Current overview of the state of the disabled population, regarding the use of the transtibial prosthesis

Una mirada actual al estado de la población en condición de discapacidad frente al uso de prótesis de miembro inferior a nivel transtibial

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Jhon Hernández Martin[1]
Luis Alberto Parra[2]

[1] Colombiano MSc. Servicio Nacional de Aprendizaje SENA, Centro de Diseño y Metrología. e-mail jhonmartin56@gmail.com.

[2] Colombiano MSc. Servicio Nacional de Aprendizaje SENA, Centro de Diseño y Metrología. e-mail ingluisparra@misena.edu.co.

Abstract

The Center of Design and Metrology of SENA-CDM (Centro de Diseño y Metrología del SENA–CDM) has found that the population with disability of lower limbs represents a technical-technological challenge, regarding locomotion recovery, since this group requires very expensive surgeries or devices, such as canes, crutches, wheelchairs or other items to help them move freely. It is important to take into account that there are doubts as to whether prosthesis on the market satisfies patients' economical and functionality needs. Through this project, we intend to solve this inconvenience and generate a solution with local technology in the Center of Design and Metrology of SENA. In Colombia, there are not many companies that design and manufacture the elements composing a prosthesis; for this reason, the CDM has been working for approximately five years on the design and adaptation of prosthesis and orthosis with imported components. Thus, we intend to design and implement a 100 %-SENA-manufactured ankle articulation for transtibial amputation, which meets the ergonomic and functional needs of patients. This original scientific article gathers the most relevant information regarding a topic affecting our society. Here, we analyze different bibliographic sources described in the existing literature. Using this knowledge, we have created the stages required to write this article, defining revision objectives and making the most relevant bibliographical search, and organizing information according to mind maps in order to write this paper.

Keywords: foot; transtibial prosthesis; articulation; ankle.

Introduction

All human beings possess an intrinsic, natural characteristic in our bodies that is moving; however, in some cases, this natural attribute is lost due to different circumstances. Most frequent factors are associated with situations such as violence, high accidentally rates, and medical causes which directly compromise the person. For the specific case of violence, some areas of the world have suffered the serious consequences of land mines, a worldwide issue that affects societies' public policies, according to the Red Cross international commission (CIRC, 2016). Countries where this issue is particularly serious are Cambodia, Angola, Bosnia-Herzegovina, Afghanistan, El Salvador, Nicaragua, and Colombia, with a high number of active landmines, due to the armed conflicts in these nations.

For the specific case of Colombia, some distressing statistics have been retrieved; according to the Observatorio De Minas Antipersonas de la Presidencia de la Republica (Contraloria General de la República, 2012; Reyes, 2011), by 2011, around 1080 people had died due to landmines (Reyes, 2011). On the other hand, in most cases, the patient does not die but loses one or both lower limbs, thus rendering landmines as one of the main causes for disability. Unofficial figures from the medic Thomas Küchenmeister indicate that, by 2011, the armed conflict in Colombia has left 20.000 victims counting deceased and disabled.

As one of the most affected countries in this situation, Colombia has a high percentage of the disabled population (Nation general comptroller's office), who require medical and psychological aid on a daily basis (Álvarez & Ospina, 2013).

Thus, retrieving locomotion of population with lower-limb disability represents quite a challenge, since it requires expensive surgery, which, depending on specific needs, may require a prosthesis, orthosis or devices which help them move freely, such as canes, crutches, wheelchairs or other items that generate the static balance of the person.

For Colombia, it becomes necessary generating around 4000 new prosthetics a year to cover the needs produced by the armed conflict (Ministerio de Posconflicto, Derechos Humanos y Seguridad, 2016) and amputations due to diabetes and accident tolls. Therefore, it is necessary to implement a bank of medical prosthetics which covers the said need. Likewise, it is also important to consider if existing prosthetics meet the economic and functional needs of each patient. It is important to be aware that these elements represent a high investment and must be imported from other countries since there is no local production.

By carrying out this research, it is sought to improve use, whether fixed or moderate, of aiding elements in order to reenable march, by implementing an electromechanical element, along with appropriate physical rehabilitation, which improves patient locomotion.

Method

Bibliography of this document complies with the following characteristics:

- The up-to-date revision or basic references.
- Both global and specific state of the art.
- Bibliographic Revision of the four work areas of the Project.

References are oriented under professional bibliographic supervision.

