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Bionic Limbs - A Review

Akshay Shankar[1], Aryn Barman[2]

[1]Computer Science Engineering, B.E. Research Scholar, RV College of Engineering, Bangalore, India
akshayshankar.cs19[at]rvce.edu.in

[2]Computer Science Engineering, B.E. Research Scholar, RV College of Engineering, Bangalore, India
arynbarman.cs19[at]rvce.edu.in

Abstract: ***Bionics is the study of mechanical systems that function like living organisms or parts of living organisms. Bionics is one of the ways in trying to restore normalcy in a person's life who has lost a part of their body. There were many other replacements for natural limbs, but with advancements in technology and materials, bionics is replacing all the previous replacements. The major need for the replacement of the limbs after injury or loss of the limb was to allow people to continue to live their own lives. There is also an elaboration of the requirements of such technology mentioned, how it works and how it helps as well. There are major confusions between prosthetic limbs and bionic limbs this confusion has been resolved in the paper. With such advanced technology the cost will also increase, the costs of the bionic limbs have been stated in the paper. In this paper different types of bionic limb, technologies have been mentioned including Nerve transferring, direct muscle, and direct nerve interfacing. Notes on Osseointegration, Passive Prosthetics and myoelectric bionic limbs have been reviewed in detail in this paper. Bionic limbs are a combination of biology and computer science as well as other fields of science. There is a role of biology because many bionic limbs require the nerve endings to be attached to the artificial limbs, the role of computer science comes into the picture because the nerve signals need to be sensed and the limb has to respond to it. These topics have been described as well.***

Keywords: Bionics, Muscle Reinnervation, Osseointegration, Prosthetics, Myoelectric

1. Introduction

Why do we need Bionic Limbs?
When an individual loses or amputates an extremity like an arm or leg, we can replace the lost part with bionic limbs. An individual's muscle uses signals to perform actions or to move easily, bionics use this signal for performing the same movements and activities for those individuals. There are electrical signals which are passed through from the brain and nerves to perform different movements, some bionics will use these signals trying to replace the lost part completely. The main reason for the use of bionics is that people who have lost their limbs can continue with their routine and manage all the activities they performed before. This helps to make the individual independent.

2. Types of Bionic Limbs

Different functions have different bionics which is used, which is why there is a huge variety. There are slight or sometimes huge differences among the types.

The amputated limb will fit into the stump of a socket. The bionic limb which is held onto the stump by the suspension:

- Shaft
- Hand, hook, or foot

Cosmetic appearances for few which is why a cover is included in some of them.[1]

To ensure proper fit and comfort, special socks are worn.[2]

3. How Bionic Limbs work and help

Bionic Limbs normally work by finding the signals from the user's muscles. The sensors execute the same movement at the limb where the person is trying to flex their muscles.

If a person wants to move their muscles around their bionic limbs, for the appropriate movement, the sensors will understand the signals passed and react to perform the same movement. Let's take an example, if you have a bionic arm and you wish to open your hand, you will need to flex your hand and the sensors will use the signals which are sent to it.

The muscle signals are detected in bionic limbs using sensors, which are done with in-built computers. Many times the limb's stump's remaining muscles, that is where the bionic limbs require sensors to be implanted. Users will be able to control their limbs with their brain, these types of bionic limbs are very advanced, if a person wishes to raise their arm, the bionic limb will do so.

Bionic limbs are made in such a way that they can be easily removed or worn when it is required. The limbs are custom made according to each user's specific needs, they do not require surgery to be attached to the person.

Maximum control and adapts as per the user's requirement, if the user wants the limb to move slowly, they will tense the muscle gently and for immediate action, the muscles need to be tensed fast.[1]

4. Difference Between a Prosthetic Bionic Limb

There is quite a bit of difference between bionic limbs and prosthetics. Prosthetics are products that are not customized as per the user and have very little functionality. One of the most significant uses is to give the appearance of a limb. The limbs can be worn and do not actively move like bionic limbs. There are different types of prosthetics, electrical and body-powered. These are better than the cosmetic limbs which are used just to hide the lost limb. The prosthetics require a battery and motors for the limb to move around.

