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Evaluación del rediseño de una unión de prótesis utilizando análisis de elementos finitos

Evaluating the Redesign of a Prosthesis Joint using Finite Element Analysis

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Resumen. El pie de Jaipur es un tipo de prótesis ideal para amputados en países en desarrollo porque está hecho de materiales económicos y se centra en la asequibilidad y la funcionalidad. Algunos estudios han examinado las áreas del pie de Jaipur que presentan mayor daño, pero no la unión entre el tubo de polietileno de alta densidad y el pie protésico. El propósito de este trabajo es evaluar diferentes diseños para la unión entre el Pie de Jaipur y el tubo de polietileno de alta densidad de esta prótesis exoesquelética mediante análisis de elementos finitos. La geometría del pie de Jaipur se modeló utilizando escaneo 3D para la forma externa y bocetos para la composición interna del pie. Se realizaron múltiples simulaciones utilizando elementos finitos, así como un estudio lineal para probar la convergencia de la malla y un estudio no lineal que reprodujo una carga variable simulando las condiciones durante la marcha. Los modelos de unión que incluyen pernos múltiples presentaron fallas por esfuerzos máximos sobre el bloque de madera y desplazamientos máximos. Por el contrario, el modelo con un solo perno no falló y el modelo adhesivo resultó ser la mejor solución a la unión entre los componentes de la prótesis. La mejor opción de unión es el adhesivo epóxico ya que, al estar más uniformemente distribuidas las cargas sobre la superficie de contacto entre el polietileno de alta densidad y el pie protésico, las tensiones se concentran menos. Por lo tanto, se puede controlar más eficientemente el daño en esa zona, alargando así la vida útil de la prótesis y mejorando sus características.

Palabras Clave. Pie de Jaipur; prótesis de bajo costo; análisis de elementos finitos, escaneo 3D; coyuntura de prótesis.

Abstract. The Jaipur Foot is a type of prosthesis ideally suited for amputees in developing countries because it is made of inexpensive materials and focused on affordability and functionality. Studies have examined the areas of the Jaipur foot that present the greatest damage, but not the juncture between the high density polyethylene tube and the prosthetic foot. The purpose of this paper is to evaluate different designs for the juncture between the Jaipur Foot and the high density polyethylene tube of this exoskeletal prosthesis by means of finite element analysis. The geometry of the Jaipur foot was modeled using 3D scanning for the external shape and sketching for the internal composition of the foot. Multiple simulations were conducted using finite elements, as well as a linear study to prove the convergence of the mesh and a nonlinear study that reproduced a variable load simulating the conditions during gait. The junction models that include multiple bolts presented failures due to maximum stresses on the wooden block and maximum displacements. On the contrary, the model with a single bolt did not fail, and the adhesive model turned out to be the best solution to the juncture between the prosthesis components. The best juncture option is epoxy adhesive because, as loads are more evenly distributed over the contact surface between the high density polyethylene and the prosthetic foot, the stresses are less concentrated. Therefore, the damage to that area can be more efficiently controlled, thus extending the lifetime of the prosthesis and improving its characteristics.

Keywords. Jaipur Foot; Low-Cost Prosthetics; Finite Element Analysis, 3D Scanning; Prosthesis Juncture.

I. Introducción

The Jaipur Foot is a rubber-based prosthetic leg for people with amputations below-knee. Even though inferior in many ways to the variants of different composites like Carbon and Glass Fiber, its diverse applicability and cost efficiency make it an adequate choice for prosthesis. Materials that are used at the foot-end are usually waterproof and mimic a real foot. These features help amputees using the foot assimilate more easily in a semi-urban or rural setup in the Indian subcontinent and other developing countries [1].

The Jaipur foot has never been patented or standardized. As a result, there has been significant variation in the quality of the feet around the world and their fitting. As a consequence of this, the foot is commonly used in low-income countries and war zones as a low-cost alternative to conventional prosthetics. It was commonly used during the war in Afghanistan to help treat land mine victims and people with congenital diseases at the lower limbs [2] and over 1.3 million amputees have been fitted with Jaipur foot/limb in India and in 26 other countries of Asia, Africa and Latin America [3]. Usually, two configurations of lower limb prosthesis with a Jaipur foot are used. A Jaipur foot attached to a metal pylon with a pyramid adapter or to an HDPE tube with screws [4].