The general state of the art in the field of orthopedic technology

An amputated patient experiences a loss in life quality, due to the difficulties in mobility or aesthetic changes (Molero-Sánchez, Molina-Rueda, Alguacil-Diego, Cano-De la Cuerda & Miangolarra-Page, 2015; Zhou *et al*., 2015). This condition generates psychological sequels (Sagawa *et al*., 2011) which lead to changes in personality and affect rehabilitation and loss acceptance (Lewis, 2008). Other psychological conditions derive in an intense sensation, originated in the location of the severed limb; this symptom is known as "phantom limb" (Lewis, 2008).

Mobility deprivation due to the loss of a limb makes many patients become a burden for their families and society since they are unable to perform an economic activity due to their condition (Sinitski, Hansen & Wilken, 2012).

Treatments are the first tool to aid patients with physical sequels (Sinitski *et al*., 2012; Morgenroth *et al*., 2011). In treatments, the patient is subjected to physical tests, in order to determine the extent to which their mobility has been compromised (Colombo, Marchesin, Vergani, Boccafogli & Verni, 2011). Some injuries require the patient to wear supporting devices and others limit them to a wheelchair (Yuan, Wang, Zhu, & Wang, 2014; Zheng & Shen, 2013). For the latter case, patients have few options to improve their conditions (Molero-Sánchez *et al*., 2015).

The first line of help for these diagnoses is prosthesis (Colombo *et al*., 2011; Wang, Yuan, Zhu & Wang, 2015). At first, or prosthesis was a solution to physical sequels (Sinitski *et al*., 2012) as patients covered the inexistence of a limb. Other types of prosthesis help the patient recover part of their lost mobility (Au *et al*., 2015; Bellman, Holgate & Sugar, 2008; Casallas, Garzón & Luengas, 2011; Chen & Wang, 2015).

Au, Herr, Weber & Martínez-Villalpando (2007); Mancinelli *et al*. (2011); Lemoyne, Mastroianni, Hessel & Nishikawa (2015) define prosthesis as help devices for the people under disability conditions, configured as a set of a mechanic, electro mechanic, orthotic and prosthetic pieces. Prosthesis design is carried out from pre-amputation, amputation and post amputation analysis (Ministerio de Salud de Colombia, 2015), thus achieving design suited to the physical and personal conditions of each (Dillon & Fatone, 2013; Murdoch, 1967; Rubiano, 2012).

The mechanical principles of each limb are studied for design, in order to obtain an approximate model of the biomechanics of the limb to be replaced with the prosthesis (Au *et al*., 2015; Casallas *et al*., 2011; Cherelle, Grosu, Matthys, Vanderborght & Lefeber, 2014; Huang, Wensman & Ferris, 2016; Shultz, Lawson &Goldfarb, 2016; Sinitski *et al*., 2012; Yuan *et al*., 2014).

The approximate model of the limb is a mathematical representation, which allows characterizing the acting forces and the position of each part of the limb (Wang, Yuan, Zhu & Wang, 2014; Yuan, Wang & Wang, 2015; Zheng & Shen, 2013). This information is used in the design of a prosthesis with an approximate functionality, degree of Liberty and forces exerted on the limb (Adebayo *et al*., 2011; Au *et al*., 2015; Bellman *et al*., 2008; Casallas *et al*., 2011; Cherelle *et al*., 2014; Sagawa *et al*., 2011).

The main inconvenience with mechanical and electro mechanical designs of the prosthesis is centered on how to obtain a device that behaves similarly to muscles (Zheng & Shen, 2013). Muscles behave as both active and passive elements within the model of the limb (Bravo & Rengifo, 2014). In one moment, they exert lever force to produce the movement of the limb and in a second moment, they absorb impact or excess energy produced by other muscles (Lee Childers, Prilutsky & Gregor, 2014; Zheng & Shen, 2013).

Simulating muscle behavior is essential for the design of the more functional prosthesis, which offers the patient a more natural experience (Bravo and Rengifo, 2014; Silverman & Neptune, 2012; Zheng & Shen, 2013). Achieving behavior similar to that of the muscles requires the use of several mechanic elements combined (Mancinelli *et al*., 2011; Shultz *et al*., 2016; Yuan *et al*., 2015, Zheng & Shen, 2013); however, the system is subjected to effects proper to the mechanical elements used, thus altering the dynamics intended to be simulated (Bravo & Rengifo, 2014; Fang, Jia, Wang & Suo, 2009; Gabriel *et al*., 2008; Mancinelli *et al*., 2011).