These do not have sensors or any other technology which helps the limb move according to the user's needs. [3-4]

Now we move onto bionic limbs, these are by far the most advanced limb replacement technology. They are able to move and control the reactions as per the user's needs with the help of a small inbuilt computer that reads the signals. These bionic limbs have much more to offer people who have lost their limbs, and the users can forget that they have lost their limbs. Compared to traditional prosthetics, bionic limbs require less effort from the user, by providing more ease and functionality. [5-6]

5. Cost of Bionic Limbs

We know that bionic limbs help people to forget that they have lost a limb, but now the issue arises of cost. Amputation is the term where a person is given a prosthetic leg to restore movement. There are various designs and prices for bionic legs. The first one is the most basic one where a patient is able to walk, run and perform various sports with the artificial leg. The range for these bionic legs ranges between Rs. 6,00,000 to Rs. 7,50,000. The advanced ones where the limbs will perform the activity requested by the brains cost much more because they are computerized models, ranging from Rs. 37,00,000 to Rs. 53,00,000. Nowadays, many insurance companies have specific altered policies for bionics. They have special plans which cover the medical expenses for the purchase of the limbs and also include the maintenance of the limbs. These medical policies will help bring the cost of the bionic limbs down by a lot.

When we talk about bionic arms, the person can get an artificial arm from the elbow to the fingers or the shoulder to the fingers, depending on their amputation. The more the size of the bionic limb, the more the cost will also be. Roughly a prosthetic arm would cost Rs. 3,70,000, whereas the cost of a fully functional bionic arm will cost around Rs. 6,00,000 to Rs. 7,50,000. The price difference between the two is not a lot, which makes it better for people to get the bionic limb instead. Certain bionic arms can also cost Rs. 18,50,000 to Rs. 75,00,000, these are called myoelectric arms, the reason for the high cost is because they look more real and perform almost the same actions as a normal hand. [7]

6. Types of Bionic limb Technologies

There are three categories of Bionic Limbs:

- Nerve-transferred muscle interfacing
- Direct muscle interfacing
- Direct nerve interfacing

a) Nerve and muscle transferring

This method involves the transfer of the remaining cut-off nerve endings to the available muscles, thereby enhancing neural control signals using their natural muscle amplifier. These signals are then registered with electrodes and sent to an implant to control its operation. When the subject is considering moving his lost hand, the regenerated muscles are triggered and the stimulus generated is then identified by electrodes and used to move the robotic arm. The same approach is true for lower limb amputations.[8-9]

In addition, the stimulation of touch above the regenerated areas may bring about the sense of touching the absent extremities. However, two-way control is still difficult to emulate because the stimulus generated has to be recorded as well as a response needs to be generated at the same time, which is difficult to address.

The above problem has been addressed, with the regeneration of nerve endings over various muscles. This method demonstrates how two-way control can be emulated. This method, aimed at regenerating the muscles, is a feasible solution for patients having severe amputations.

In a recent development, an agonist-antagonist myoneural interface (AMI) has been developed. It is a new concept that combines the provided structure made of the following muscles - agonist and antagonist - that are attached adjacent to each other so that the shrinking of the first leads to the expansion of the second.[10]

This concept re-establishes the strong muscle connections that were present in the body without amputations, thus enabling both muscle contraction stimuli to be passed on to the central nervous system. Promising results have been obtained using this method. Such a fine surgical procedure appears to be very promising for people who have had small limb amputations, while it may be extremely difficult to use in patients who undergo blood transfusions. [11]

b) Direct muscle Interfacing

In these bionic limbs, the stimulus received in the remaining muscle tissue is acted upon by the insertion of implants onto the muscle.

