Advancements in upper body prosthetic limb technology: Providing effective solutions for medical amputations in the young population

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ABSTRACT

The loss of a limb for a child is a life-altering event, impacting their ability to perform everyday tasks and engage socially, highlighting the urgent need for advanced prosthetic solutions catered to the young population. This review examines the challenges unique to this population, including the need for prosthetics that adapt to rapid growth and active lifestyles. Current prosthetic technologies often fall short in comfort, functionality and affordability. However, focusing on the emerging technologies, such as 3D printing, integration of artificial intelligence, and programmable biosensors, offers promising solutions, providing customizable and cost-effective prosthetics with enhanced functionality and improved physiological compatibility and sensory feedback. Future developments like regenerative technologies and direct brain-controlled neural interfaces have the potential to completely transform prosthetics and make them even more individualized and integrated. In order to ensure that young amputees can lead

independent, satisfying lives, these advancements aim to create prosthetic limbs that not only address present limitations but also offer transformative benefits.

Introduction

Prosthetic limbs are vital in improving quality of life, allowing users to regain functionality of the limbs and independence. While now prosthetic limbs are available for all ages, a more challenging subgroup of patients to work with would be the young population with various problems like the acute and long term management of the prostheses (Khan et al., 2016). Medical amputations in children, although not a common sight, result from several factors such as congenital conditions traumatic accidents, or severe illness, with the leading cause being congenital amputations, 84% of the cases, followed by 13.5% for trauma in an observational study published in PubMed estimating the prevalence of lower limb loss (McLarney et al., 2021). Solutions that are adaptable to the rapid growth and active lifestyles typical of young users are important for the integration of them into their lives with minimal disruption.

The objective of this review article is to shed light on the improvements needed in current prosthetic arms, especially catering for young children. It will help explore the adverse effects and limitations of existing prosthesis, specifically comparing the existing prosthetic technology with emerging technology, highlighting the specifications that companies need to consider, physiological compatibility, cost-effectiveness, aesthetic customization, safety features, etc. tailored to the unique needs of young users.

Overview of the problem

Whether it be congenital or traumatic, the loss of a hand for a child is a life-altering event that extends far beyond the immediate physical injury. Globally, 291.2 million children suffer from traumatic and congenital hand amputations or reductions (Haagsma et al., 2020). Profoundly impacting their ability to perform everyday tasks and engage in social interactions, it can limit their development and integration into society. Without appropriate intervention, these children lose the potential to live productive, fulfilling lives. This alarming reality, highlights the urgent need for effective solutions tailored to the needs of these young victims, essentially a new arm, prosthesis.

The existing prosthesis options, while beneficial, are often designed with adult users in mind, lacking the specific considerations necessary for the young populations, such as comfort, ease of use and long term adaptability of the ever-growing adolescent body.

A recent study conducted in December 2020 suggests in children, years 5 – 14, the highest prevalence of traumatic amputations occurred in South Asia, followed by North Africa, Middle East and East Asia (McDonald et al., 2020). This indicates the higher incidence of young amputees in developing and underdeveloped countries.

Moreover, 80% of the disabled population lives in low-income countries (Harkins, McGarry and Buis, 2013), with 95% of the ones living in developing nations lacking access to prostheses (Laferrier et al., 2018a). The socio-economic barriers in those countries make access to advanced prosthetic technology challenging, leaving many young amputees reliant on outdated and insufficient solutions, calling for a need for change.

The future of prosthetics lies in further enhancing the functionality and accessibility of these devices, catering to individual patients. Innovations in Computer-Aided Design (CAD) and 3D printing are making it possible to create more customized and adaptable prosthesis solutions, which in the case for the younger population, may serve as a much needed solution to the problem stated.

Current technology in arm prosthetics

Modern arm prosthesis come in various types, each designed to meet specific needs and preferences of the user.