Lee *et al*.(2014), Silverman & Neptune (2012), Wang & Brown (2016) state that a mechanical system formed by a spring, and an engine exerting compression force on it, as well as contention of spring elongation simulate the behavior of a muscle (Au *et al*., 2007; Brasil & Rosa, 2011; Chen, Wang, & Wang, 2015; Cherelle *et al*., 2014; Hill & Herr, 2013; Huang *et al*., 2016). More accurate studies on the biomechanics of certain limbs have proven that with the system previously described, it is possible to fully model them and even producing functional prototypes of prosthesis (Chen *et al*., 2015; Chen & Wang, 2015; Cherelle *et al*., 2014; Cherelle, Matthys, Grosu, Vanderborght, & Lefeber, 2012; Eilenberg, Geyer & Herr, 2010).

Linear pneumatic cylinders are another alternative to simulate muscle behavior (Zheng & Shen, 2013). In their internal structure, cylinders have a spring that is compressed using a piston and pressurized air. The spring becomes an actuator which incorporates cylinder insertion within the pneumatic muscle, thus generating piston displacement, resembling the active part of the muscles in a lower limb (Zheng & Shen, 2013).

A clear example of the application of this mechanism is provided by Masum, Bhaumik & Ray (2014); Yuan, Zhu, Wang & Wang (2011), in the development of the prototype for a prosthesis for cases of transtibial amputation. They use the mechanical system to simulate the effect of compensation forces necessary for the patient to maintain balance as s/he moves (Adebayo *et al*., 2011; Arotaritei, Turnea, Filep, Ilea & Rotariu, 2015; Casallas *et al*., 2011; Chen & Wang, 2015; Wang *et al*., 2015). The prototype is able to absorb the force generated when the prosthesis comes into contact with a surface, avoiding bounce effects, and it also compensates the angle between the basis of the prosthesis and the coupling axis, thus allowing the user to walk on steep surfaces (Bravo and Rengifo, 2014; Morgenroth *et al*., 2011; Yuan *et al*., 2014; Zheng & Wang, 2016; Zhu, Wang, Li, Sun & She, 2015; Zhu, Wang & Wang, 2014).

In the prototype by Yuan *et al*.(2011) a digital control system is implemented to calculate the magnitude of the force necessary for the patient to maintain balance from its own weight; the angle between the components of the prosthesis regarding the ground and the part of the prosthesis coming into contact with the floor (Adebayo *et al*., 2011; Bellman *et al*., 2008; Cherelle *et al*., 2014, 2012; Yuan *et al*., 2011; Yuan *et al*., 2014; Zheng & Wang, 2016; Zhu *et al*., 2015, 2014). There is only one parameter left to the patient, the other ones are calculated by sensors located in different parts of the prosthesis. With these characteristics, it is possible to obtain a prosthesis that compensates changes in patients' steps (Cherelle *et al*., 2014, Yuan *et al*., 2015).

Previously cited prototypes only use the stages of the walking sequence to control actuators on the prosthesis (Shultz *et al*., 2015; Wang *et al*., 2014), requiring constant adjustments in each design, and their functionality is limited to a single use (Cherelle *et al*., 2014). The prosthesis is adjusted to walk or run, not both options, by changing the timing in the walking sequence (Wang *et al*., 2014).

The use of electromyography will enable the development of prostheses which adjust to the patient's walking pace without previous adjustment required (Chen, Wang & Wang, 2014; Chen *et al*., 2015; Kannape, Member, Herr & Member, 2014). Placement of electrodes on certain muscles of the limb will deliver useful signals to determine the natural position of the limb (Chen *et al*., 2014, 2015; Kannape *et al*., 2014). This response from the limb to changes in the muscles will help patients to adapt to the prosthesis (Kannape *et al*., 2014).

Prosthesis with these adaptation characteristics can be used in different patients by only adjusting the parameters of weight and physical length of the prosthesis (Ferris, Aldridge, Rábago, & Wilken, 2012; Laferrier & Gailey, 2010; Zhou *et al*., 2015). Other prosthesis technologies require personal study of each patient, which consumes a considerable amount of time and does not guarantee patient's comfort with the result (Ferris *et al*., 2012; Laferrier & Gailey, 2010; Molero-Sánchez *et al*., 2015; Zhou *et al*., 2015).

Patients' rejection of the use of prosthesis propels the study of new techniques to make their use more natural (Ferris *et al*., 2012; Laferrier & Gailey, 2010; Rusaw & Ramstrand, 2010; Sanders, Zachariah, Baker, Greve & Clinton, 2000; Zhou *et al*., 2015). Changes in design, type of actuators, sensors and control techniques enable the improvement of commodities and functionality of prosthesis (Cherelle *et al*., 2014, 2012; Shultz *et al*., 2016; Zheng & Shen, 2013).