Tiny devices that receive and record the stimulus generated are implanted onto the muscle and these signals are then transmitted and acted upon.[12]

As yet, no sense of touch can be perceived using this method. This method is most suited for amputations where a lot of external muscles are preserved, while in amputations when the muscle is lost it can be difficult to use. However, in the case of severe amputations, various advancements have been made in the field of medical science, which can be incorporated into this method.

c) Direct Nerve Interfacing

In this method, there is actual contact between the remaining nerves using implanted electrodes that enable them to receive electrical stimuli from artificial prosthetic devices. Electrode implantation involves identifying the location of nearby nerves, properly presenting, positioning, and adjusting electrodes and cables, while maintaining extremity and nerve movements, to prevent neural damage. A sensation can be perceived using this method. Sensation to the limbs is restored in this method.[13]

This technology instills a feeling of the presence of the limb with an electrode inserted surgically into the remaining nerves, regenerating the upper limbs or lower limbs. To

restore and improve the sensitivity of the bionic limbs, electrodes were introduced and placed intraneural through the fascicles, or around the nerves through the epineural cuff.[14-15]

Research suggests that intraneural stimulation can stimulate neural pathways and improve control of the bionic limb by following certain predefined procedures. We determine the motive of the motor from the remaining muscles and by inserting the sensor by stimulating the electrical impulses with electrodes, which are inserted into the sensor during the surgical procedure. In some studies, the insertion carries the outer wires that are attached to the superficial sensory nerves and a device that generates a sensation of stimulus to the bionic limb.[16]

Using this process, sensations are sent to the brain by mapping what the user experiences when touching the artificial limb. These patients show increased splendor and texture recognition.

7. Technologies involved

a) Targeted Muscle Reinnervation

In this method, the nerve endings that have lost their functionality are reassigned to the remaining lumbar muscle to improve sensory and autonomic muscle stimuli. The procedure followed involves the replacement of unwanted muscle by fixed nerves and therefore these muscles are stimulated by a new set of nerves that earlier performed certain motor functions.[17]

As a result, targeted muscle activity is stimulated by a new spinal region and cortical region. After an elaborate recovery period, this method makes the target muscle of the missing limb to be identified at the actual position on the cortex. This redistribution of highly regulated corticospinal structures of the missing limb creates precise signs for implant purposes. In this process, intricate motor movements are performed by connecting nerve endings to adjacent muscles.[18]

Central to developing this concept, a large number of stimuli are needed to control a systematic feedback-driven system. To this end, biological feedback systems are used to teach patients to control and use the newly developed muscle stimuli to control the prosthetic limb in all regular activities.[19-20]

Targeted muscle rehabilitation is a surgical nerve transfer process, designed to provide patients with precise control of the upper extremity prostheses by combining available technology with the remodeling of the existing limbs. The residual nerves in the amputated limbs are provided to new muscles that have lost their capabilities in some way. Using this procedure, the identified muscles are distinguished from their motor nerve implants so that the newly transferred nerves can regenerate themselves. These muscles are then regenerated and act as biological enhancers of sensory signals. By regenerating various sensory nerves, this process allows precise control, simultaneously for numerous joints.[21]

Clinical studies have shown that this process shows significant improvements in reducing pain in neuromas. About one-fourth of the patients having amputations in the bigger limbs will experience chronic local discomfort due to the symptoms of neuromas at the remaining limbs. Neuromas consist of irregular axons embedded in the scar and form at the end of a cut or damaged nerve. Neuromas form due to haphazard efforts of nerve endings to restore their functionality and this can lead to chronic discomfort which is very hard to treat. Neuromas are the main reason for the physical discomfort leftover after painful amputation. Additionally, neuromas often make dressing and utilization of artificial limbs difficult and painful, thus hindering the pain-free movement of the patient. Compared to other therapies, this method provides a resulting organ for nerves that are less sensitive.

In this process, after the removal of a neuroma, remaining nerves are bound to sever the nerves that regenerate new target muscles. This method provides a good physical scenario for regenerating axons, promoting systematic nerve regeneration into targeted muscles, and preventing uncoordinated and indirect nerve growth leading to neuroma formation. Research shows that there is a large decrease of pain due to neuroma after this process was used by patients having large degrees of amputations. [22]

b) Osseointegration

Osseointegrated implants are biocompatible metal tools inserted into the remaining bone to connect to the bone and attach to the external implant, eliminating the need for artificial sockets and problems that may be associated with their use.

