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Development of a hand prosthesis controlled by electroencephalographic signals using Arduino and Mindflex technology

María Fernanda Carballo Turcios[1], Manuel Adalid Gamero-V.[2],
[1]Universidad Tecnológica Centroamericana (UNITEC), Honduras, mariafercarballo@unitec.edu,
[2]Universidad Tecnológica Centroamericana (UNITEC), Honduras, manuelgamero@unitec.edu

Abstract– This paper presents the development of a brain-controlled hand prosthesis using Arduino and Mindflex tech- nology. The objective of this research is to design a system that enables individuals with disabilities to control a hand prosthesis through their brain signals. Electroencephalographic (EEG) signals are utilized to capture and interpret the user's intention to perform specific hand movements. The Neurosky chip is integrated with Arduino to acquire real-time EEG signals, while the Mindflex technology, employing EEG headsets, serves as a non-invasive and user-friendly interface for capturing brain signals. By analyzing these signals, commands are generated to control the movements of the hand prosthesis. The prototype implementation includes the integration of electromechanical components, such as servo motors, for prosthesis activation. Extensive tests and simulations are conducted to evaluate sys- tem performance and efficiency. Validation data from both the openbci device and Mindflex are analyzed and compared to assess the accuracy and reliability of the brain commands. The results demonstrate successful interaction between the user and the servo motor, indicating the feasibility of controlling a hand prosthesis using EEG signals. The achieved accuracy in generating brain commands validates the effectiveness of the developed system. This research contributes to the advancement of prosthetics technology, offering new possibilities for enhancing the quality of life for individuals with disabilities.

Keywords-- Arduino technology, control, disability, Mind- flex, Neurosky chip, hand prosthesis, electroencephalographic signals.

I. INTRODUCTION

The development of advanced technologies in the field of prosthetics has significantly improved the quality of life for individuals with limb disabilities. One area of focus is the design and implementation of brain-controlled prosthetic devices, which enable users to control artificial limbs using their brain activity [1]. This approach offers a promising solution for individuals who have lost hand functionality, aiming to restore their ability to perform daily tasks and regain independence [2].

This paper introduces a brain-controlled hand prosthesis developed with Arduino and Mindflex technology, aiming to empower individuals with disabilities. Electroencephalographic (EEG) signals capture the user's intention for hand movements. The Neurosky chip integrates with Arduino to acquire real-time EEG signals, while Mindflex technology serves as a user-friendly interface. Commands generated from EEG analysis control hand prosthesis movements. The prototype includes servo motors for activation, tested extensively for performance. Results show successful user-servo motor interaction, confirming the feasibility of EEG-based hand prosthesis control. This research contributes to prosthetics technology, offering new possibilities for enhancing the quality of life for individuals with disabilities.

II. STATE OF THE ART

A. Antecedents

This section provides an overview of the relevant antecedents in the field of brain-controlled prosthetics and related technologies.

In the field of EEG-controlled hand prostheses,numerous studies have been conducted. Some investigations have explored the development and evaluation of low-cost brain-computer interface systems [3] [4]. Other studies have investigated the use of artificial neural networks for device control through brain-computer interfaces [5]. Furthermore,hybrid systems combining brain-computer interfaces with exoskeletons for hand rehabilitation have been proposed [6] [7]. Non-invasive brain-computer interfaces for prosthesis control have also been developed [8]. Some studies have investigated reversible large-scale modifications in cortical networks during neuroprosthetic control [9]. Additionally, machine learning based co-adaptation of brain-computer interfaces has been explored [10]. Other works have reviewed the past, present, and future of brain-machine interfaces [11]. Moreover, stud- ies have demonstrated reach and grasp control of robotic arms through brain-machine interfaces in individuals with tetraplegia [12] [13]. Furthermore, invasive and non-invasive approaches to decoding the neural control of prosthetic hands have been reviewed. Some studies have shown restoration of reaching and grasping movements through brain-controlled muscle stimulation [14] [15]. Additionally, hybrid systems based on SSVEP and EMG signals for two-dimensional cursor control have been proposed.