The non-profit organization Mahavir Kmina Artificial Limb Center uses this last configuration. They design and adapt exoskeletal prostheses using Jaipur Feet and a High-Density Polyethylene (HDPE) pipe. Such foot is made of blocks of different materials: a microcellular rubber compound, cosmetic rubber, cushion rubber, and tread rubber [5].

Several studies have approached the Jaipur foot from different perspectives. Krishnamoorthy and Karthikeyan [6] have used this prosthetic foot to determine the pressure, weight, position, and movement of the remaining appendage as for the prosthetic attachment, and have create sensors and actuators-based prostheses, which plays an important role in the prosthetic socket fabrication, modification and optimal fit.

Instead, Cardenas et al. [7] have identified the effect of the transfemoral alignment prosthesis on ground reaction forces and thermal images of the residual limb using Jaipur foot. They found no significant changes in the average temperature of residual limbs and the transfemoral prosthesis misalignment produced an irregular heat diffusion on the anterior, posterior, and lateral sides of the stump contour. A similar work using thermography was reported by Olaya and Viloria [8] trying to predict the failure of different prosthesis configurations through the temperature profiles in the union zone with the prosthetic foot.

Also, Wolynski et al. [9] used finite element analysis to parametrically simulate the Jaipur Foot. They determined potential improvements to the prosthesis design because the found that the interface between microcellular rubber blocks is a concern zone for failure, which agrees with epidemiological studies of the prosthesis.

Some studies have specifically addressed the wear in the structure of this type of prosthetic foot, especially in the area of the heel and the midfoot [10]–[13], but not at the juncture between the HDPE pipe and the foot. Frequently, said juncture presents failures for users of this type of technology, which implies technical reworks or an accelerated deterioration that is reflected in a higher production cost of the prosthetic elements for the organization that donates them. In recent years, several attempts to redesign the Jaipur Foot have been made. However, the high cost of the technological solutions and the lack of technical follow-up on the proposed redesigns have made it impossible to implement an optimal and definitive solution to the juncture.

Finite Element Analysis (FEA) overcomes those problems by reducing a complex geometry to a finite number of elements with simple geometries [14]. It also enables users to change the properties of materials and redesign the juncture area in order to obtain information about the stresses, deformations, displacements, and safety factors of each juncture, without generating additional costs and considering the manufacturing process of the foundation that produces the prostheses.

The purpose of this study is to evaluate different designs for the juncture between the Jaipur Foot to an HDPE pipe using 3D scanning and advanced modeling, then to apply Finite Element Analysis in order to redesign the orthotic device trying to extend its lifespan and reduce the cases of product returns after the manufacturing processes.

II. Methods

Due to the nature of this problem and its context, unconventional design and simulation tools were used:

A. Modeling

The dimensions of the foot in this study are those of an average Colombian adult beneficiary of the non-profit organization mentioned above. We decided to use a 3D scanning system (i.e., the Geomagic Capture from 3D Systems) to faithfully capture the external geometry of a Jaipur Foot with an accuracy of 60 ţm with respect to the original model (see Figure 1A). The 3D scan directly provided a polygonal mesh in Standard Triangle Language (STL) format using the software Geomagic Design X (GDX), which also enabled us to correct errors in the mesh to make it hermetic (see Figure 1B). Subsequently, smoothing was applied to obtain a more uniform surface, removing physical imperfections in the model (see Figure 1C). Afterward, using the automatic surfacing tool, we performed a specific triangulation of the organic geometries over the mesh, thus generating a more precise CAD model. Said model was directly exported as a solid without operation history into SolidWorks v.2018 software.