1. Passive Prostheses

Primarily cosmetic, passive prostheses are designed to mimic and restore the natural appearance of the arm but do not offer functional movement. They are lightweight, requiring minimal materials and easy to maintain. They are highly realistic and meant for users who prioritize aesthetics or do not require active hand or arm movements. They usually have a durable metal such as Titanium or Aluminium to provide structural support along with cosmetic material such as silicon or rubber. While they may provide a higher degree of flexibility, their maintenance can be an added burden on the user (Brack and Amalu, 2021). Image 1 below shows an example of passive prosthesis in use, holding a can.

Figure 1. Passive Prostheses. Figure 1 shows an example of a passive prosthesis worn by a person. (Arm Dynamics, 2024)

2. *Body powered prostheses*

Body powered prostheses are connected by a system of harnesses and cables with your body and their functionality, such as gripping, or movement of the arm relies on movements of the shoulders or other body parts the cables are connected to. Essentially making them totally manual to use. They tend to be more durable and less expensive than myoelectric prostheses, and are favored by those who need a robust and economical solution, however, enable limited functionality of the hand and arm. They usually have connected hooks, making them ideal for users who need a functional prosthesis for daily tasks and physical activities. The hooks are usually made of durable, but corrosive, steel, and soft silicon liners improving the fit and comfort of the prosthesis, reducing skin irritation (Brack and Amalu, 2021). Image 2 below shows a diagram of a body powered prosthesis connected to the person using a system of cables that move the prosthesis with the movement of the triceps and upper body.

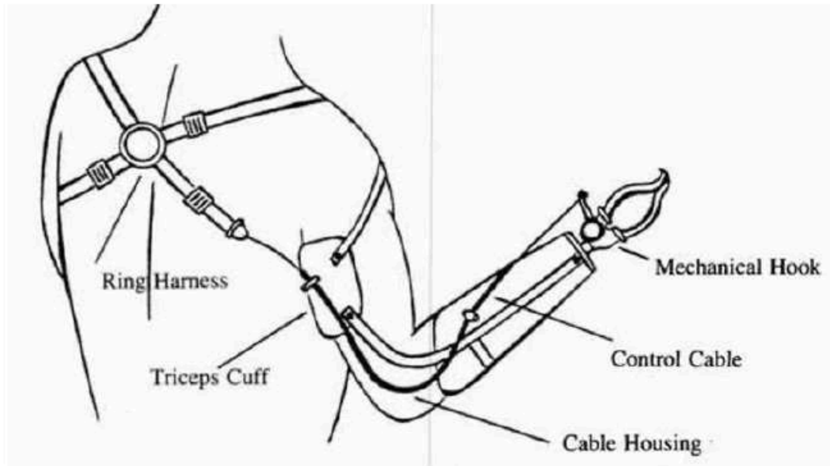

Figure 2. Body powered Prostheses. Figure 2 is a model of body powered prosthesis and its structure (Orthobullets, 2021)

3. Myoelectric prostheses

Myoelectric prostheses are externally powered, i.e. from a battery or any other power source. The advanced biosensors placed on the muscles of the user enables them to control movements using electrical signals from the user's muscles. Electrodes placed on the skin detect muscle contractions, which are then translated into movements of the prosthetic hand or arm. Hence, providing a more natural and precise control, allowing for a wide range of movements and greater grasp force. However, they tend to be the more expensive option among the others due to extensive personalization required, as electrodes are placed according to each patient's muscle stimuli. They are made from plastics that can be easily molded and shaped to fit the user's residual limb, enhancing comfort and usability, along with aluminum for structural support (Lee et al., 2017). Hence, suitable for users who require high functionality and are willing to invest in a more sophisticated and costly solution. Image 3 below shows a model of a myoelectric prosthesis with electrodes at one end connecting to the user’s muscles.