B. Problematic

In the field of assistance to people with motor disabilities,a constantly growing demand arose for the creation of hand prostheses that were precise and at the same time affordable [16].Although the use of EEG (Electroencephalogram) signals to control prostheses promised to be an innovative solution,technical and design challenges persisted that hindered its large-scale adoption [17]. For this reason, the research was oriented towards the conception and development of a hand prosthesis with a simple design, whose control was based on the detection of EEG signals, using Arduino technology and the MindFlex device [18]. The central problem of this research was based on the need to overcome the current limitations surrounding prostheses controlled by EEG signals, especially with regard to costs and accessibility. Therefore, the purpose of this project was to offer an effective and affordable solution that would have a positive impact on the quality of life of people facing motor disabilities. The focus of this study was on merging and combining different technologies and simplified design to address a problem that affects a significant number of people around the world. Arduino technology and the MindFlex device were innovatively combined to enable control of the prosthetic hand, while seeking to keep costs within reasonable limits [19]. This represented a solution to overcome the economic barriers that often limited access to assistive technologies. The research was situated in a context in which improving the quality of life of people with motor disabilities was a priority, and the convergence of various disciplines, such as engineering, neuroscience and computer science, became essential to effectively address this problem. This multidisciplinary approach sought to drive widespread adoption of prosthetics controlled by EEG signals, providing tangible hope to people who relied on these technologies to carry out daily activities independently and effectively.

III. METHODOLOGY

This chapter presents the methodology adopted to address the development of hand prostheses controlled by electroencephalographic signals, using the combination of technologies such as Mindflex and Arduino. This section clearly states the research variables and describes how they will be operationalized to facilitate accurate measurement and analysis. The choice of the method is made with the objective of achieving effectiveness in achieving the objectives, thus allowing the replicability and authentication of the results obtained. The research process is coherently synthesized, from the conceptual phase to evaluation, and presented visually to facilitate a comprehensive understanding of the approach adopted. The selected evaluation metrics play a crucial role in determining the effectiveness and user acceptance towards the prototype, thus contributing to bridging the gap between theory and practical application.

A. Research Variable

A research variable is a construct, characteristic, property, or factor that is examined and quantified in the context of a research study for the purpose of analyzing its relation- ship with other phenomena or variables. These variables are conceptualized as constructs, attributes or characteristics that are susceptible to variation. In the framework of the research, the independent variable are those that can be manipulated or controlled, while the dependent variables are those that are subjected to observation and measurement in order to discern the effect or influence of the independent variables ”Figure 1”.

1) Independent Variable:

- Hand prosthesis powered by a Neurosky and Arduino chip through high and low beta brain waves called concentration and deconcentration waves.

2) Dependent Variables:

- Prosthetic hand movement commands: *The* commands established and developed through the programming language for prosthetic movement include actions such as opening and closing. These commands are based and executed in terms of the brain waves that you want to acquire.
- Precision of the commands generated by the brain waves: Corresponding to the commands generated from the brain conditions (concentrated and deconcentrated) were interpreted and executed by the prosthesis. The precision measure is expressed in percentage terms.
- Prosthesis movements: The particular movements executed by the prosthesis in response to instructions generated by brain conditions. These movements included actions such as opening and closing the prosthetic hand.
- Response speed: The passage of time from the acquisition and emission of brain electrical signals to the execution of commands generated based on the brain conditions and the programming conditions established in the Arduino program. The speed depends on the users’ concentration levels.
- Number of tests: Corresponding to the number of tests carried out per user to obtain brain waves in terms of high and low beta waves. the font type sizes in Table I. The font type sizes are given in MS Word font size points. Times New Roman is the preferred font.

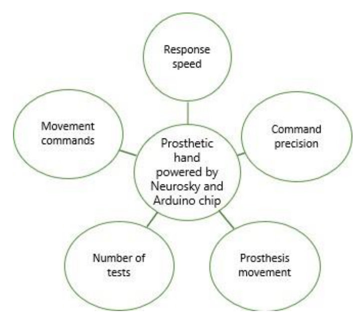

Fig. 1 Diagram research variables

B. Materials

The materials that were used for the development of the prototype such as the electronic components are:

1) Prosthetics:

- PLA Filament (Polylactic Acid).
- 4 gauge fishing line.
- Plastic fishing line.

2) Electronic components:

- Microservo 9g.
- Mindflex device.
- Arduino UNO microcontroller.