Figure 1. Jaipur foot modeling; (A) real foot; (B) scanned foot-STL file; (C) final model-CAD file
Source: Created by the authors

To model the internal composition and produce a more faithful approximation of a real prosthesis, we used photogrammetry, taking a cross-section image of a Jaipur Foot to sketch and measure its inner structures. Once the sketch of the interior of the Jaipur Foot was completed, we used basic 3D modeling techniques to perform Boolean operations and define, in three dimensions, the internal areas of Microcellular Rubber (MCR) and the wooden blocks. To produce a suitable internal geometry, the MCR block of the forefoot area was restructured, making the mesh equidistant 6 mm inward and limited by the plane of the MCR block. For that purpose, it was necessary to use the operations of the GDX mesh, which was a more flexible modeling process and enabled us to create a more complex internal geometry, because the Jaipur Foot does not present symmetries in any plane, which would have made this task easier (see Figure 2).

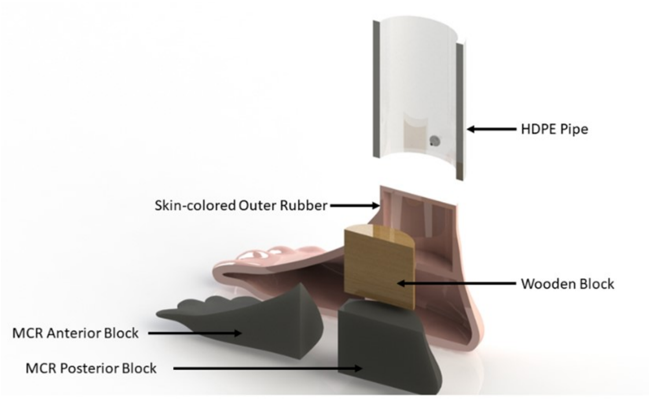

Figure 2. Internal geometry of the Jaipur Foot
Source: Created by the authors

Finally, the HDPE pipe was modeled and assembled with the Jaipur Foot using the Configuration Editor, which enabled us to create multiple variations of the assembly model in a single file. As a result, we designed four different juncture configurations: Two Opposite Screws (TOS), Four Equidistant Screws (FES), Single Self-drilling Bolt (SSB), and Epoxy Adhesive (EAD). The two first configurations (TOS and FES) consist of 8x1 in stainless steel hex head screws; the third one (SSB) is based on a stainless steel bolt with dimensions 6×1.0×60; and the fourth configuration (EAD) uses commercially available epoxy adhesive with a resistance to traction and strain of 3.3 N/mm^2 and 2.1 N/mm^2, respectively, according to the manufacturer (see Figure 3)

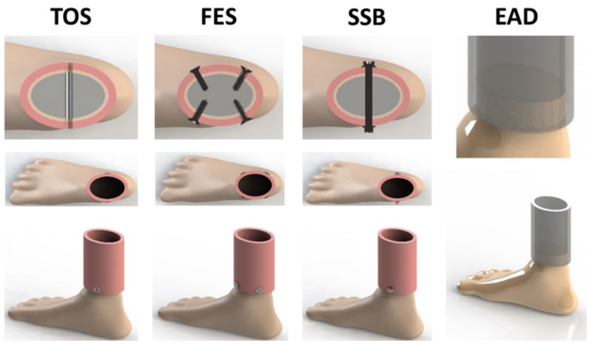

Figure 3. Juncture configurations
Source: Created by the authors

B. Simulation

After the model was optimized, we configured the parameters for the *linear analysis* (by means of Finite Element Analysis) in SolidWorks Simulation 2022 fully licensed academic version [15]. Considering their mechanical properties, the materials used to manufacture the prosthesis were assigned specific characteristics that were simulated based on the software library and taking into account their internal and external areas (which are reported in Table 1). Subsequently, we defined the internal contact conditions or limitations of the hard juncture to simulate the model as a single body. A non-penetration contact condition was applied, so that the contacting regions of the components can slide. Furthermore, we established its border conditions or limitations, restricting the radial and tangential degrees of freedom of the polyethylene body and only allowing axial movements. Likewise, we fixed the upper part of the HDPE pipe and applied a static load, 100 kg, which