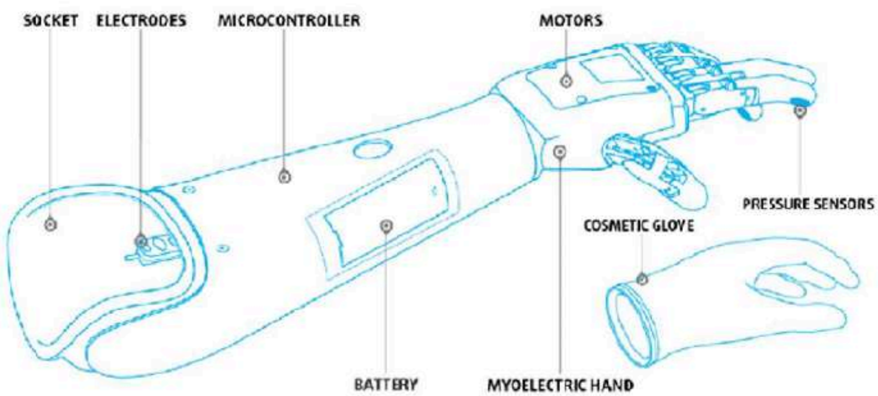

Figure 3. Myoelectric Prostheses. Figure 3 shows a model of myoelectric prostheses and its various parts (Calado, 2019)

These various types of arm prostheses cater to different needs, from purely aesthetic purposes to highly functional, ensuring that users can find a solution that best fits their lifestyle and requirements. However, issues such as balancing affordability with advanced technology remain key hurdles.

Technological challenges

Developing effective prosthesis for children involves several key challenges that should be taken into consideration.

A. Physiological compatibility

Ensuring a prosthesis is a perfect fit is vital for end-user experience being crucial for both comfort and functionality. According to Alison Middleditch for ScienceDirect, skeletal maturity of an individual is "a measure of development incorporating the size, shape and degree of mineralization of the epiphyses and physeal plates of bone to define their proximity to full maturity", or put in other words, an age after which the child achieves majority their adult height. For instance, girls are estimated to have achieved 95.8% of their adult height at the age of 13, while boys achieve 96.8% of adult height at the age of 15 (McCormack et al., 2016). Children's limb's grow rapidly, between the age of 7 and skeletal maturity, the humerus grows around 1.2 cm in girls, and 1.3 cm in boys per year (Pritchett, 1988).

Hence, a study in the journal of the Paediatric Orthopaedic Society of North America reveals that children's prostheses need to be replaced every 12 – 24 months until skeletal maturity.

Moreover, ill-fitted prosthesis in young children can not only lead to discomfort and hinder daily activities, but can also cause nerve compression, leading to pain, tingling, numbness, or even symptomatic neuroma: disorganized growth of nerve cells due to disruption at the nerve (Massachusetts General Hospital, n.d.). Approximately every 1 in 5 lower limb amputees develop this condition (Huang et al., 2021). The challenge is to create designs that not only accommodate growth but also support a wide range of motion and physical activities, enabling children to engage fully in their environments.

B. Cost

On average, a cosmetic prosthesis costs $5,000, while a functioning hook costs $10,000 and prices go up to $100,000 for the latest myoelectric arm technology (Vandersea, n.d.).The high cost of prosthetics limits accessibility for many families in developing and low-income countries, where the main problem lies. This economic barrier highlights the need for more affordable solutions, developing modular prosthetics - capable of effectuating almost all of the movements as a human arm with more than 100 sensors (Johns Hopkins Applied Physics Laboratory, n.d.) - with the use of less expensive materials, and cost-effective manufacturing techniques without compromising quality.

C. Functionality

Allowing for seamless integration into their daily lives, children's prosthetics need to be easy to learn and operate, while not compromising on functionality and adaptability. Many prosthetic arms still struggle to replicate the full range of natural arm movements, restricting the user's ability to perform everyday tasks with ease. While the costly current technology, such as the myoelectric prosthetics offer a wider range of movements, another issue encountered is the lack of advanced sensory feedback systems. Users often cannot feel pressure, temperature, or texture through their prosthetic limbs, limiting the user's ability to interact effectively. This absence of sensory input can make tasks such as gripping or manipulating objects more challenging and less intuitive. Another obstacle to tackle for myoelectric and other advanced current prosthesis is battery life. Users may need to recharge their devices multiple times a day, which can be inconvenient and disruptive, particularly for young users who are active throughout the day.