C. *Methodology in "V"*

This study adopts an experimental research design with a cross-sectional approach using a "V"-shaped methodology to address the challenges in the development of a hand prosthesis controlled by brain signals for people with motor disabili- ties or lower extremity amputation. The "V" methodology consists of two main phases: the top-down phase, where design requirements and specifications are established, and the bottom-up phase, where the proposed design is implemented and validated "Figure 2". This approach provides consistency, traceability and the ability to identify early problems to achieve an optimal and functional solution in the creation of advanced prostheses adapted to the needs of people with motor disabilities.

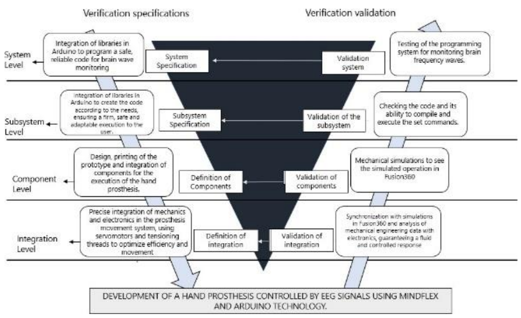

Fig. 2 Methodology in V

IV. RESULTS

A. *Characterizations and specifications if the Prototype*

programming and decoding of the brain waves, acquired through the Neurosky chip, were executed through the use of two fundamental programs intended for data visualization and integration with the prototype. The two development environments selected to carry out the decoding and inter- pretation of the brain wave data were the Arduino Uno IDE and Processing. These programs operated in conjunction, performing complementary functions in order to validate the correct extraction of data and verify its adequacy during the implementation of the Mindflex system. It is important to take into account the operation of the process detailed in "Figure 3"

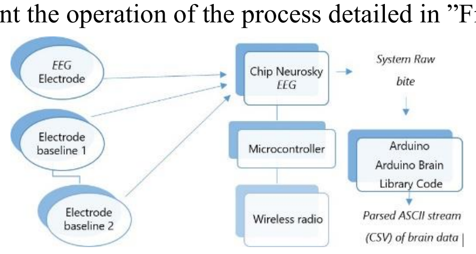

Fig. 3 Mindflex headset operation diagram

B. *Prototype design and Printing*

In the current results stage, it was designed and implementedthe hand prototype using digital illustrations. This approach aimed to align the design with pre-established requirements, easing the transition to the three-dimensional modeling phase in Fusion 360. The design was materialized using 3D printing technologies, ensuring the physical realization of the proto- type. This method, supported by advanced digital tools and additive manufacturing, laid a robust foundation for realizing and validating the handheld prototype while ensuring align- ment with ergonomic and functional criteria set during the planning phase.

1) Prototype design: In the design of the prototype, the technologies to be implemented and the mechanical com- ponents necessary to enable the operation of the prosthetic hand, outer part "Figure 4" and lower part "Figure 5", were carefully considered. Once the design concept was established, the implementation phase proceeded using the fusion 360 program. This software provided the ability to carry out a detailed design, based on real components, which served as the basis for the subsequent three-dimensional printing of the prototype. This integrated approach ensured an accurate and functional representation of the conceptual design, enabling a seamless transition from planning to prototype materialization using advanced manufacturing technologies.

Fig. 4 Prototype outer part

C. Integrations Of components to the prototype

Electromechanical components were integrated into the printed prototype to initiate assembly, ensuring precise ar- rangement. The mini 9g servo motor, controlling the pros- thesis, was connected to the pre-assembled Arduino micro-

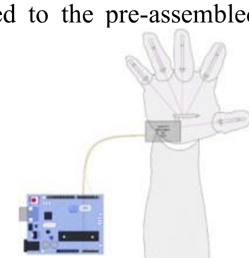

Fig. 5 Prototype lower part

controller circuit with the mindflex device. This allowed the Neurosky chip signal to activate the servo, facilitating prosthesis operation "Figure 6".

Fig. 6 Integrations of components mecanical and electrical

D. Analysis of data obtained from validation and constrastation between OpenBCI and Mindflex

For developing an experimental prototype to interact with the human central nervous system, we used the open-source Brain-Computer Interface (BCI) device, OpenBCI. Neurophysiological data collected through this prototype underwent statistical analysis, confirming or refuting hypotheses about validating MindFlex device results. This not only assessed the effectiveness of both prototypes in acquiring neurophysiological data but also contributed to the knowledge in Brain-Computer Interfaces research.