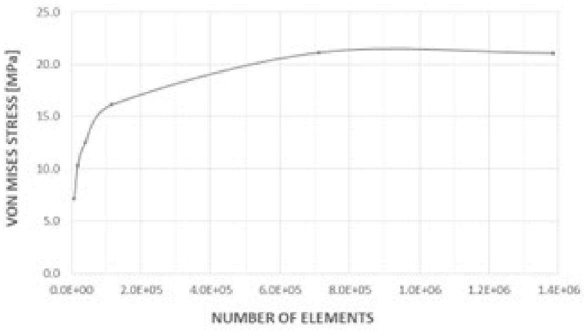

Figure 4. Convergence curve of the mesh
Source: Created by the authors

Table 1. Mechanical properties of the materials in the prosthesis
Source: [16]

Component	**Material**	**Properties**
Pipe (socket)	High Density Polyethylene	Density (ρ): 924 Kg/m^3 Elastic modulus (E): 450 MPa Poisson's ratio: 0.46 Yield strength: 4.00 MPa
Jaipur Foot exterior	Skin-Colored Rubber	Density (ρ): 2530 Kg/m^3 Elastic modulus (E): 1.5 MPa Poisson's ratio: 0.27 Yield strength: 0.63 MPa
Wooden block	Ardu Wood	Density (ρ): 340 Kg/m^3 Elastic modulus (E): 260 MPa Poisson's ratio: 0.08 Yield strength: 3.37 MPa
MCR block	Microcellular Rubber	Density (ρ): 250 Kg/m^3 Elastic modulus (E): 2.17 MPa Poisson's ratio: 0.16 Yield strength: 0.27 MPa

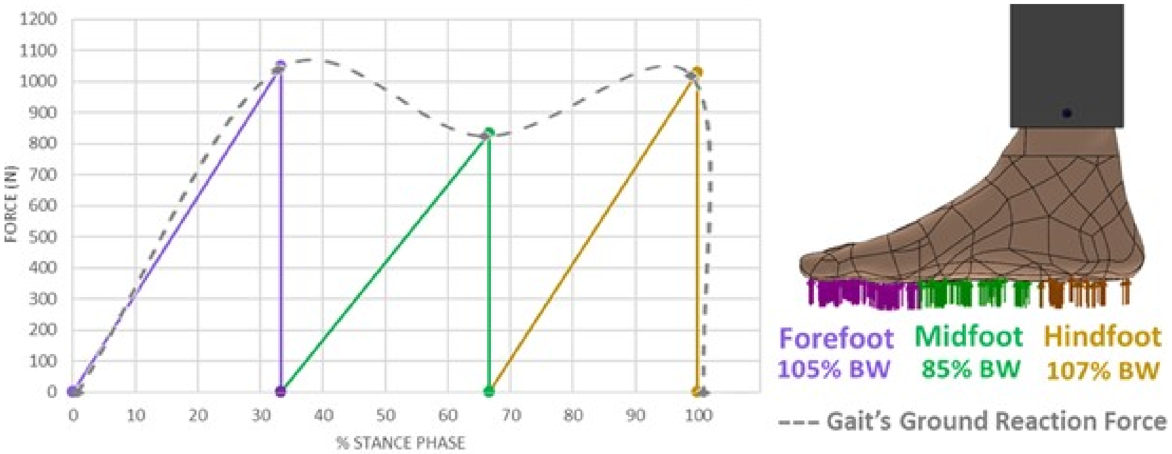

Figure 5. Configuration of dynamic loads
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represent the weight of a patient standing on the foot sole during bipedestation. Said load was initially configured as static to verify the meshing by performing a convergence analysis. As a result, the simulation was optimized by reducing the computational time without affecting the magnitudes of the final result.

Thus, we obtained an ideal configuration for conducting the FEA.

The convergence analysis revealed a progressive increase in stress, which stabilized at a value near 21.2 MPa in the case a medium-sized mesh with a minimum element size of 19.88 mm. However, an optimization was applied based on curvature and a meshing control of 2.5 mm to the areas where stresses concentrated using 20839 second-order tetrahedral elements (see Figure 4).

After the simulation parameters were correctly configured, we adjusted a new nonlinear analysis using the Mooney-Rivlin (M-R) hyperelastic material model, which offers better computational efficiency for the size of the model simulated here and also this model is often used for the characterization of hyperelastic rubber-like materials. Similarly, we redefined a dynamic load that represented the reaction force of the floor during human normal gait, which oscillated around 107%, 85%, and 105% of the bodyweight during the stages of support on the hindfoot, midfoot, and forefoot, respectively [17] (see Figure 5).