Follow-up on the prosthesis using the principles described by Masum *et al*., (2014); Yuan *et al*., (2011), have achieved several military-use versions, thanks to their resistance, and modular structure (Fergason, Keeling & Bluman, 2010). The modular approach of the prosthesis allows the swift replacement of defective parts without jeopardizing the patient's health every time reparations are required.

On the other side, glancing at the local, Latin-American perspective, specifically in Colombia, several developments have been achieved in the field of orthopedic technology (Hernández-Castillo, Álvarez-Camacho & Sánchez-Arévalo, 2013; Valladares, 2015), although many of them are patented, but not under production. Developments have been relevant, since they provided conditioning of costume-made prosthesis, component conditioning and, in turn, applied research (Estupiñán, Garzón & Suárez, 2007).

This type of development has been achieved from different fields of action; meaning, advances in applied technology are occurring due to research in universities with costume-made laboratories. A good example is the ankle movement march analysis laboratory, where foot movement can be recreated (Borrás, Gómez Serrano & Pinto, 2011; Raschke *et al*., 2015). This laboratory displays the mechanical and mathematical process of said movement, all the way to the design of a prosthesis. Another example (Díaz & Cely, 2009) consists of a transtibial prosthesis, based on a CAT scan and validating design, through the method of analysis by finite elements. It is worth noting the use of this technique for prosthesis design. In 2015, Universidad San Buenaventura (Romero, 2012) designed and built a transtibial prosthesis, which takes electrical signals from the muscles and generates movement through it, using a control technique for motion compensation.

Discussion

Along with the information analysis, the different variables surrounding prosthesis use have been observed. Having said that, these variables increase and grow to a higher number of variables if we change the height and condition of the amputation. Therefore, and considering the information reviewed, we can provide the corresponding technical recommendations for the implementation of the prosthesis to be used in case of amputation. Technical parameters are as follow:

Technical or engineering parameters

- Patient's weight, height, and biotype.
- The prosthesis must be similar in weight and length to the original limb.
- The system must offer great power and torque output during push.
- The system must be able to change rigidity.
- The prosthesis must be able to control articulation in the impulse phase.
- The Prosthesis must be impact resistant to avoid damage.
- The Prosthesis mustgeneratea low energetic expense,sinceit is strictly linked to battery use.

Materials

- The material used on prosthesis depends on the type of physical activity of the patient, but it is directly connected to his/her economic condition, since, depending on the level of resistance and low weight, the type of components may have a higher cost.
- Another important aspect of material management is life span of the components since all these elements have pieces that wear out. Depending on the selection of components vs material characterization, it is possible obtaining a greater cost-weight benefit.
- Currently, ultralight materials are preferred, along with morphology similar to that of a normal leg, so that a patient with lower-limb disability is not excluded from practicing any sport or everyday activity and, on the other hand, his/her disability may go unnoticed by the rest of the community.

Psychosocial parameters

Although the ideal purpose of a prosthesis is reincorporating patients to their old social environment, with the same characteristics prior to amputation of lower limb, it becomes necessary, through different classes of rehabilitation and therapy, to minimize the impact of the missing limb, since the patient may be prone to future behavior, such as:

- Depression.
- Social dependence for routine activities.
- Social exclusion.

All these factors influence and are immersed in the proper treatment and rehabilitation to be provided for a patient.

Conclusions

- As the patient's degree of disability increases, along with the degree of liberty of the prosthetic component, the complexity index of the challenge increases proportionally, as kinetic and cinematic control vary accordingly.
- In order to implement an appropriate prosthetic component, which functioning depends on the acquisition and posterior control of electromyographic signals of the stump, experimental results in such practice must be excellent, as they are directly linked to the efficiency of the component as well as proper transmission of movement to the prosthetic device.
- Information analysis shows different transmission mechanisms, but the one reflecting the highest degree of efficiency and performance is the device composed by a ball screw, which has the main characteristic of increasing lineal displacement at very low speed and, surprisingly, with a minimum energetic consumption, thus making the machine easy to elaborate in a compact, lower-consumption manner.
- For proper implementation of the prosthetic component, the relation between the stump and the socket must generate minimum pressure, since it produces a sense of stability and confidence on the patient during the march.

References

Adebayo, O., George, L., Marchand, M., Marrion, J., Gielo-Perczak, K., Higgins, L. & Hoffman, A.