1) Confidence interval Mindflex vs OpenBCI:

- Subject 1 and subject 2:

Comparison of attention scores of two devices, Mindflex and OpenBCI. On average, OpenBCI scores are significantly higher than Mindflex, with a 95% confidence interval of -29.55 to -8.59. This suggests that OpenBCI is likely to be more accurate in measuring attention than Mindflex"*Table I and II*".

TABLE I
95% CONFIDENCE INTERVAL FOR THE DIFERENCE SUBJECT 1

Difference	95% Confidence Interval
-3.88	(-11.86; 4.10)

TABLE II
95% CONFIDENCE INTERVAL FOR THE DIFERENCE SUBJECT 2

Difference	95% Confidence Interval
-19.07	(-29.55; -8.59)

2) Two-Sample T-test Mindflex vs OpenBCI:

- Subject 1 and subject 2:

The two-sample T-test and confidence interval assessment re- vealed a p-value of 0.923, surpassing the significance threshold of 0.05. Acceptance of the null hypothesis indicates that, statistically, there is no significant difference between the means of the devicesTable III and IV.

TABLE III
HYPOTHESIS TEST RESULTS SUBJECT 1

Null Hypothesis	H: - μ = 0
Alternative Hypothesis	H: - μ 0
T Value	0.10
Degrees of Freedom (DF)	53
P-Value	0.923

TABLE IV
HYPOTHESIS TEST RESULTS SUBJECT 2

Null Hypothesis	H: - μ = 0
Alternative Hypothesis	H: - μ 0
T Value	-3.84
Degrees of Freedom (DF)	17
P-Value	0.001

3) Final analysis Mindflex vs OpenBCI: Descriptive statistics, including mean, standard deviation, median, and range, were used to assess the Mindflex and OpenBCI de- vices. The two-sample t-test was employed to evaluate mean differences. A 95% confidence interval estimated the disparity between device means. Subject 1 showed a non-significant disparity of 3.88 units. In subject 2, OpenBCI scored significantly higher than Mindflex, with a mean disparity of-19.07 across both subjects, indicating OpenBCI's superior performance. The OpenBCI may prove to be a more valuable tool for researchers investigating attention, while the Mindflex could be better suited for recreational or educational purposes. Manufacturers of attention-tracking devices should take into account the findings of this study when developing new products.

4) Global Results: The comprehensive evaluation of the EEG-controlled hand prosthesis revealed consistent performance and effective adaptability to users' intentions. During general operational tests, the prosthesis consistently demonstrated the ability to respond to changes in the user's concentration state, validating the efficacy of the EEG signal interpretation system and the prosthetic hand's responsiveness. Detailed subsystem evaluation confirmed precise coordina- tion between the EEG signal capture system and the Arduino platform. The prototype's capability to interpret changes in concentration states and translate them into control commands for the prosthesis was evident.

A performance table was generated to assess the system's responsiveness, specifically the prototype's response in opening when the user was concentrated and closing when they were disengaged. The study presented data in microvolts over a 60-second interval for each subject "Table V".

TABLE V
GLOBAL RESULTS OF PROSTHESIS ACTIVATION

Subject	Activation Time	Functioning Percentage
1	60 seconds	50%
2	60 seconds	66.67%
3	60 seconds	60%
4	60 seconds	16.67%
5	60 seconds	83.33%
6	60 seconds	100%
7	60 seconds	60%
8	60 seconds	80%
9	60 seconds	100%
10	60 seconds	66.67%

Individuals exhibit varying levels of attention, each with their unique concentration patterns. Some subjects, such as Subject 6 and 9, demonstrate a high control index and the ability to achieve profound concentration, thereby attaining greater control over the prosthesis. Conversely, Subject 4 tends to be easily distracted, struggling to concentrate even in an optimal environment without noise or interference. This behavior may suggest attention deficit hyperactivity disorder (ADHD) in this individual.

Statistical tests were employed to ascertain that the Mindflex device exhibits a 100% activation rate, as subjects, at some juncture within the 60-second trial, successfully triggered the prototype through concentration. It is noteworthy that each participant demonstrates a unique concentration index or method throughout the experiment ”Figure 7”.