Emerging technologies in advancement of prosthetic limbs

In the next five years, several promising technologies are set to revolutionize prosthetic limbs, making them more accessible and functional for young users.

A. 3D Printing

3D printing also called additive manufacturing creates three dimensional object layer-by-layers using a computer created design.

3D printing technology is set to revolutionize the field of pediatric prosthetics in several ways:

1. <u>Customization:</u> With 3D scanning and printing technology the exact shape of a child's residual limb can be captured. A 3D scanner works by capturing data from a physical object, the child's limb in this case, and describing its shape in an accurate digital, 3D format (Capture 3D, n.d.). As the child grows, new scans can be taken and new prosthetics can be printed quickly, ensuring the creation of consistently physiologically well-fitted prostheses. Not only being perfect-fit, 3D printing also enables the creation of complex internal structures (TWI, 2024) that can make prosthetics lighter while maintaining strength, which is particularly beneficial for children and their activity levels. Moreover, children can choose colours, patterns, or even incorporating characters, i.e. personalization, and it can improve acceptance and use of the prosthetic (Rehacare, 2023).

2. <u>Cost effectiveness:</u> As described earlier, traditional prosthetics can be expensive to the pocket, especially considering frequent replacement every 12 – 24 months for children. 3D printing can not only reduce the labour and assembly costs, it would also reduce materials cost, overall reducing the cost of production of

the prostheses, making cheap yet effective prostheses more accessible to families across different economic backgrounds (Miley, 2023).

B. Artificial Intelligence Integration

“Artificial intelligence (AI) enables computers and machines to stimulate human learning, comprehension, problem solving, decision making, creativity and autonomy” (Stryker and Kavlakoglu, 2024).

In the near-coming future, AI is poised to drastically improve the functionality and programming of the prosthetic limbs, creating easier to use devices (Borowsky, 2023).

1. <u>Adaptive Control</u>

AI-powered prostheses could utilize machine learning algorithms that adapt to the user’s movements over time. Learning from real-life data and analyzing patterns in the user's muscle signals or nerve impulses, these systems can adjust their responses to improve control accuracy. For instance, the Esper Hand, made by Esper Bionics, a company developing next-gen bionics, employs electromyographic sensors to monitor muscle impulses, allowing the device to learn and refine its movements based on the user’s unique patterns (Dickstein, 2022). In the context of prostheses for the young population, it can enhance adaptability and provide personalized assistance as children grow and their movement patterns change.

2. <u>Predictive Movements</u>

Through machine learning and past data, AI’s predictive capabilities can allow prosthetics to anticipate the user's intended movements based on context. For example, the Utah Bionic Leg (Stevenson, 2022) integrates multiple sensors that gather data about the user's muscle signals, correlating them with specific movements. As a result, making the prostheses perform everyday tasks with greater ease, a crucial consideration for child prostheses.

The integration of AI looks promising in startups, as for instance, Social Hardware, an Indian based startup, focuses on practical prostheses for low income communities. Their device ‘Avocado’ incorporates AI-based software for design optimization and stress analysis, while still being relatively cheaper than its alternatives (USD 130 - 1800) (Ranjit Devraj, 2019), proving that technological advancement does not always come with the increased prices.

C. Biosensors

A biosensor is an analytical device that measures biological changes by translating them into electrical signals and can utilize a wide range of biological substances, such as enzymes, tissues, microorganisms, cells, and acids. (Naresh and Lee, 2021)

A major functionality missing from current age prostheses would be the sensory feedback. Bio-integrated sensors represent a significant leap forward in that direction (Roche et al., 2023).

1. Direct Neural Interface

Sensors implanted at the nerve endings and the electrodes connected to the muscles could provide a direct neural interface, allowing for more intuitive interface of prosthetic limbs. These implanted sensors have the potential to enable sensations of touch, pressure, grip, and even temperature enhancing the experience of the users, as if the external arm was an extension of the body itself.

