Manufacture of soles for footwear using digitized designs with flexible filaments for 3D printers

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Abstract

The purpose of the research is to develop shoe soles by digitized designs with flexible filaments in 3D printers. The motivation to conduct the research was the conceptualization of the process of transferring digitized and simulated data to 3D objects that meet the needs of the customer. For the digitization process of the sole through software design and 3D scanning, the sole of a women's shoe size 36 (24.6 cm.) in the Peruvian standard was replicated. In addition, some variants were made using Rhinoceros 6.0 software, allowing to make meshes to generate the piece which was later exported in STL file format. On the other hand, the shoe sole was produced with Thermoplastic Polyurethane (TPU) and Thermoplastic Elastomer (TPE) filaments, with 5% and 12% infill variants printed on an Anet A8 and M3D Crane Quad printer. A total of 16 samples were printed as a result of one piece per combination. Moreover, the software "Voxelizer 2.1" was used to generate the GCODE which allows 3D reading and printing. Finally, two tests were performed on the printed sole patterns: elongation and tensile strength: The tensile test applies a variable vertical force to each pattern to determine how it will behave under pressure. The elongation test consists of applying a variable force to each pattern in order to measure the material's ability to resist changes in shape until finding its point of fracture. The results show that the sole designs do not have significant variations in the elongation test, but the software design digitizing process has higher performance versus 3D scanning. In the tensile strength test, the design digitization process has also a higher performance versus 3D scanning; however, as it is not significant, both processes can be used for the manufacture of footwear soles. Thus, there is no interaction or average dependence between the filler percentages and the type of filament (TPU, TPE). Finally, the elaboration of footwear soles by digitized designs with flexible filaments does not present a significant difference among the means of factors involved in this study: Infill density, type of filament, printer.

KeyWords: Footwear, Digitized design, Flexible filament, 3D printing, Sole shoe.

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Introduction

Technology is developing rapidly and has a direct impact on various industrial sectors, such as the textile, footwear, and others. Especially, stereolithography (SL), is conceptualized as the process of transferring digitized data and 3D simulated objects to physical products by 3D printing [1]. 3D modeling is the process of digitalizing an image that the user previously shaped.

In [2], digital manufacturing is broader than the idea of bringing a 3D object modelling into physical item. It goes through some aspects such as: 1) Technical, the precision for replication and self-replication, and 2) Social, since digital fabrication will change the way of living to everyone. In addition, it includes different areas such as: 1) Integrated systems, referring to the hardware involved (electronic integrated systems with specific functionality); 2) CNC, which are automated systems to control the different machines 3) CAD software, a specialized software that allows the 3D simulation (three-dimensional).

Also, the concept of digital additive manufacturing allows to improve either real objects or previously digitally manufactured by adding details to the objects [2], If we apply this concept to the footwear manufacturing, the extension could be performed in the upper part, depending on the design of the sole. As a result, the most likely addition would be the traditional laces or some internal adjustments to make the shoe softer and more comfortable

With digital manufacturing and 3D printing, as well as the development of new production processes, such as clothing and footwear, Danit Peleg has been one of the pioneers in the production of clothing from flexible Fibers and 3D printers [3],

The processes of development and production of clothing, footwear and other textile products from digitized objects and 3D modelling and subsequent printing, not only involves a different form of manufacturing, but new challenges especially in customization and hyper-personalization which involves the industry 4.0. Such process allows the user to model a certain object in 3D and print it without needing 3D printers, but specialized centers called Fablab [4].

Among the main functions of the National University of Juliaca (UNAJ) it can be found the academic, research and social responsibility, covered by Law No. 30220, better known as the "University Law". Thus, all its faculties, especially Textile Engineering and Apparel, and their respective lines of research such as "Production processes, design, safety and quality in the textile and apparel industry" [5], seek to generate new knowledge and projects exploring areas like digital manufacturing, 3D printing and industry 4.0. All of this with the purpose of innovating new manufacturing processes for garments, footwear, and other products, in order to improve costs, quality, resistance, washing fastness and other aspects.