III. Results and Discussion

The Von Mises theory is more applicable to ductile materials, the principal stress theory is more applicable to failure of brittle materials. Analyzing the failure mode of the Jaipur parts and the materials used, it was determined that the principal stress would give us a more conservative approach. So, we employed principal stress (P1) as a comparison criterion, in addition to displacements and strains, which were classified by component to facilitate the analysis (see Table 2).

Table 2. Results of the components of each model
Source: Created by the authors

Model	Component	Principal stress (MPa)	Displacement (mm)	Strain
TOS	Pipe (socket)	3.73	1.2×10^3	9.2×10^4
	Jaipur Foot exterior	5.50	104.0	5.9×10^1
	Wooden block	8.04	104.0	2.8×10^2
	MCR block - Forefoot	0.68	98.7	0.2
	MCR block - Hindfoot	1.78	46.3	0.4
FES	Pipe (socket)	6.12	3.0×10^3	2.5×10^3
	Jaipur Foot exterior	6.95	59.5	0.2
	Wooden block	11.68	1.6	3.5×10^2
	MCR block - Forefoot	0.74	56.5	0.1
	MCR block - Hindfoot	0.96	24.2	0.2
SSB	Pipe (socket)	5.84	0.3	1.21×10^2
	Jaipur Foot exterior	5.84	65.5	0.3
	Wooden block	2.46	2.8	1.16×10^2
	MCR block - Forefoot	1.13	62.2	0.1
	MCR block - Hindfoot	1.06	27.5	0.2
EAD	Pipe (socket)	6.67	0.3	1.3×10^2
	Jaipur Foot exterior	3.78	54.5	0.2
	Wooden block	1.89	2.2	9.0×10^3
	MCR block - Forefoot	0.43	51.8	0.1
	MCR block - Hindfoot	0.82	22.4	0.2

In the TOS configuration, the greatest concentration of stresses was found on the wooden block, more specifically on the surface in contact with the screws and the external frontal area of the foot subjected to flexion; the principal stresses there were 8.04 MPa and 5.5 MPa, respectively. The stress on the wooden block was greater than the elastic limit of the material (3.37 MPa); for that reason, when the piece was subjected to the conditions under analysis, it presented a failure in said area. The external part subjected to the flexion reached a maximum displacement of 104 mm.

The same behavior was observed in the FES model, which exhibited a maximum stress on the wooden block of 11.68 MPa and a maximum displacement in the exterior of the foot of 59.5 mm. Thus, we concluded that this juncture would also present failures.

Nevertheless, the SSB model presented an isolated principal stress of 5.84 MPa between the interior of the HDPE pipe and the exterior of the foot (stress concentration) (see Figure 6), in addition to a displacement of 65.5 mm on the exterior of the foot. The bolt did not produce a failure on the wooden block because its principal stress was 2.46 MPa, which means a factor of safety of 1.36 for wood.

Finally, the EAD configuration presented principal stresses of 6.67MPa and 5.13 MPa (stress concentrations) over isolated areas of the pipe, but on the internal surface of the HDPE pipe the stresses remained under 3 MPa. Comparing those values with the manufacturer specifications, we can expect no failures in the pipe. Moreover, this configuration presented the shortest displacement due to foot flexion (54.5 mm).

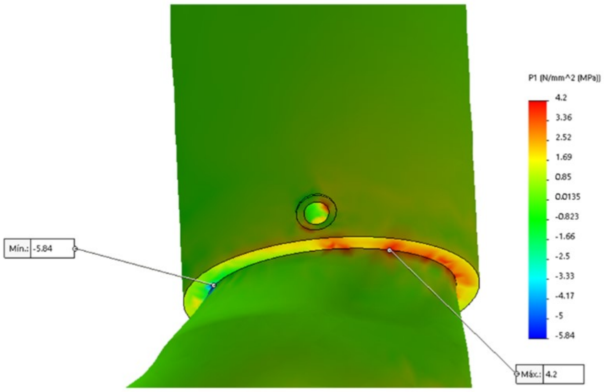

Figure 6. Juncture stress concentration
Source: Created by the authors

The contact area between the pipe and the foot was 3485 mm^2, and a shear force of 667.6 N was applied to it, thus generating a shear stress of 0.19 N/mm^2. Comparing the latter value with the resistance to traction and strain of the adhesive, we can calculate a factor of safety of 10.96 against strain.