(2011). Design of a new prosthetic alignment adaptor with quantitative alignment and height adjustment. *Bioengineering Conference (NEBEC), 2011 IEEE 37th Annual Northeast*, 1-2. doi: https://doi.org/10.1109/NEBC.2011.5778538

Álvarez, R. J. & Ospina, N. J. (2013). Reparación integral a las víctimas de MAP, MUSE, AEI. Recuperado de http://repository.unimilitar.edu.co/bitstream/10654/3669/2/AlvarezMarquezRafaelJesus2011.pdf

Arotaritei, D., Turnea, M., Filep, R., Ilea, M. and Rotariu, M. (2015). Analyze of Liner Influence in Transtibial Prosthetic taking into account Tribological Aspects. *Advanced Topics in Electrical Engineering (ATEE), 2015 9th International Symposium on* (pp. 299-302). doi: https://doi.org/10.1109/ATEE.2015.7133784

Au, S. K., Herr, H., Weber, J. & Martínez-Villalpando, E. C. (2007). Powered ankle-foot prosthesis for the improvement of amputee ambulation. *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*, 3020–3026. doi: https://doi.org/10.1109/IEMBS.2007.4352965

Au, S. K., Weber, J., Herr, H., Versluys, R., Desomer, A., Lenaerts, G. & Gopura, R.A.R.C.. (2015). System Identification of Human Joint Dynamics. *Rehabilitation Robotics (ICORR), 2015 IEEE International Conference*, *18*(1), 55–87.

Bellman, R. D., Holgate, M. A. & Sugar, T. G. (2008). SPARKy 3: Design of an active robotic ankle prosthesis with two actuated degrees of freedom using regenerative kinetics. *Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. 2nd IEEE RAS & EMBS International Conference*, 511-516. doi: https://doi.org/10.1109/BIOROB.2008.4762887

Borrás, C., Gómez, C. & Pinto, W. (2011) (s.f.). *Estudio, diseño y construcción biomecánica de un emulador de tobillo articulado para prótesis de miembro inferior.* Recuperado de http://www.xixcnim.uji.es/CDActas/Documentos/ComunicacionesOrales/01-21.pdf

Brasil, L. M. & Rosa, S. F. (2011). Desenvolvimento de Prótese Ativa para Amputados Transtibiais Development of an Active Prosthesis for Transtibial Amputees, *Health Care Exchanges (PAHCE), 2011 Pan American* (pp. 223-224). IEEE.

Bravo, A. M. & Rengifo, F. R. (2014). Modelo biomecánico de una prótesis de pierna. *RIAI - Revista Iberoamericana de Automática e Informática Industrial, 11*(4), 417–425. doi: https://doi.org/10.1016/j.riai.2014.08.003

Casallas, E. C., Garzón, E. Y. & Luengas, L. A. (2011). Modeling a transtibial prosthesis. *Medicine and Education (ITME), 2011 International Symposium 1*, 708-712. IEEE. doi https://doi.org/10.1109/ITiME.2011.6130758

Chen, B. & Wang, Q. (2015). Combining human volitional control with intrinsic controller on robotic prosthesis: A case study on adaptive slope walking. *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*, 4777–4780. doi: https://doi.org/10.1109/EMBC.2015.7319462

Chen, B., Wang, Q. & Wang, L. (2014). Promise of using surface EMG signals to volitionally control ankle joint position for powered transtibial prostheses. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2545–2548.

Chen, B., Wang, Q. & Wang, L. (2015). Adaptive slope walking with a robotic transtibial prosthesis based on volitional emg control. *IEEE/ASME Transactions on Mechatronics, 20*(5), 2146–2157. doi: https://doi.org/10.1109/TMECH.2014.2365877

Cherelle, P., Grosu, V., Matthys, A., Vanderborght, B. and Lefeber, D. (2014). Design and validation of the ankle mimicking prosthetic (AMP-) Foot 2.0. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 22*(1), 138–148. doi: https://doi.org/10.1109/TNSRE.2013.2282416

Cherelle, P., Matthys, A., Grosu, V., Vanderborght, B. & Lefeber, D. (2012). The AMP-Foot 2.0:

Mimicking intact ankle behavior with a powered transtibial prosthesis. *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference*, 544-549.