For this purpose, la UNAJ and The Textile Engineering and Apparel Faculty investigated some characteristics of the 3D printed object (sole shoe) by subjecting it to various tests such as traction and elongation.

RELATED WORKS

The author in [6] applied 3D technology to the footwear, highlighting the 3D modeling software: Rhinoceros, Blender, and 3D Max. For the shoe last, the author mentioned that it can be obtained by a 3D scanner and add adjustments with a 3D software to customize the footwear. The production was carried out using 3D printers, however, the research is informed at a descriptive level without mentioning any tensile, elongation or bending test.

In [7], the author carried out the work "Design of a sneaker. 3D printing and customization of the midsole"; obtaining a customized shoe with 3D printing. Some characteristics of the work are the division into zones such as last, midsole, lower intensity zone, heel counter, sole (with 3D printing) and inner pattern (without 3D printing). A 3D scanner with geometric precision of 0.16 and 0.50 mm was used to obtain the last (customization), as well as a 3D printer with FDM technology. For the manufacturing process, the printing was not done in one piece, on the contrary, it was divided into different processes: 3D Printing, Cutting, Gluing, Sewing and Riveting. The thickness of the sole was between 20.2 mm and 30.2 mm. and the materials used were PLA filament (for last), TPU filament (for midsole, sole), NYLON filament (for heel counter) and polyester fabric (different patterns), in addition to sewing thread, Coolmax Mesh fabric, laces, solvents, adhesives and eyelets. Among the tests performed are flexion, traction, abrasion, and others, however, the work does not mention the values obtained.

In [8], the author made a water shoe design with 3D printing from flexible materials. The shoe design was made with Meshmixer software and the rendering with Keyshot. Up to six very similar models with a circular structure as a base and small differences between the upper area were created. The sole completes the design for which, four proposals were generated from completely solid to variations in certain areas. The final print was developed in European size 43 with dimensions of 200 x200 x100 mm. The material used was the rigid filament Z-Ultrat in flexible material of the company "ShapeWay". This project focuses more on the economic aspect of production and does not mention the tests carried out.

In [9], the Spanish Association of 3D and Additive Manufacturing Technologies presented the case study "Development of prototypes of shoe soles by 3D printing" developed in CAD software and with CNC machines, highlighting the limitations that may exist in certain countries. He framed that the use of CAD as modeling for 3D printing, requires certain considerations for subsequent precise printing. INESCOP used the footwear design software ICad3dp, which incorporates many models of soles that can be easily exported to the GCODE of 3D printers without generating errors. These have as main process the "tessellation" (conversion of surfaces into geometric meshes) as the Delaunay triangle which requires a correct printing. It also specifies that the guidelines to be met must be: 1) Solid surfaces; 2) Objects must have the normal surface facing outwards; and 3) There must not be any holes in the modeled object. The benefits highlighted in additive manufacturing are: 1) Reduced time-to-market; 2) Cost savings; 3) Reduced design uncertainty; and 4) Flexibility and creativity.

The work presented in [10] tries to show the advantages and opportunities of the additive manufacturing technology (AM) as an emerging technology for modeling 3D in CAD software and with a subsequent treatment by different techniques to finish the modelled object. This prototype generated as a result of the AM, tries to give us an approach to the new process design and validate it as a new paradigm to traditional manufacturing. AM is being applied in different fields such as industrial design, medicine, garments, footwear, among others, which motivates to increase the exploration and innovation.

In [11], they developed and printing garments with digitized designs of natural patterns with flexible filaments such as TPU and TPE using 3D printers Anet A8 and M3D Crane Quad. They also executed tensile, elongation and bending tests to the garments which were printed using the natural patterns Snowflake, Flower of Life and Honeycomb with variant of organized line and filling percentage at 12%. For the design, the Rhinoceros software was used and for the generation of the GCODE the Voxelizer software. The results showed that, while the TPU filament obtained better performance in the elongation and traction test with 51. 4 % and 77.04 N. the bending test did not show any adittional indicator.