Osseointegration is the process by which a direct link is formed between the bone and the implant excluding the intervention of tissues.

An osseointegrated implant is generally made up of titanium and is directly attached to the bone. This process enables external bionic limbs to be attached directly to the skeleton of the person. After the development of this technology, the numerous difficulties faced by patients due to regular socket-based limb prosthetics like skin irritation and uncomfortable fitting of the artificial limb can be easily overcome.

In this process, the physical and chemical properties of the prosthetic limb have a significant impact on a molecular level. Since the last hundred years, various substances and materials have been used for the purpose of implantation but the most successful implants are those which are made of titanium or calcium phosphate. The main difference between this method and other technologies is that in this method there is no socket. Irritation due to sweating or discomfort is removed using this process. Before deciding to undergo this process, it is imperative to consider all other bionic limb technologies as well. This method is suitable for patients who feel too uncomfortable wearing artificial limbs or do not want to take a chance with the surgical procedures involved as it may lead to serious consequences. The surgically inserted implant need not be completely attached

to the bone in its entirety. That is the specialty of this method.[23]

After implantation, healing usually takes weeks or months before integrating completely into the bone. Integration starts after a few weeks but may take several months or even years to complete.

This process is suited for patients having large degrees of amputation and it offers many advantages in comparison to artificial limbs having sockets. This method allows for improved limb and joint movement. These artificial limbs do not cause skin degeneration. These artificial limbs are connected directly to the bone which causes the patients to think and feel that the artificial limb is an actual part of their body.[24]

Advantages:

- The artificial limbs can be worn for larger periods of time
- Does not cause any skin allergies or discomfort
- Patients can walk continuously for larger periods of time
- The artificial limb can be worn and removed in a very short time
- These artificial limbs are very safe and stable
- Improves the standard of day to day life

c) Passive Prosthetic

Passive prostheses are designed to make it look like the person has a natural limb. These do not have active or actual movement, but they might help a person carrying objects or stabilization a surface.

It is made of silicon, lightweight, and has no active movement, it is colored according to the user's color to look like a natural limb, finger, or the lost part of the body.[25]

Passive prostheses are combined for multi-positional joins. These are done so they can be used in the position of the shoulder, elbow, or other joints to improve the function of the prostheses, almost replacing the natural limb, joint, etc. To allow high definition restoration to grasp objects which are not that big, so they can be moved into the position.[26]

d) Body powered prosthesis

Body Powered Prostheses gives people the ability to pick up and grasp objects which are needed to assist the user's second hand. These are useful because it is not about looks, but more about usefulness. These prostheses can withstand rugged environments where they may be exposed to dirt, this helps people who are involved in manual labor or for them to do work around their house. These prostheses can handle various loads, moisture, they are very durable. By a harness or cable is how the operation of body-powered prostheses takes place. They can use the movements of their limbs where it is attached to open or close things, ride bicycles, this is done by capturing the harness and transferring it to a cable system. An improved sense of the position of the limb and the degree of opening on a terminal device can be done once the user gets used to the tension. The prosthesis can be hooks, a spanner, or anything which the user might require in their everyday work.[27-29]

e) Myoelectric

Electric properties of muscles is the term best suited for "Myoelectric". A powered exterior prosthetic limb is a myoelectric controlled limb, which can be controlled by natural electric signals which can be generated by a person's muscles. [30]

There are many myoelectric components that are available to replace natural parts. Hybrid Prosthesis occurs when there is an amputation above the elbow, these are a combination of myoelectric and body powdered components together to perform the function of natural limbs.[31]

Functions of myoelectric in the limbs are to control functions using the existing muscles present or left after the amputation. There are quite a number of sensors that are present to accept the electric signals which are received in the amputated sockets to perform voluntary actions. There is a transfer and translation of information, first, the sensors send the information to a controller where the commands are understood after translation. This helps in the movement of your hands and legs or even joints. If there are no muscle signals then there must be a switch with a touchpad, rocker, or pull-push in order to be in place of the muscle signals.[32]