Colombo, C., Marchesin, E. G., Vergani, L., Boccafogli, E. & Verni, G. (2011). Study of an ankle prosthesis for children: Adaptation of ISO 10328 and experimental tests. *Procedia Engineering, 10*, 3510–3517. doi: https://doi.org/10.1016/j.proeng.2011.04.578

Comisión Internacional de la Cruz Roja -CICR- (2016). *Minas terrestres: legado de la guerra.* Recuperado de https://www.icrc.org/es/minas-terrestres-legado-de-la-guerra

Contraloría General de la República. (2012). *Primer informe de seguimiento y monitoreo de los entes de control a la Ley 1448 de 2011 de víctimas y restitución de tierras.* Bogotá: CGR.

Díaz, A. & Cely, M. M. (2009). *Tomografía computarizada en 3D para análisis y diseño de prótesis transtibial.* Recuperado de http://repositorio.uac.edu.co/bitstream/handle/11619/1362/Tomograf%C3%ADa%20computarizada%20en%203D.pdf?sequence=1&isAllowed=y

Dillon, M. P. & Fatone, S. (2013). Deliberations about the functional benefits and complications of partial foot amputation: do we pay heed to the purported benefits at the expense of minimizing complications? *Archives of Physical Medicine and Rehabilitation*, *94*(8), 1429-1435. doi: https://doi.org/10.1016/j.apmr.2013.03.023

Eilenberg, M. F., Geyer, H. & Herr, H. (2010). Control of a powered ankle-foot prosthesis based on a neuromuscular model. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 18*(2), 164–173. doi: https://doi.org/10.1109/TNSRE.2009.2039620

Estupiñán, C. A., Carrillo, A. & Suárez, H. (2007). Diseño y fabricación de una prótesis de pie de respuesta dinámica en fibra de carbono. *IV Latin American Congress on Biomedical Engineering 2007, Bioengineering Solutions for Latin America Health*, 1233-1237. Springer, Berlin, Heidelberg. doi: https://doi.org/10.1007/978-3-540-74471-9_286

Fang, L. D., Jia, X. H., Wang, R. & Suo, S. (2009). Simulation of the Ligament Forces Affected by Prosthetic Alignment in a Trans-tibial Amputee Case Study. *Medical Engineering and Physics, 31*(7), 793–798. doi: https://doi.org/10.1016/j.medengphy.2009.02.010

Fergason, J., Keeling, J. J. & Bluman, E. M. (2010). Recent Advances in Lower Extremity Amputations and Prosthetics for the Combat Injured Patient. *Foot and Ankle Clinics, 15*(1), 151–174. doi: https://doi.org/10.1016/j.fcl.2009.10.001

Ferris, A. E., Aldridge, J. M., Rábago, C. A. & Wilken, J. M. (2012). Evaluation of a powered ankle-foot prosthetic system during walking. *Archives of Physical Medicine and Rehabilitation, 93*(11), 1911–1918. doi: https://doi.org/10.1016/j.apmr.2012.06.009

Gabriel, R. C., Abrantes, J., Granata, K., Bulas-Cruz, J., Melo-Pinto, P. & Filipe, V. (2008). Dynamic joint stiffness of the ankle during walking: Gender-related differences. *Physical Therapy in Sport*, *9*(1), 16–24. doi: https://doi.org/10.1016/j.ptsp.2007.08.002

Hernández-Castillo, A., Álvarez-Camacho, M., & Sánchez-Arévalo, FM. (2013). Protocolo para el análisis funcional de prótesis para pacientes con amputación parcial de pie. *Revista Mexicana de Ingeniería Biomédica, 34*(1), 97-107.

Hill, D. & Herr, H. (2013). Effects of a powered ankle-foot prosthesis on kinetic loading of the contralateral limb: A case series. *Rehabilitation Robotics (ICORR), 2013 IEEE International Conference,* 1-6. doi: https://doi.org/10.1109/ICORR.2013.6650375

Huang, S., Wensman, J. & Ferris, D. (2016). Locomotor Adaptation by Transtibial Amputees Walking with an Experimental Powered Prosthesis Under Continuous Myoelectric

Control. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *24*(5), 573-581. doi: https://doi.org/10.1109/TNSRE.2015.2441061

Kannape, O. A., Member, I., Herr, H. M., & Member, I. (2014). Volitional Control of Ankle Plantar Flexion in a Powered Transtibial Prosthesis during Stair-Ambulation. *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*, 1662-1665. doi: https://doi.org/10.1109/EMBC.2014.6943925

Laferrier, J. Z. & Gailey, R. (2010). Advances in Lower-limb Prosthetic Technology. *Physical Medicine and Rehabilitation Clinics of North America*, *21*(1), 87–110. doi: https://doi.org/10.1016/j.pmr.2009.08.003

Lee Childers, W., Prilutsky, B. I. & Gregor, R. J. (2014). Motor adaptation to prosthetic cycling in people with trans-tibial amputation. *Journal of Biomechanics*, *47*(10), 2306–2313. doi: https://doi.org/10.1016/j.jbiomech.2014.04.037

Lemoyne, R., Mastroianni, T., Hessel, A. & Nishikawa, K. (2015, Novem.). Implementation of machine learning for classifying prosthesis type through conventional gait analysis. *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*, 202-205.