2. Improved Proprioception

Proprioception is the body's ability to sense movement, action, and location, and is present in every muscle movement (Brennan, 2021). Bio-integrated sensors could provide feedback about the position and movement of the prosthetic limb, improving the user's ability to control it without relying solely on visual feedback, helping better the prosthetic hand-eye coordination.

3. Integration of Low-cost Biosensors

Low-cost, open-source platforms like Arduino could be explored for creating programmable biosensors. Not only would these reduce cost, however, also avail the benefits the biosensors would provide, and once connected to a direct neural interface, could be a game changer for low-cost prostheses, a viable solution for young age amputees requiring frequent change of their prosthesis.

Overall, the integration of biosensors represents a significant step towards restoring natural sensory feedback and intuitive control in prosthetic limbs, which is essential for enhancing usability for prostheses for children.

Technological hope for the future

With leading technological advances and so many already in the making, the scope for the future of prosthetic technology looks bright

1. *Direct brain-controlled neural interfaces*

The future of AI and neural interfaces in prosthetics is promising, with ongoing research focused on integrating more sophisticated neural interfaces allowing a direct brain control of prosthetic limbs, further blurring the line between biological and artificial limbs. Moreover, further development in the field of AI proves to be pivotal as prostheses aim not only to learn and adapt to individual users, but also to communicate with other devices, such as multiple prostheses on a single person. A cyborg body may not be too far from reality with prosthetic limbs essentially acting as extensions of your own body. For instance, Elon Musk's Neuralink "aims to restore personal control over limbs, prosthetics, or communication devices" as per Capitol Technology University (Laurel and Md 20708 800.950.1992, 2024). This advancement would enable young prosthesis users to achieve more natural and intuitive control over their artificial limbs, significantly improving their daily functionality and quality of life.

2. *Regenerative Technologies*

The integration of regenerative engineering principles with prosthetic technology holds immense potential for groundbreaking advancements in the field of limb replacement. By not only being a replacement for the limb, rather a treatment for amputees, regenerative prostheses can incorporate self-healing methods such as by delivering growth factors, stem cells, or other biological stimuli to the residual muscle tissue. Additionally the use of electrical stimulation can further enhance nerve regeneration and functional recovery of the residual limb. Recent advances in bone regeneration materials as well offer innovative solutions for reconstruction of the bone itself (Liu et al., 2022), and integrated into prostheses these regenerative technologies can add value to the treatment, aiding young amputees as their whole life lies in front of them.

Conclusion

The potential for transforming the lives of young amputees through the advancement of prosthetic technology is significant, as it can address their present needs as well as their future limitations. Through the incorporation of cutting-edge technologies like artificial intelligence, biosensors, direct brain-controlled neural interfaces, 3D printing, and regenerative engineering concepts, in the future, prosthetic limbs will gain increased customisation, functionality, and accessibility.

Technological advancements provide answers to important problems: Biosensors improve physiological compatibility and provide sensory feedback, AI improves functionality through predictive movements and adaptive control, and 3D printing lowers costs, making prosthetics more accessible. These innovations improve the lives of young users by restoring lost functionalities and facilitating full participation in daily activities, making sure that every young amputee has the chance to live an independent and satisfying life.

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References

Arm Dynamics (2024). *Redirect Notice*. [online] Google.com. Available at: https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.armdynamics.com%2Fupper-limb-library%2Fintroduction-to-passive-prostheses&psig=AOvVaw3ea23ATL-N-fKwunsNqLDJ&ust=1722327515585000&source=images&cd=vfe&opi=89978449&ved=0CAMQjB1qFwoTCMC_k5Poy4cDFQAAAAAdAAAAABAV [Accessed 29 Jul. 2024].

Borowsky, L. (2023). *How Artificial Intelligence Is Making Prosthetics Smarter*. [online] Amplitude. Available at: https://livingwithamplitude.com/artificial-intelligence-prosthetic-technology/ [Accessed 30 Jul. 2024].