In [1],[12] the author developed a garment printed on a 3D printer using natural coral brain motif as a base pattern, which he digitized into the hexagonal geometry of the surface of the garment using Rhinoceros and Grasshopper Graphics software. In addition, he studied the PLA, ABS and Filaflex (TPE) yarns and performed bending tests to them. Finally, to join the pieces of the garment, extrusions of the filament were made, resembling yarns for the garment.

In [13], tensile and elongation tests were performed on six PLA filaments with the use of specific materials using two 3D printers: Cetus MKII and Instron 5566. The results showed that the filament with the best performance in the tensile test was PLA and metallic additives, which obtained 121.36N. For the elongation test, it was the PLA filament with technical additive with 20.16 %.

For [14] the research "Determination of elastic properties of polymeric pieces constructed by 3D printing, subjected to bending", elongation tests were performed with PLA, NAYLON and HIPS filaments. The work generated test specimens with dimensions of 80 mm x 10 mm and thickness of 4mm with 100% filling. For this test the Prusa Mendel M90 3D printer was used, and the conclusions reached were that the specimens with 0˚/0˚ angle line infill had 3% elasticity.

In [15] the research "Influence of infill parameter on the mechanical resistance in 3D printing, using the Fused Deposition Modeling method"; had as object of study to measure the influence of the resistance in terms of the tensile test (application of force) in ABS filaments varying the infill from 0% to 100%. It should be emphasized that this project used the ATSM D638-10 standard and the Makerbot Duplicator 2X was employed as 3D printing equipment. The conclusion stated that the percentage of resistance to the tensile test is directly proportional to the increase in the percentage of infill, so that with a 0% infill the application of force was 14.62 Mpa and with 100% infill the resistance was 34.57. In the manufacture of footwear with 3D printing, it is important to consider that the tensile test, elongation, and bending must be closely linked to the properties of the filament.

THEORETICAL BACKGROUND

A. 3D Printing

In [16], 3D printing is directly interrelated with digital fabrication, it is the physical materialization of a digital file, using the machine controlled by instructions and not necessarily connected to a computer, which allows to produce complex objects different from traditional or manual fabrication technologies. Currently there is a variety of 3D printers and materials (filaments); as well as techniques such as additive or subtractive. In addition, 3D printing has different benefits in the domestic or industrial area, and applications such as clothing, jewelry, industrial textile, prosthetics, etc. These processes are new and help to improve the process in some areas, while, in other fields are experimental, such as housing construction or production of human tissues.

In [17], the work states similarities between additive manufacturing and 3D Printing, remarking that the second one is the layered manufacturing, and set of processes that are produced from the additive technique, and mentions that there are up to seven different techniques such as material extrusion, material projection, binder projection, paper lamination, photopolymerization, powder melting and direct energy deposition.

Although 3D printing technology has existed since 1976, in 1984 Charles Chuck Hull patented his system called Stereolithography. In his work titled "Apparatus for Production of Three-Dimensional Objects by Stereolithography" it describes it as a process in which the resin layer was solidified by ultraviolet light. Subsequently, 3D printing incorporated new concepts such as additive manufacturing of casting patterns, manufacturing tools with injection molds and easy manipulation for users [18], especially through the process of digitizing objects [19].

B. Digital fabrication

In [20], digital fabrication is defined as "The transition from the bit world to the physical world", going through 3 stages: 1) Conceptualization of the object with ergonomic considerations, 2) Digitization of the object with considerations of vectorizing to be scaled, and 3) Materializing the object through equipment such as 3D printer and others that are controlled by computer. In addition, there are other concepts that digital manufacturing incorporates such as personalization, which will allow the manufacturing to be tailored to the specific person.

In [4], the term digital manufacturing is not only "digitization of manufacturing processes", but is much broader, encompassing technical and social aspects. For Jorquera "the digital manufacturing revolution is based on a simple idea: to convert information into things and things into information". In other words, the ideas are embodied in physical form, emphasizing that the object can be required in different quantities and with all the adaptations demanded by the user.