In the graph depicting the average subjects' performance over activation time Figure 8” the y-axis represents the average of 10 subjects normalized to 100, while the x-axis displays the 60-second test duration. It is evident that 50% of the subjects successfully activated the prosthesis using the Mindflex headband within the initial 10 seconds. Additionally, 20% accomplished this between the 10th and 20th seconds, and another 20% between the 30-second mark. Merely 10% managed to activate the prosthesis starting from the 50-second point of the trial.

5) Final observations on the evaluation of the prototype observations on the evaluation systems and subsystems: The developed prototype's final assessment involved evaluating its performance and subsystems. Findings were documented, focusing on conformity with objectives and requirements. The analysis covered system performance, subsystem function- ing, noting positives, areas for improvement, and identified problems. This holistic approach provided valuable insights for adjustments and informed decision-making before final implementation.

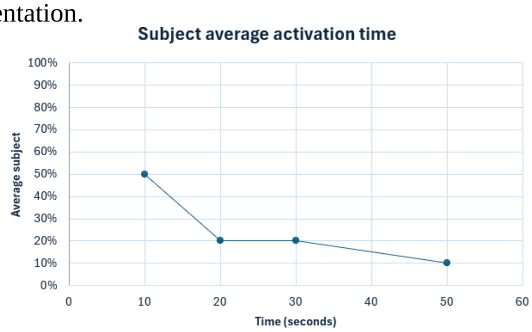

Fig. 7 Subject's average activation time graphic

6) Prototype description: The innovative hand prosthesis, incorporating EEG signals captured through MindFlex technology and processed via an Arduino-based system, showcased a groundbreaking advancement in brain-computer interfaces. Through operational tests, the prosthetic hand demonstrated an effective response to variations in the user's concentration levels.

In instances where the user exhibited a concentrated state, the hand maintained a closed position. Conversely, during periods of reduced concentration, the hand opened, granting the user greater freedom of movement. These findings un- derscore the efficacy of the adopted approach, emphasizing the prosthesis's dynamic adaptation to the user's intentions. Such adaptability holds significant potential for substantial improvements in the overall quality of life for individuals utilizing hand prostheses ”Figure 8”.

Fig. 8 Mindflex with hand prosthesis

IV. CONCLUSIONS

- A successful design for a brain-controlled hand prosthesis using MindFlex headgear and Arduino UNO microcon- troller has been achieved, with users demonstrating an average performance of 78.4% in controlling prosthesis movements through brain signals detected by the head- gear over a 60-second period.
- Research on the fundamental principles of electroencephalography (EEG) technology and its application in hand prosthesis control was conducted. The study identified key features for capturing and processing brain signals, contributing to a comprehensive understanding of assistive technology. Among 23 Brain-Computer Interface projects, 17.39% utilized NeuroSky technology, providing insights into the landscape of assistive technology and potential applications for specific user groups, guiding future developments.
- Research identified suitable components for 3D-printed hand prosthesis construction. Materials and components meeting requirements for strength, durability, and inte- gration with brain signal-based control technology were selected.
- An analysis of the Arduino UNO microcontroller response to EEG signals from MindFlex headgear was conducted. Subjects achieved a 60-second timeframe, with signal processing techniques and control algorithms optimizing microcontroller functionality for precise hand prosthesis control based on detected brain signals. The evaluation, based on six activations per subject, demonstrated a 100% success rate.
- A comprehensive platform for EEG-based hand prosthe- sis was developed using adapted MindFlex technology. Integration of MindFlex headgear with Arduino UNO enabled the detection and processing of

brain signals to control hand prosthesis movements. Despite some sub- jects facing difficulty in activation due to concentration parameters, the prototype achieved 100% functionality within the test duration.

• This research project successfully designed and developed a brain-controlled hand prosthesis utilizing Mind-Flex headgear and Arduino UNO microcontroller technology. The achieved objectives, with a 100% success rate in functionality, highlight the potential of EEG technology in the prosthetics field, enhancing the quality of life for individuals with upper limb disabilities.

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REFERENCES

[1] Gentiletti, G., Tabernig, C., Acevedo, R. (2007). Interfaz Cerebro - Computadora: Estado del arte y desarrollo en Argentina.