Brack, R. and Amalu, E.H. (2021). A review of technology, materials and R&D challenges of upper limb prosthesis for improved user suitability. *Journal of Orthopaedics*, 23, pp.88–96. doi:https://doi.org/10.1016/j.jor.2020.12.009.

Brennan, D. (2021). *What Is Proprioception?* [online] WebMD. Available at: https://www.webmd.com/brain/what-is-proprioception.

Calado, A. (2019). *Figure 2: Typical components of a transradial myoelectric prosthesis*. [online] ResearchGate. Available at: https://www.researchgate.net/figure/Typical-components-of-a-transradial-myoelectric-prosthesis_fig2_332644633.

Capture 3D (n.d.). *How Does a 3D Scanner Work?* [online] www.capture3d.com. Available at: https://www.capture3d.com/knowledge-center/blog/how-does-a-3d-scanner-work#:~:text=A%203D%20scanner%20works%20by.

Cordella, F., Ciancio, A.L., Sacchetti, R., Davalli, A., Cutti, A.G., Guglielmelli, E. and Zollo, L. (2016). Literature Review on Needs of Upper Limb Prosthesis Users. *Frontiers in Neuroscience*, 10. doi:https://doi.org/10.3389/fnins.2016.00209.

D'Cruze, D. (2023). *Thousands in line to get brain chip implant by Elon Musk's Neuralink*. [online] Business Today. Available at:

https://www.businesstoday.in/technology/news/story/thousands-in-line-to-get-brain-chip-implant-by-elon-musks-neuralink-405100-2023-11-08 [Accessed 31 Jul. 2024].

Dickstein, L. (2022). *Esper Hand: The 200 Best Inventions of 2022*. [online] Time. Available at: https://time.com/collection/best-inventions-2022/6228818/esper-hand/.

Exobot (2024). *Exobot - Future of Bionic Limbs*. [online] Exobot.in. Available at: https://exobot.in/ [Accessed 30 Jul. 2024].

Haagsma, J., Westcott-McCoy , S., R. Weaver, M. and L. McDonald, C. (2020). Global prevalence of traumatic non-fatal limb amputation. *Prosthetics and Orthotics International Publish*. [online] doi:https://doi.org/10.1177/0309364620972258.

Hall, M., Cummings, D., Welling Jr., R., Kaleta, M., Koenig Jr., K., Laine, J. and Morgan, S. (2020). Essentials of Pediatric Prosthetics. *Journal of the Pediatric Orthopaedic Society of North America*, 2(3). doi:https://doi.org/10.55275/jposna-2020-168.

Harkins, C.S., McGarry, A. and Buis, A. (2013). Provision of prosthetic and orthotic services in low-income countries. *Prosthetics & Orthotics International*, 37(5), pp.353–361. doi:https://doi.org/10.1177/0309364612470963.

He (Helen) Huang, Hargrove, L.J., Ortiz-Catalan, M. and Sensinger, J.W. (2024). Integrating Upper-Limb Prostheses with the Human Body: Technology Advances, Readiness, and Roles in Human–Prosthesis Interaction. *Annual Review of Biomedical Engineering*, 26(1), pp.503–528. doi:https://doi.org/10.1146/annurev-bioeng-110222-095816.

Huang, Y.J., Assi, P.E., Drolet, B.C., Al Kassis, S., Bastas, G., Chaker, S., Manzanera Esteve, I.V., Perdikis, G. and Thayer, W.P. (2021). A Systematic Review and Meta-analysis on the Incidence of Patients With Lower-Limb Amputations Who Developed Symptomatic Neuromata in the Residual Limb. *Annals of Plastic Surgery*, Publish Ahead of Print. doi:https://doi.org/10.1097/sap.0000000000002946.

James, R. and Laurencin, C.T. (2015). Regenerative engineering and bionic limbs. *Rare Metals*, 34(3), pp.143–155. doi:https://doi.org/10.1007/s12598-015-0446-0.