1) Additive manufacturing: The term refers to the three-dimensional manufacturing by the addition of materials, instead of subtracting them and starting from an existing 3D object (modeled)[4]. 3D printing is a good example of additive manufacturing, because it is the process of adding of certain material (filaments) on layers.

2) Subtractive Manufacturing: It is considered among the first technologies that appeared being controlled by Computer Numerical Controlled Machines (CNC). The main idea is that certain pieces are to be removed through one or several processes from different materials, such as plastic, wood, thermoplastic among others as well as with different machines such as CNC, laser cutter, milling machines. It also includes a digital file in CAD system, to perform the subtractive process [10].

C. Industry 4.0

En [21], Industry 4.0 is defined as the fourth industrial revolution with a particularity of "coexistence of a large number of converging technologies, which erase the boundary between the physical, digital and biological" thus, generating a new paradigmatic approach. The Internet plays an important role in Industry 4.0 since it allows the social actors (users, companies, government, etc.) to connect in real time and from different devices (cell phones, computers, etc.) supported by digital platforms (e.g., e-commerce, e-learning, etc.), generating new manufacturing and communication processes. When talking about communication not only covers people but also focuses on the communication of objects (pc's, cell phones, etc.), and this is achieved thanks to the internet. The keys to the success of Industry 4.0 are achieved thanks to informatization and digital transformation.

In [22], Industry 4.0 is defined as "a new industrial model for self-organization and self-management of fully automated production systems", based mainly on new technologies and the internet. Despite being interpreted as the fourth industrial revolution, its influence on each sector is decisive. Industry 4.0 can be considered as a digital ecosystem since it affects direct on the manufacturing process and operation of objects and products. Industry 4.0 refers not only to the digital and intelligent manufacturing process, but also to the creation of added value such as customization, including global production centers such as FabLabs. In simple words, it is digitalization and automation going beyond the physical barriers.

In [22], the work remarks that Industry 4.0 must be absolute integration and describes its main characteristics:

1) Vertical integration of smart production systems: Smart factories cannot operate independently; it requires cyber-physical production systems that allow the establishment of intelligent networks for manufacturing to be personalized according to the customer or order.

2) Horizontal integration through global networks of value chains: Facilitates the networking mechanism to create added value, establishing alliances and business partners. It is even capable to generate new business models, for example a garment with 3D simulation of a company can be printed in a Fab Labs center not necessarily of the same company and that is closer to the customer's residence, saving logistical costs.

3) Engineering throughout all the value chain: The engineering is present throughout the life cycle, until reaching the final consumer. In addition, the product quality is not only focused on production, but on the product design.

4) Manufacturing acceleration: The product or order is present since the manufacturing stage, with the use of information and communication technologies. Starting when the object is modelled and ready for digital manufacturing, until the distribution to the customer.

D. 3D Modeling

In [23], the 3D image or graphic is a simulation in three dimensions considering the width, length and depth. Computers can only process in two dimensions; therefore, 3D images are a representation of reality in three dimensions, but they also consider other characteristics such as illumination, shading and texture. There is a difference between 3D and 2D images, being that 2D images only have elements of width and height; in other words, a simple drawing, while 3D images use three-dimensional geometry techniques that computers provide and with the help of a visual projection on a screen or printer.

In the production of 3D images, Enrique and Francisco [23] state that the process requires mathematical formulas to allow objects to represent attributes such as texture, depth, illumination, reflections, transparency, and so on, thus developing the 3D model. Regarding the process of creating 3D images, they go through different stages, which Enrique and Francisco [23], detail below:

1) Design: This is the sketch of the image or object that constitutes the drawing and forms the basis for the creation of the simulated 3D. It is described as the starting idea at this stage.

2) Modelling: This is the process of applying basic volumes to the objects that were designed. There is a big difference between design and simulation, because this stage is about analyzing what shape should be given to the object from basic forms, which are called "primitive patterns". Modelling can be made complex when the object requires a variety of curves. Depending on the item, different kinds of shapes may be needed, such as organic forms when it is desired to simulate nature or living beings. Modelling throughout its evolution has developed different types of geometries such as meshes, triangles, polygonal elements or NURBS. The latter are incorporated in most of the 3D simulation software and facilitate the task of complex simulations.