The models that used screws presented maximum principal stresses on the wood and the area where the screws were fixed. In those cases, the elastic limit of the material was exceeded; for that reason, we can expect this component of the prosthetic foot to fail. According to J. Steen Jensen et al. [13] this was caused by the capping being too short, preventing a solid grip in the wooden block. The literature reports that the Jaipur Foot presents less displacement in general compared to other similar prosthetic feet [5]. However, the TOS configuration can exhibit greater displacements than its FES counterpart because the movement of the 4 screws is more restricted, even more than in the SSB version. All the juncture models analyzed in this study were subjected to a "high torque generation during the toe-off portion of the gait cycle and subsequent bending of the foot piece" [10], [18].

The configurations with larger contact areas (using a single bolt or adhesive) presented localized stress concentrations over the contact areas between the pipe and the foot. Except for those localized stress values, the stresses calculated on the pipe were below the elastic limit of the HDPE; for that reason, we can expect no failures in those types of junctures.

These results coincide with those obtained in the experimental validation in which the four types of assemblies between a Jaipur foot and a polyethylene tube were evaluated using infrared thermography to find the best mechanical configuration in terms of thermal behavior [19]. In this study, the best foot-ankle assembly used epoxy adhesive because it presented the lowest temperature in the six positions and the lowest thermal index.

IV. Conclusions

The TOS model is the least recommendable option for the juncture area because it produces great displacements and maximum stresses on the wooden component. On the contrary, the most appropriate solution is the EAD model because, as the loads are more uniformly distributed (less localized), less stress concentrations are produced and, therefore, the juncture presents a more optimal behavior. These recommendations aim to improve the design and standardize the supply chain and manufacturing processes of the Jaipur Foot [10], [11], [20].

The limitations of this analysis correspond to the limitations of the software, the model and the method used for the simulation. Also, the stump-socket interface was not of interest in this analysis. which could be a further study based on the results presented.

By the other hand, changes in amputees' gait patterns were neglected since good adaptation restores gait patterns similar to normal ones. In addition, there are not many studies that establish a characteristic pattern since the etiology of amputation introduces great changes to gait patterns to establish a single pattern for all amputees. This analysis may consider those changes to make the results more accurate.

V. Future Works

Future work could be aimed at continuing the mechanical analysis, including fatigue calculations and the life cycle of the different models. Likewise, other designs that involve load transfer in the center of the Jaipur foot could be considered. Also, another method such as boundary elements could be used instead of finite elements and try the same approach but with other software to establish an interesting comparison.

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References

[1] A. P. Arya, L. Klenerman, and E. Professor, "The jaipur foot," *J Bone Joint Surg [Br]*, pp. 90–1414, 2008. DOI: 10.1302/0301-620X.90B11.

[2] R. Bhargava, "The Jaipur foot and the 'Jaipur Prosthesis'," *Indian Journal of Orthopaedics*, vol. 53, no. 1, pp. 5–7, Jan. 1, 2019. DOI: 10.4103/ortho.IJOrtho_162_18.

[3] H. S. Mali and A. Singh, "Manufacturing standardization of jaipur foot by additive manufacturing," pp. 149–158, 2020. DOI: 10.1007/978-981-32-9433-2_12.

[4] L. Herdiman, S. Susmartini, and I. Priadythama, "Application of the total ergonomics in designing functional prosthetic ankle with low cost in indonesia," in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing Ltd, Dec. 2020. DOI: 10.1088/1757-899X/1003/1/012004.

[5] P. Sharma, S. Sharma, S. Vidhya, and M. K. Mathur, "Comparative finite element analysis of jaipur foot and polyurethane foot," *Engineering*, vol. 5, no. October, pp. 518–521, 2013. DOI: 10.4236/eng.2013.510B106P.