Johns Hopkins Applied Physics Laboratory (n.d.). *Research - Revolutionizing Prosthetics | Johns Hopkins University Applied Physics Laboratory*. [online] www.jhuapl.edu. Available at: https://www.jhuapl.edu/work/projects-and-missions/revolutionizing-prosthetics/research#:~:text=Environment%20(VIE).- [Accessed 29 Jul. 2024].

Khan, M.A.A., Javed, A.A., Rao, D.J., Corner, J.A. and Rosenfield, P. (2016). Pediatric Traumatic Limb Amputation: The Principles of Management and Optimal Residual Limb Lengths. *World Journal of Plastic Surgery*, [online] 5(1), pp.7–14. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4904133/.

Laferrier , J., Groff, A., Hale, S. and A. Sprunger, N. (2018a). *Prosthetics in Developing Countries*. [online] ResearchGate. Available at: https://www.researchgate.net/publication/238088826_Prosthetics_in_Developing_Countries.

Laferrier, J., Groff, A., Hale, S. and Sprunger, N.A. (2018b). A Review of Commonly Used Prosthetic Feet for Developing Countries: A Call for Research and Development. *Journal of Novel Physiotherapies*, 08(01). doi:https://doi.org/10.4172/2165-7025.1000380.

Laurel, C.T.U. 11301 S.R. and Md 20708 800.950.1992 (2024). *Neuralink's Brain Chip: How It Works and What It Means | Capitol Technology University*. [online] www.captechu.edu. Available at: https://www.captechu.edu/blog/neuralinks-brain-chip-how-it-works-and-what-it-means [Accessed 31 Jul. 2024].

Lee, K.H., Bin, H., Kim, K., Ahn, S.Y., Kim, B.-O. and Bok, S.-K. (2017). Hand Functions of Myoelectric and 3D-Printed Pressure-Sensored Prosthetics: A Comparative Study. *Annals of Rehabilitation Medicine*, [online] 41(5), pp.875–880. doi:https://doi.org/10.5535/arm.2017.41.5.875.

Liu, H., Tian, Y., Zhao, C. and Ding, J. (2022). *Editorial: Bioactive bone regenerative materials and bionic prosthesis interfaces*. [online] Frontiers. Available at: https://www.frontiersin.org/journals/bioengineering-and-biotechnology/articles/10.3389/fbioe.2022.1111743/full [Accessed 30 Jul. 2024].

Massachusetts General Hospital (n.d.). *Neuromas and Complex Regional Pain Syndrome*. [online] Massachusetts General Hospital. Available at: https://www.massgeneral.org/surgery/plastic-surgery/treatments-and-services/procedures/neuromas-and-complex-regional-pain-syndrome#:~:text=A%20neuroma%20is%20a%20disorganized [Accessed 29 Jul. 2024].

McCormack, S.E., Chesi, A., Mitchell, J.A., Roy, S.M., Cousminer, D.L., Kalkwarf, H.J., Lappe, J.M., Gilsanz, V., Oberfield, S.E., Shepherd, J.A., Mahboubi, S., Winer, K.K., Kelly, A., Grant, S.F. and Zemel, B.S. (2016). Relative Skeletal Maturation and Population Ancestry in Nonobese Children and Adolescents. *Journal of Bone and Mineral Research*, 32(1), pp.115–124. doi:https://doi.org/10.1002/jbmr.2914.

McDonald, C.L., Westcott-McCoy, S., Weaver, M.R., Haagsma, J. and Kartin, D. (2020). Global prevalence of traumatic non-fatal limb amputation. *Prosthetics and Orthotics International*, 45(2), p.030936462097225. doi:https://doi.org/10.1177/0309364620972258.

McLarney, M., Pezzin, L.E., McGinley, E.L., Prosser, L. and Dillingham, T.R. (2021). The prevalence of lower limb loss in children and associated costs of prosthetic devices: A national study of commercial insurance claims. *Prosthetics and Orthotics International*, [online] 45(2), pp.115–122. doi:https://doi.org/10.1177/0309364620968645.