Now when a person needs to move their hands at different speeds or lift items that are heavy, they require more strength. The user needs to perform these activities all in an instant, they can do so by controlling the muscle intensity for the various activities, how they would normally do so if the natural limb was present.[33]

Hand, articulatio radiocarpea, elbow, or knee myoelectric elements square measure offered. There are specific areas where the myoelectric parts are to be used, mentioned above. They are made to look as natural as possible, so others will not be able to notice.[34-35]

When myoelectric are being used in the joints, they must receive the intensity variation of only one muscle that connects these joints. In order to do so each joint needs to be positioned one at a time in order for succeeding with this method. This is called serial management.

8. Role of Biology in Bionics

Engineering biology mainly revolves around the application of biology in different fields to get an all-around association with wherever biology exists. These include animals, plants, organisms, and many more. We are trying to connect technology and life forms.

Computer Science has various fields which have been included in the working of bionics, these include artificial neural networks, swarm intelligence, artificial neurons, and many more. With improvements in these fields, there have been many improvements being done to bionics as well.[36]

There is a train of concepts that are continuously shuttling between biology and engineering in order to complete the proper working of bionics. If we are talking about medicine, we are focusing on replacing or improving parts of the body that are amputated or defective. We use bionic limbs to copy

the existing working and the appearance of the limbs and try to mimic it into an artificial limb, making it work almost to the level of a natural limb or to surpass it.[37-38]

As people are striving to bring about changes in technology and improvements to bionics, there are many pre-existing successful bionic devices. These devices are almost a perfect replacement for the amputated part. Bionic eyes work in place of actual eyes, this gifts blind people's sight. It does not stop there, there is a bionic ear for helping deaf people hear. There are many parameters which need to be viewed before the bionics are placed, to check for compatibility and if it will work and improve the current condition of the user. The most recent research for bionics is to solve problems like neurological and psychiatric problems and people are working to find a solution as good as bionics limbs.[39]

9. Role of Computer Science in Bionics

Computer Science plays a major role when it comes to Bionics. In earlier days, there was no role of computers because in plastic prostheses there was no programming or computing required. The plastic prosthesis did not require computing because it was just an artificial arm without any function except for appearance. [40]

With the evolution in technology, there has been a bridge that has covered the gap between biology and computer science. Now with this growth of technology, we can see the improvement in the fields of prosthetics with the occurrence and the discovery of bionic limbs.

Computer science is playing a role by accepting the signals which are being transmitted by the muscles which have been severed from the original limb and attached to the bionic limb. The bionic limb has a mini-computer that senses the muscle trying to move or senses the strain. On sensing this strain the mini-computer on the bionic limb reads it and sends the message almost instantaneously to the joint or controller where the limb is attached and where movement takes place.

Analyzing these sensors and understanding the intensity of strain on the muscles, the mini-computer must give the perfect and apt movement in the limb. Failure can cause major issues, such as when a person with a bionic limb wishes to hold the hand of a baby, the user wishes to be delicate, but if the reading faults the user might crush the baby's hand.[41]

We see there is a very important role of Computer Science in Bionic limbs which is essential for the proper functioning of these limbs. With this technology, we can help those people with amputated limbs to feel normal and join the rest of society without having any kinds of drawbacks.

10. Conclusion

Bionics as we see are continuously helping and changing the world and making it a better place. It is the perfect combination where we see the interlinking between biology and computer science. These advancements in bionics will help people who have lost their limbs during any unforeseen accidents, this will help them continue with their life without any hindrances. Bionics will continue to grow as the years go by, and the cost will reduce so it will be more affordable and useful for everyone.