Lewis, R. A. (2008, November 11). Miembro fantasma. In D. Pravikoff (Ed.) *CINAHL Nursing Guide*. Glendale, California: Cinahl Information Systems.

Mancinelli, C., Patritti, B. L., Tropea, P., Greenwald, R. M., Casler, R., Herr, H. & Bonato, P. (2011). Comparing a passive-elastic and a powered prosthesis in transtibial amputees. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, 8255-8258. doi: https://doi.org/10.1109/IEMBS.2011.6092035

Masum, H., Bhaumik, S. & Ray, R. (2014). Conceptual Design of a Powered Ankle-foot Prosthesis for Walking with Inversion and Eversion. *Procedia Technology*, *14*, 228–235. doi: https://doi.org/10.1016/j.protcy.2014.08.030

Ministerio de Postconflicto Derechos Humanos y Seguridad (2016). *Asistencia a víctimas*. Bogotá: Dirección para la Atención Integral contra Minas Antipersona, Ministerio de Postconflicto Derechos Humanos y Seguridad.

Ministerio de Salud de Colombia 2015). *Guía de práctica clínica*. Bogotá: MS.

Molero-Sánchez, A., Molina-Rueda, F., Alguacil-Diego, I. M., Cano-de la Cuerda, R., & Miangolarra-Page, J. C. (2015). Comparison of Stability Limits in Men With Traumatic Transtibial Amputation and a Nonamputee Control Group. *PM&R*, *7*(2), 123–129. doi: https://doi.org/10.1016/j.pmrj.2014.08.953

Morgenroth, D. C., Segal, A. D., Zelik, K. E., Czerniecki, J. M., Klute, G. K., Adamczyk, P. G. & Kuo, A. D. (2011). The effect of prosthetic foot push-off on mechanical loading associated with knee osteoarthritis in lower extremity amputees. *Gait & Posture*, *34*(4), 502–507. doi: https://doi.org/10.1016/j.gaitpost.2011.07.001

Murdoch, G. (1967). Levels of amputation and limiting factors. *Annals of the Royal College of Surgeons of England*, *40*(4), 204.

Raschke, U., Orendurff, S., Mattie, M., Kenyon, J.L., Jones, D. E. A., Moe, D., & Kobayashi, T. (2015). Biomechanical characteristics, patient preference and activity level with different prosthetic feet: A randomized double blind trial with laboratory and community testing. *Journal of Biomechanics*, *48*(1), 146–152. doi: https://doi.org/10.1016/j.jbiomech.2014.10.002

Reyes, C. (2011). La amenaza de las armas pequeñas, ligeras y explosivos ALP-ME. Borradores de Investigación: *Serie Documentos Ciencia Política y Gobierno y de Relaciones Internacionales*, (1).

Romero, M. A. (2012). *Diseño y construcción de una órtesis de rodilla, destinada a la rehabilitación automatizada de la extremidad* *inferior*. Recuperado de dspace.ups.edu.ec/bitstream/123456789/2814/1/UPS-CT002463.pdf

Rubiano, L. F. (2012). *Líderes de la comunidad como agentes rehabilitadores "yo, incluso"*. Recuperado de http://intellectum.unisabana.edu.co/handle/10818/3487

Rusaw, D. & Ramstrand, N. (2010). Sagittal plane position of the functional joint centre of prosthetic foot/ankle mechanisms. *Clinical Biomechanics*, *25*(7), 713–720. doi: https://doi.org/10.1016/j.clinbiomech.2010.04.005

Sagawa, Y., Turcot, K., Armand, S., Thevenon, A., Vuillerme, N. & Watelain, E. (2011). Biomechanics and physiological parameters during gait in lower-limb amputees: A systematic review. *Gait & Posture*, *33*(4), 511–526. doi: https://doi.org/10.1016/j.gaitpost.2011.02.003

