://doi.org/10.1186/s13104-015-0971-9