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References

[1] Scheck & Siress, "The Latest Technology and Materials to help Amputees", Scheck & Siress 2019.
[2] Di Pino G, Guglielmelli E, Rossini PM. Neuroplasticity in amputees: main implications on bidirectional interfacing of cybernetic hand prostheses. Prog Neurobiol 2009;88:114e26.
[3] Frossard L, et al. (2019) Automated characterization of anthropomorphicity of prosthetic feet fitted to bone-anchored transtibial prosthesis. IEEE Transactions on Bio-Medical Engineering. 66(12):3402-10.
[4] Rang M." Amputations and prostheses in the story of orthopaedics." Philadelphia, London, Sydney, Toronto: WB Sounders Co., 2000:293–305. [Google Scholar]
[5] Australian Academy of Science, "Bionic Limbs", Australian Academy of Science 2020
[6] Scheck & Siress, "The Latest Technology and Materials to help Amputees", Scheck & Siress 2019.
[7] Human Technology, Prosthesis, and Orthonics, "The cost of bionic limbs", Human Technology 2018.
[8] Micera S, Sergi PN, Carpaneto J, Citi L, Bossi S, Koch KP, et al. Experiments on the development and use of a new generation of intra-neural electrodes to control robotic devices. Conf Proc IEEE Eng Med Biol Soc 2006;1:2940e3.
[9] Ottobock, "Myoelectric Prosthesis", Otoobock, 2020
[10] Rossini PM, Micera S, Benvenuto A, Carpaneto J, Cavallo G,Citi L, et al. Double nerve intraneural interface implant on a human amputee for robotic hand control. Clin Neurophysiol 2010;121:777e83.
[11] Folgheraiter M, Gini G. Human-like reflex control for an artificial hand. Biosystems 2004;76:65e74.
[12] Kim G, Asakura Y, Okuno R, Akazawa K. Tactile substitution system for transmitting a few words to a prosthetic hand user. Conf Proc IEEE Eng Med Biol Soc 2005;7:6908e11.
[13] Lanzetta M, Perani D, Anchisi D, Rosen B, Danna M, Scifo P, et al. Early use of artificial sensibility in hand transplantation. Scand J Plast Reconstr Surg Hand Surg 2004;38:106e11.
[14] Raspopovic S, Petrini FM, Zelechowski M, Valle G." Framework for the development of neuroprostheses: from basic understanding by sciatic and median nerves models to bionic legs and hands." Proc IEEE 2017;105:34–49. [Google Scholar]
[15] Grill WM, Kirsch RF. Neuroprosthetic applications of electrical stimulation. Assist Technol 2000;12:6e20.
[16] Kuiken TA, Marasco PD, Lock BA, Harden RN, Dewald JP. Redirection of cutaneous sensation from