3) Texturing: It is the allocation of properties to the simulation such as colour, brightness, texture, structure, etc. At first sight it seems that the simulation stage is the most important one, but the reality is that the texturing stage is also important because it contributes realism to the simulation.

4) Illumination: This stage contributes to the realism of the image, working on highlighting or concealing the simulated object from a certain angle of the camera (camera position). The illumination should also be considered as three-dimensional.

5) Rendering: It is the final process of the simulation, transferring the 3D image to the 3D modelling. In other words, it is the conception of the image or scene in three-dimensional form, made by the computer. As the item must be captured in the screen or printer, it becomes a bidimensional object with three-dimensional simulation.

METHODOLOGY

A. Research Sample

This research explores two flexible filaments, two scanning processes, two infill density percentage variants printed with two 3D printers.

TABLE I. SAMPLE STUDY

Filament	Process	% Filler	3D Printer		Total
			A8 Anet	*M3D Crane Quad*	
TPU	Software Design	5%	1	1	2
		12%	1	1	2
	3D Scanning	5%	1	1	2
		12%	1	1	2
TPE	Software Design	5%	1	1	2
		12%	1	1	2
	3D Scanning	5%	1	1	2
		12%	1	1	2

B. Research equipment and software

The software used to develop this research project is described in the followings:

- Rhinoceros 6: A 3D design and modelling software applied to the creation of STL files. It was used for both processes: software design and retouching of the software scanning process.
- XYZHandy Scan: A 3D scanning software provided by XYZPrinting and used for the scanning process.
- Voxelizer: 3D Printing Software used for the generation of the GCODE file from the STL file.
- Trace: Plug-in for automated line sketching based on images and easy integration into the Rhinoceros software.

Regarding the equipment employed to develop the research project:

TABLE II. 3D PRINTERS FEATURES

Characteristics	3D Printer	
	Anet A8	*M3D Crane Quad*
Nozzle Diameter	0.4 mm.	0.35 mm.
Build Volume	220 x 220 x 240 mm.	200 x 200 x 230 mm.
Printing Speed	40 -120 mm / s	Up to 80 mm / s
Filament diameter	1.75 mm	1.75 mm

Fig. 1. Anet A8 3D Printer.

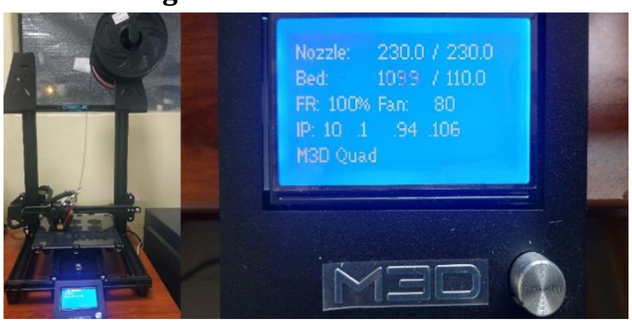

Fig. 2. M3D Crane Quad Printer.

Dynamometer

- Model: Thread Dynamometer model 848 from Instruments J. Bot S.A.
- Maximum capacity: 10kg.
- Elongation: 0,1% over 500mm.
- Upper clamp for wire
- Lower clamp for driving roller

Fig. 3. Thread Dynamometer model 848 from Instruments J. Bot S.A.

3D Scanner

- Scan Engine: Intel® RealSense™ Camera
- Scan size (W x D x H): 5 x 5 x 5 ~ 100 x 100 x 200 cm
- Scanning resolution: 0.2 ~ 1.5 mm
- Image size with depth: 640 x 480 px at 30 fps
- Color image size: Up to 1920 x 1080 px at 40 fps
- Scanning software: XYZscan Handy
- Output File Types: .obj, .ply, .stl, .fbx

Fig. 4. 3D Scanner from XYZPrinting.