[6] S. Krishnamoorthy and M. Karthikeyan, "Design and analysis of sensor centered prostheses for handicaps," in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 1992–1996. DOI: 10.1016/j.matpr.2020.09.303.

[7] A. M. Cárdenas, J. Uribe, J. M. Font-Llagunes, A. M. Hernández, and J. A. Plata, "The effect of prosthetic alignment on the stump temperature and ground reaction forces during gait in transfemoral amputees," *Gait Posture*, vol. 95, pp. 76–83, Jun. 2022. DOI: 10.1016/j.gaitpost.2022.04.003.

[8] N. Olaya Mira, and C. Viloria Barragán, “Development of a protocol for the evaluation of the mechanical behavior of a transtibial prosthesis by infrared thermography,” in *IFMBE Proceedings 75*, 2020, pp. 805–811.

[9] J. G. Wolynski, B. B. Wheatley, H. S. Mali, A. K. Jain, and T. L. Haut Donahue, “Finite element analysis of the jaipur foot: Implications for design improvement,” *Journal of Prosthetics and Orthotics*, vol. 31, no. 3, pp. 181–188, 2019. DOI: 10.1097/JPO.0000000000000253.

[10] I. Huber, “Epidemiological study of failures of the jaipur foot,” *Disabil Rehabil Assist Technol*, vol. 13, no. 8, pp. 740–744, 2018. DOI: 10.1080/17483107.2017.1369593.

[11] H. S. Mali, A. Jain, L. Abrams, S. A. Sorby, and T. L. Haut Donahue, “Cad/cae of jaipur foot for standardized and contemporary manufacturing,” *Disabil Rehabil Assist Technol*, vol. 0, no. 0, pp. 1–6, 2019. DOI: 10.1080/17483107.2018.1555865.

[12] R. H. Teater, “Assessment of the compressive and tensile mechanical properties of materials used in the jaipur foot prosthesis,” *Prosthet Orthot Int*, vol. 42, no. 5, pp. 511–517, 2018. DOI: 10.1177/0309364618767143.

[13] J. S. Jensen, J. G. Craig, L. B. Mtalo, and C. M. Zelaya, “Clinical field follow-up of high density polyethylene (hdpe)-jaipur prosthetic technology for trans-tibial amputees,” *Prosthet Orthot Int*, vol. 28, no. 3, pp. 230–244, 2004. DOI: 10.3109/03093640409167755.

[14] O. Panagiotopoulou, “Finite element analysis (F-EA): Applying an engineering method to functional morphology in anthropology and human biology,” *Ann Hum Biol*, vol. 36, no. 5, pp. 230–244, 2004. DOI: 10.1080/03014460903019879.

[15] A. Erdemir, T. Guess, J. Halloran, S. Tadepalli, and T. Morrison, “Considerations for reporting finite element analysis studies in biomechanics,” *J. Biomech*, vol. 45, no. 4, pp. 625–633, 2012. DOI: 10.1016/j.jbiomech.2011.11.038.

[16] R. H. Teater, “Assessment of the compressive and tensile mechanical properties of materials used in the jaipur foot prosthesis,” *Prosthet Orthot Int*, vol. 42, no. 5, pp. 511–517, Oct. 2018. DOI: 10.1177/0309364618767143..

[17] T. Marasovi, M. Ceci, and V. Zanchi, “Analysis and interpretation of ground reaction forces in normal gait,” *WSEAS Transactions on Systems*, vol. 8, no. 9, pp. 1105–1114, 2009.

[18] J. S. Jensen and W. Raab, “Clinical field testing of vulcanized jaipur rubber feet for trans-tibial amputees in low-income countries,” *Prosthet Orthot Int*, vol. 30, no. 3, pp. 225–236, 2006. DOI: 10.1080/03093640600867233.

[19] N. Olaya Mira, C. Viloria Barragán, and J. A. Plata, “Evaluation of different Jaipur footankle assemblies using infrared thermography,” *Prosthet Orthot Int*, 2020. DOI: 10.1177/0309364620958510.

[20] G. Narayanan, “Improved design and development of a functional moulded prosthetic foot,” *Disabil Rehabil Assist Technol*, vol. 11, no. 5, pp. 407–412, 2016. DOI: 10.3109/17483107.2014.979331.