Sanders, J. E., Zachariah, S. G., Baker, A. B., Greve, J. M. & Clinton, C. (2000). Effects of changes in cadence, prosthetic componentry, and time on interface pressures and shear stresses of three trans-tibial amputees. *Clinical Biomechanics*, *15*(9), 684–694. doi: https://doi.org/10.1016/S0268-0033(00)00026-7

Shultz, A. H., Lawson, B. E., & Goldfarb, M. (2016). Variable cadence walking and ground adaptive standing with a powered ankle prosthesis. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *24*(4), 495-505. doi: https://doi.org/10.1109/TNSRE.2015.2428196

Silverman, A. K. & Neptune, R. R. (2012). Muscle and prosthesis contributions to amputee walking mechanics: A modeling study. *Journal of Biomechanics*, *45*(13), 2271–2278. doi: https://doi.org/10.1016/j.jbiomech.2012.06.008

Sinitski, E. H., Hansen, A. H. & Wilken, J. M. (2012). Biomechanics of the ankle-foot system during stair ambulation: Implications for design of advanced ankle-foot prostheses. *Journal of Biomechanics*, *45*(3), 588–594. doi: https://doi.org/10.1016/j.jbiomech.2011.11.007

Valladares, D. L. (2015). *Diseño y modelado virtual del mecanismo policéntrico de una prótesis de rodilla.* Recuperado de http://www.dspace.espol.edu.ec/xmlui/handle/123456789/31033?show=full

Wang, H. & Brown, S. (2016, March). The effects of total ankle replacement on ankle joint mechanics during walking. *Journal of Sport and Health Science*, 1–6.

Wang, Q., Yuan, K., Zhu, J. & Wang, L. (2014). Finite-state control of a robotic transtibial prosthesis with motor-driven nonlinear damping behaviors for level ground walking. *Advanced motion control (AMC), 2014 IEEE 13th international workshop*, 155-160. doi: https://doi.org/10.1109/AMC.2014.6823274

Wang, Q., Yuan, K., Zhu, J., & Wang, L. (2015). Walk the walk: A lightweight active transtibial prosthesis. *IEEE Robotics & Automation Magazine*, *22*(4), 80-89. doi: https://doi.org/10.1109/MRA.2015.2408791

Yuan, K., Wang, Q. & Wang, L. (2015). Fuzzy-logic-based terrain identification with multisensor fusion for transtibial amputees. *IEEE/ASME Transactions on Mechatronics*, *20*(2), 618–630. doi: https://doi.org/10.1109/TMECH.2014.2309708

Yuan, K., Wang, Q., Zhu, J., & Wang, L. (2014, June). Motion control of a robotic transtibial prosthesis during transitions between level ground and stairs. I*Control Conference (ECC), IEEE, 2014 European*, 2040-2045.

Yuan, K., Zhu, J., Wang, Q. & Wang, L. (2011). Finite-state control of powered below-knee prosthesis with ankle and toe. *IFAC Proceedings Volumes*, *44*(1), 2865-2870. doi: https://doi.org/10.3182/20110828-6-IT-1002.03064

Zheng, E. & Wang, Q. (2016). Noncontact Capacitive Sensing Based Locomotion Transition Recognition for Amputees with Robotic Transtibial Prostheses. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 4320(c), 1–1.*

Zheng, H., & Shen, X. (2013, June). Sleeve muscle actuator and its application in transtibial prostheses. *Rehabilitation Robotics (ICORR), 2013 IEEE International Conference*, 1-5. doi: https://doi.org/10.1109/ICORR.2013.6650444

Zhou, Z., Zhou, Y., Wang, N., Gao, F., Wei, K. & Wang, Q. (2015). A proprioceptive neuromuscular facilitation integrated robotic ankle-foot system for post stroke rehabilitation. *Robotics and Autonomous Systems, 73*, 111–122. doi: https://doi.org/10.1016/j.robot.2014.09.023

Zhu, J., Wang, Q. & Wang, L. (2014). On the design of a powered transtibial prosthesis with stiffness adaptable ankle and toe joints. *IEEE Transactions on Industrial Electronics*, *61*(9), 4797–4807. doi: https://doi.org/10.1109/TIE.2013.2293691

Zhu, J., Wang, Q., Li, X., Sun, W. & She, H. (2015). Importance of Series Elasticity in A Powered Transtibial Prosthesis with Ankle and Toe Joints, *Robotics and Biomimetics (ROBIO), 2015 IEEE International Conference*, 541–546. Retrieved from www2.coe.pku.edu.cn/subpaget.asp?id=472