C. Procedure Research

1) Design by Software: A standard sole was chosen for the digitization process by software design. The shaped size was 36 for women in the Peruvian standard (246 mm. including the outer edges) [24].

For the design, variants of a shoe sole were shaped using Rhinoceros 6.0 software. It allowed to make solids and meshes to create the model which was then exported in STL file format (see Fig. 5). The STL file was exported to the Voxelizer software for the generation of the GCODE file, creating different files for each 3D printer (Anet A8 and M3D Crane Quad), fill percentage (5% and 12%) (see Fig. 6).

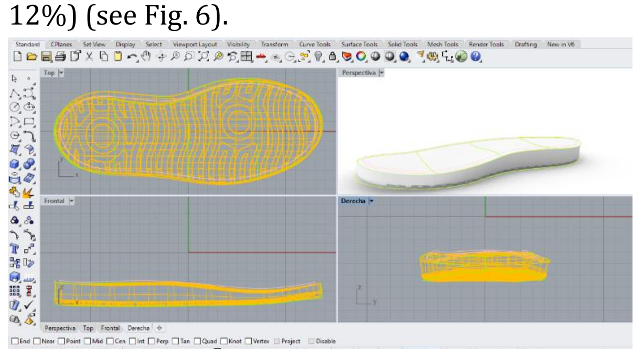

Fig. 5. Shoe sole digitization process using software design.

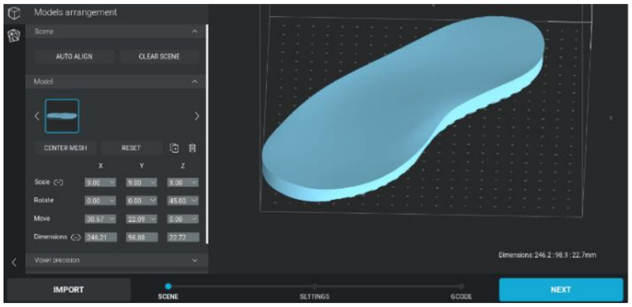

Fig. 6. Generation of the GCODE file using Voxelizer to digitize items by software design.

Fig. 7. Digitized sole by software design and printed with M3D Crane Quad equipment in TPU Flexible Filament with 5% infill.

Fig. 8. Digitized sole by software design and printed with ANET A8 equipment in TPE Flexible Filament with 12% infill.

2) Design by 3D Scanning process: The digitization process of the sole by 3D scanning was done from a standard sole size 36 (24.6 cm) for women in Peru [24], which was purchased in a shoe repair shop (see Fig. 9). For the scanning process, the 3D Scanner 2.0 and the XYZScan Handy software [25], were used. The sole was fixed from 3 points (ceiling, wall, and floor) to avoid movement during the process of digitizing the sole. The portable 3D scanner moved clockwise from top to bottom and vice versa, visualizing the data capture in the software and going over the sectors where it was needed according to the software's report (see Fig. 10 abd 11).

Fig. 9. Shoe sole utilized in the 3D scanning process.

Fig. 10.Digitization process of the base mold by 3D scanner.

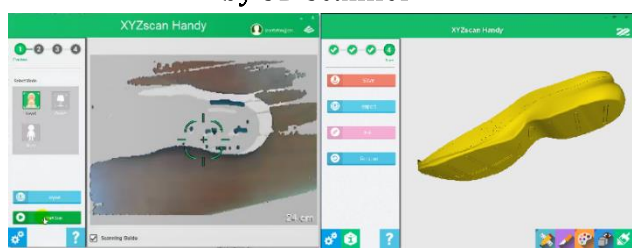

Fig. 11.3D Scanning process by XYZ Handy software.

After the 3D scanning, and with the use of Rhinoceros 6 software, the necessary corrections were made and the STL file was generated (see Fig. 12). The mentioned file was used in the Voxelizer software and creation of the GCODE file, for reading and 3D printing (see Fig. 13).