the hand to the chest skin of human amputees with targeted reinnervation. Proc Natl Acad Sci U S A 2007;104:20061e6.
[17] Kuiken TA, Dumanian GA, Lipschutz RD, Miller LA, Stubblefield KA. The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee. Prosthet Orthot Int 2004;28:245e53.
[18] Dhillon GS, Horch KW. Direct neural sensory feedback and control of a prosthetic arm. IEEE Trans Neural Syst Rehabil Eng, 2005;13:468e72.
[19] Farina D, Aszmann O. Bionic limbs: "clinical reality and academic promises." Sci Transl Med 2014;6:257ps12. [PubMed] [Google Scholar]
[20] Kuiken TA, Miller LA, Lipschutz RD, Lock BA, Stubblefield K, Marasco PD, et al. Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: a case study. Lancet 2007;369:371e80.
[21] Edin BB, Ascari L, Beccai L, Roccella S, Cabibihan JJ, Carrozza MC. Bio-inspired sensorization of a biomechatronic robot hand for the grasp-and-lift task. Brain Res Bull 2008;75:785e95.
[22] Christian Cipriani, Member, IEEE, "Online Myoelectric Control of a Dexterous Hand Prosthesis by Transradial Amputees", IEEE. Transactions on Neural Systems and Rehabilitation Engineering, vol. 19, no. 3, June 2011, p. 260-270.
[23] Clites TR, Herr HM, Srinivasan SS, Zorzos AN, Carty MJ. The Ewing Amputation: The First Human Implementation of the Agonist-Antagonist Myoneural Interface. *Plast Reconstr Surg Glob Open*. 2018;6(11):e1997. Published 2018 Nov 16. doi:10.1097/GOX.0000000000001997
[24] Prochor P, et al. (2020) Effect of the material's stiffness on stress-shielding in osseointegrated implants for bone-anchored prostheses: a numerical analysis and initial benchmark data. Acta Bioeng Biomech. 2020(2):69-81
[25] Arm Dynamics, "Introduction to Body Powered", Arm Technology, 2018
[26] Weir R, Troyk P, Demichele G, Kerns D. Technical details of the implantable myoelectric sensor (IMES) system for multifunction prosthesis control. Conf Proc IEEE Eng Med Biol Soc 2005;7:7337e40.
[27] Chen X, Zheng YP, Guo JY, Shi J. Sonomyography (SMG) control for powered prosthetic hand: a study with normal subjects. Ultrasound Med Biol 2010;36:1076e88.
[28] Weir R, Mitchell M, Clark S, Puchhammer G, Kelley K, Haslinger M, et al. New multifunctional prosthetic arm and hand systems. Conf Proc IEEE Eng Med Biol Soc 2007;2007: 4359e60.
[29] Ortiz-Catalan M, Håkansson B, Brånemark R. "An osseointegrated human-machine gateway for long-term sensory feedback and motor control of artificial limbs." Sci Transl Med 2014;6:257re6.[PubMed] [Google Scholar]
[30] Arm Dynamics, "Introduction to Passive", Arm Technology, 2016
[31] Guo JY, Chen X, Zheng YP. Use of muscle thickness change to control powered prosthesis: a pilot study. Conf Proc IEEE Eng Med Biol Soc 2009;2009:193e6.
[32] Micera S, Rigosa J, Carpaneto J, Citi L, Raspopovic S, Guglielmelli E, et al. On the control of a robot hand by extracting neural signals from the PNS: preliminary results from a human implantation. Conf Proc IEEE Eng Med Biol Soc 2009;2009:4586e9.
[33] Carrozza MC, Massa B, Dario P, Zecca M, Micera S, Pastacaldi P. A two DoF finger for a biomechatronic artificial hand. Technol Health Care 2002;10:77e89.
[34] Clement RGE, Bugler KE, Oliver CW. "Bionic prosthetic hands: a review of present technology and future aspirations." Surgeon 2011;9:336–340. [PubMed] [Google Scholar]
[35] Jun-Uk Chu, Member, IEEE, Inhyuk Moon, "A Supervised Feature-Projection-Based Real-Time EMG Pattern Recognition for Multifunction Myoelectric Hand Control", IEEE/ASME Transactions on Mechatronics, vol. 12, no. 3, June 2007, p. 282-290. [Google Scholar]
[36] Rosen B, Ehrsson HH, Antfolk C, Cipriani C, Sebelius F, Lundborg G. Referral of sensation to an advanced humanoid robotic hand prosthesis. Scand J Plast Reconstr Surg Hand Surg 2009;43:260e6.
[37] Zhou P, Lowery MM, Englehart KB, Huang H, Li G, Hargrove L, et al. Decoding a new neural machine interface for control of artificial limbs. J Neurophysiol 2007;98:2974e82.
[38] Marko Bumbaširević, Aleksandar Lesic, Tomislav Palibrk, Darko Milovanovic, Milan Zoka, Tamara Kravić-Stevović, and Stanisa Raspopovic. "The current state of bionic limbs from the surgeon's viewpoint." EFORT Open Rev, February 2020.
[39] Bumbaširević M, Lesic A, Palibrk T, et al." The current state of bionic limbs from the surgeon's viewpoint." *EFORT Open Rev*. 2020;5(2):65-72. Published 2020 Feb 26.
[40] Frossard, L., et al. (2019) In-vivo kinetic system to sustain residuum health of service members with lower limb loss: From proof-of-concept to digital twin. Military Health System Research Symposium (MHSRS)
[41] Britannica, "Bionics as Technology", Britannica, 2017.