Middleditch, A. (2010). *Bone Maturation - an overview | ScienceDirect Topics*. [online] www.sciencedirect.com. Available at: https://www.sciencedirect.com/topics/immunology-and-microbiology/bone-maturation [Accessed 29 Jul. 2024].

Miley, J. (2023). *Revolutionizing prosthetics for kids: A modular approach that grows with the user*. [online] www.wevolver.com. Available at: https://www.wevolver.com/article/revolutionizing-prosthetics-for-kids-a-modular-approach-that-grows-with-the-user [Accessed 29 Jul. 2024].

Naresh, Varnakavi. and Lee, N. (2021). A Review on Biosensors and Recent Development of Nanostructured Materials-Enabled Biosensors. *Sensors*, 21(4), p.1109. doi:https://doi.org/10.3390/s21041109.

Orthobullets (2021). *Rehab & Prosthetics - Basic Science - Orthobullets*. [online] www.orthobullets.com. Available at: https://www.orthobullets.com/basic-science/9072/rehab-and-prosthetics.

Pritchett, J.W. (1988). Growth and predictions of growth in the upper extremity. *The Journal of Bone and Joint Surgery. American Volume*, [online] 70(4), pp.520–525. Available at: https://pubmed.ncbi.nlm.nih.gov/3356718/#:~:text=From%20the%20age%20of%20seven%20to%20skeletal%20maturity%2C%20the%20humerus [Accessed 29 Jul. 2024].

Ranjit Devraj (2019). *For thousands of Indians searching for smarter, cheaper prosthetic limbs, AI may be the answer*. [online] Scroll.in. Available at: https://scroll.in/article/947084/for-thousands-of-indians-searching-for-smarter-cheaper-prosthetic-limbs-ai-may-be-the-answer [Accessed 29 Aug. 2024].

Rehacare (2023). *3D-printed prosthetic devices for children – individualized care yields multiple benefits*. [online] www.rehacare.com. Available at: https://www.rehacare.com/en/business/3d-print-prosthetic-devices-children.

Roche, A.D., Bailey, Z.K., Gonzalez, M., Vu, P.P., Chestek, C.A., Gates, D.H., Kemp, S.W.P., Cederna, P.S., Ortiz-Catalan, M. and Aszmann, O.C. (2023). Upper limb prostheses: bridging the sensory gap. *Journal of Hand Surgery (European Volume)*, 48(3), pp.182–190. doi:https://doi.org/10.1177/17531934221131756.

Saikia, A., Mazumdar, S., Sahai, N., Paul, S., Bhatia, D., Verma, S. and Rohilla, P.K. (2016). Recent advancements in prosthetic hand technology. *Journal of Medical Engineering & Technology*, 40(5), pp.255–264. doi:https://doi.org/10.3109/03091902.2016.1167971.

Segura, D., Romero, E., Abarca, V.E. and Elias, D.A. (2024). Upper Limb Prostheses by the Level of Amputation: A Systematic Review. *Prosthesis*, 6(2), pp.277–300. doi:https://doi.org/10.3390/prosthesis6020022.

Stevenson, D. (2022). *Utah Bionic Leg in Science Robotics*. [online] Mechanical Engineering | University of Utah. Available at: https://www.mech.utah.edu/utah-bionic-leg-in-science-robotics/.

Stryker, C. and Kavlakoglu, E. (2024). *What is artificial intelligence (AI)?* [online] IBM. Available at: https://www.ibm.com/topics/artificial-intelligence.

TWI (2024). *What are the Pros and Cons of 3D Printing?* [online] Twi-global.com. Available at: https://www.twi-global.com/technical-knowledge/faqs/what-is-3d-printing/pros-and-cons.

Vandersea, J. (n.d.). *The Complete Guide To Arm & Hand Amputations and Prosthetics | MCOP*. [online] MCOP Prosthetics. Available at: https://mcopro.com/blog/resources/arm-hand-prosthetics/#:~:text=How%20much%20does%20a%20prosthetic [Accessed 29 Jul. 2024].