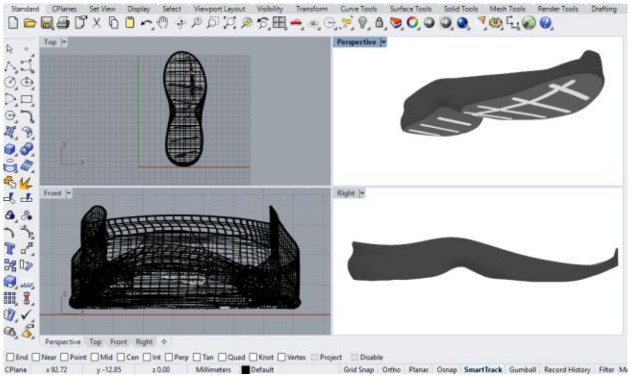

Fig. 12.Corrections applied in Rhinoceros to the digitized item by 3D scanning.

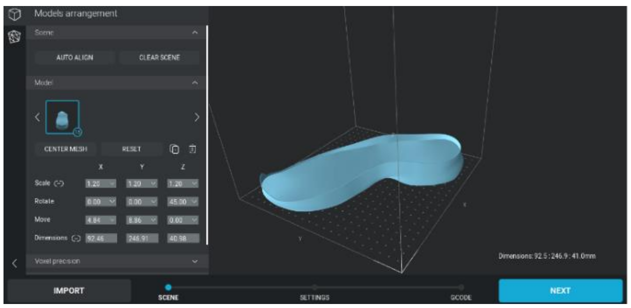

Fig. 13.Generation of the GCODE file using Voxelizer to digitize items by 3D Scanning.

3) Printing: TPU and TPE filaments were used, with Anet A8 and M3D Crane Quad printers. The filler variants at 5% and 12%, and the 3D scanning and software design processes. One sample per each combination was printed which resulted in total of 16 samples (see Fig. 14 and 15).

Fig. 14. Digitized sole by 3D Scanning and printed with M3D Crane Quad equipment in TPU Flexible Filament with 5% infill.

Fig. 15.Digitized sole by 3D Scanning and printed with ANET A8 equipment in TPE Flexible Filament with 12% infill.

TABLE III. TECHNICAL SPECIFICATIONS OF THE 3D PRINTER PARAMETERS

Parameter	3D Printer	
	Anet A8	*M3D Crane Quad*
Extruder temperature	240°	240°
Hotbed temperature	70°	70°
Quality Print	60%	60%
Infill density	12%	12%
Raft	Brim	Brim
Retraction	No	No
Support	Yes	Yes
Resolution	0.22 mm.	0.22 mm.

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TABLE IV. MEASUREMENTS OF PROPOSED SOLE

Process	Dimension (in mm.)		
	Length	*Width*	*Height*
Software Design	246.2	98.8	20.0
3D Scanning	246.9	92.4	40.9

TABLE V. STATISTICAL DATA OF THE 3D PRINTING

Process	Filament	3D Printer	% Infill	Parameter	
				Time	*Weight*
Software Design	TPU	A8 Anet	5%	11 h. 30 m.	55.70 g.
			12%	13 h. 49 m.	69.14 g.
		M3D	5%	11 h. 51	57.43

Process	Filament	3D Printer	% Infill	Parameter	
				Time	*Weight*
		Crane Quad		m.	g.
			12%	14 h. 01 m.	71.04 g.
	TPE	A8 Anet	5%	10 h. 51 m.	75.29 g.
			12%	11 h. 19 m.	96.30 g.
		M3D Crane Quad	5%	10 h. 55 m.	78.13 g.
			12%	11 h. 54 m.	96.45 g.
3D Scanning	TPU	A8 Anet	5%	12 h. 54 m.	58.78 g.
			12%	16 h. 04 m.	80.33 g.
		M3D Crane Quad	5%	13 h. 09 m.	61.12 g.
			12%	16 h. 51 m.	84.24 g.
	TPE	A8 Anet	5%	12 h. 45 m.	64.23 g.
			12%	16 h. 58 m.	87.80 g.
		M3D Crane Quad	5%	13 h. 55 m.	65.21 g.
			12%	17 h. 54 m.	88.12 g.