[2] Moreno, I., Batista, E., Serracin, S., Moreno, R., Go´mez, L., Serracin, J., Quintero, J., Boya, C. (2019). Los sistemas de interfaz cerebro-computadora basado en EEG: Caracter´ısticas y aplicaciones. I+D Tecnolo´gico, 15(2), Article 2. https://doi.org/10.33412/idt.v15.2.2230

[3] Peterson, S. M. (2020). Development and Evaluation of a Low-Cost Brain-Computer Interface System. Journal of Neural Engineering, 17(4), 046029.

[4] Gargava, A. (2014). Brain-Computer Interface Control of an Arduino-Based Robot. International Journal of Advanced Research in Computer Science and Software Engineering, 4(7), 878-883.

[5] Muhammad, G., Vaino, N. (2019). Brain-Computer Interface for Device Control Using Artificial Neural Networks. Proceedings of the International Conference on Artificial Intelligence and Robotics, 1-6.

[6] Wang, Y., Zhang, D., Xu, G., Wang, Y. (2019). A Hybrid BCI System for Hand Exoskeleton Control. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 27(4), 668-678.

[7] Li, Z., Zhang, L., Li, Y., Zhang, X. (2018). A Hybrid BCI-Based Exoskeleton for Hand Rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26(11), 2186-2195.

[8] Bhattacharyya, S., Konar, A., Tibarewala, D. N., Nagar, A. K. (2017). Non-Invasive Hybrid Brain-Computer Interface for Control of Prosthe- ses. Proceedings of the 9th International Conference on Communication Systems and Networks, 1-5.

[9] Ganguly, K., Dimitrov, D. F., Wallis, J. D., Carmena, J. M. (2014). Reversible Large-Scale Modification of Cortical Networks during Neuroprosthetic Control. Nature Neuroscience, 17(5), 683-691.

[10] Vidaurre, C., Sannelli, C., Mu¨ller, K. R., Blankertz, B. (2011). Machine-Learning-Based Co-Adaptation of Brain-Computer Interfaces. Neural Computation, 23(3), 791-816.

[11] Lebedev, M. A., Nicolelis, M. A. (2006). Brain-Machine Interfaces: Past, Present and Future. Trends in Neurosciences, 29(9), 536-546.

[12] Hochberg, L. R., Bacher, D., Jarosiewicz, B., Masse, N. Y., Simeral, J. D., Vogel, J., ... Donoghue, J. P. (2012). Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. Nature, 485(7398), 372-375.

[13] Collinger, J. L., Wodlinger, B., Downey, J. E., Wang, W., Tyler-Kabara,

[14] C., Weber, D. J., ... Boninger, M. L. (2013). High-performance neuroprosthetic control by an individual with tetraplegia. The Lancet, 381(9866)

[15] Blabe, C. H., Gilja, V. (2020). Decoding the neural control of prosthetic hands: a review of invasive and non-invasive approaches. Journal of Neural Engineering, 17(1), 011001.

[16] Ajiboye, A. B., Willett, F. R., Young, D. R., Memberg, W. D., Murphy,

[17] B. A., Miller, J. P., ... Simeral, J. D. (2017). Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration. The Lancet, 389(10081), 1821-1830.

[18] Bouton, C. E., Shaikhouni, A., Annetta, N. V., Bockbrader, M. A., Friedenberg, D. A., Nielson, D. M., ... Ludwig, K. A. (2016). Restoring cortical control of functional movement in a human with quadriplegia. Nature, 533(7602), 247-250.

[19] Li, G., Chen, W., Zhang, J., Zhang, Z., Li, Y. (2014). A hybrid BCI system for 2D cursor control based on SSVEP and EMG. Journal of Neural Engineering, 11(3), 036021.

[20] Aportes en Ciencias Ingenieriles Biome´dicas. (2013). Instituto Tecnolo´gico Metropolitano.

[21] Romero Erazo, B. M. (2016). Disen˜o de prototipos tridimensionales de pro´tesis externa para reemplazo de pierna y pie por amputacio´n infra- genicular en humanos. [bachelorThesis, Escuela Superior Polite´cnica de Chimborazo]. http://dspace.espoch.edu.ec/handle/123456789/5844