4) Performed tests: Two tests were conducted: (i) Elongation, which consisted of applying a variable force to each pattern in order to obtain the percentage of elongation and overcome its elastic limit to reach its corresponding fracture point. (ii) Tensile, which consisted of applying a variable vertical force to each pattern, in order to increase its length until reaching the fracture resistance.

Fig. 16.Tensile and elongation test applied to the sole created by software design.

Fig. 17.Tensile and elongation test applied to the sole created by 3D Scanning.

RESULTS

A. Elongation

Table VI shows the results during the elongation test. This is the main test to produce footwears' soles.

TABLE VI. ELONGATION TEST DATA (IN %)

Flexible Filament	Process	3D Print			
		A8 Anet		*M3D Crane Quad*	
		5%	*12%*	*5%*	*12%*
TPU	Software Design	29.40	24.50	21.10	18.90
	3D Scanning	25.40	21.50	18.90	18.60
TPE	Software Design	24.40	12.00	20.00	16.90
	3D Scanning	21.10	21.60	18.40	15.60

In Table VII, the analysis of variance shows that the model is not significant and therefore is not applicable for the factors of filament type and percentage of filler. The description of each factor is described in the followings:

TABLE VII. ANALYSIS OF VARIANCE - ELONGATION TEST

Source	df	Sum of Squares	Mean Square	F	Sig.
Filament (A)	1	46.581	46.581	3.452	0.088
% Infill (B)	1	56.626	56.626	4.196	0.063
A x B	1	3.516	3.516	0.261	0.619
Error	12	161.943	13.495		
Total	**15**	**268.664**			

- Filament (A). - The value of the filament equality contrast statistic, F = 3.452 leaves a p-value 0.088, greater than the 5% significance level. The effectiveness of this design does not depend on the filament type and does not have a significant effect; therefore, the design is not effective. The inclusion of the filament type factor in the model is not accurate. Thus, the production of the footwear does not depend on filament type.
- Infill Density (B). - The value of the test condition equality contrast statistic, F = 4.196 leaves a p-value 0.063, greater than the 5% significance level. It means that the test condition does not influence on footwear production. Thus, there is no significant difference in shoe production between the two test conditions for elongation in footwear.
- A x B. - The interaction between filament type and test condition, obtains a non-significant F=0.261 value. It can be concluded that there is enough evidence to state that there is no interaction between filament type and test condition, i.e., the factors in the study are not dependent on each other.
- Error. - This row shows the variances of the dependent variable, which is the elongation of the garment, not explained by the model.
- Total. - This row states the variance observed in the dependent variable due to all causes.

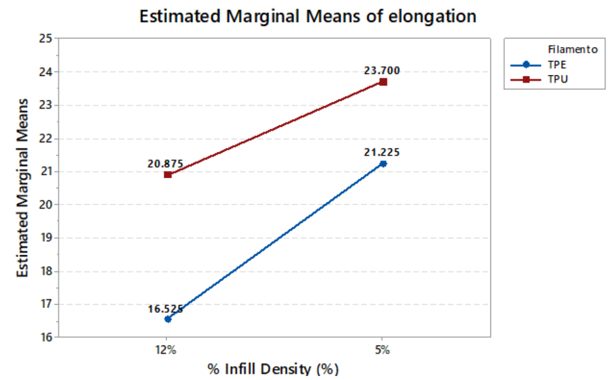

Fig. 18.Estimated Marginal Means of elongation.

However, the analysis of variance does not allow to conclude which is the procedure with the highest average increase. For this, a test of difference of means such as the T-test must be performed for the factors: test condition (B) and for the type of filament (A).

Filament (A). Table XI and Fig. 19, shows the outcome of the T-test (P≥0.971), when applying the type of filament: TPE and TPU in the traction performance of the shoes. Results show that there is no statistical difference among both type of filaments to produce shoes.

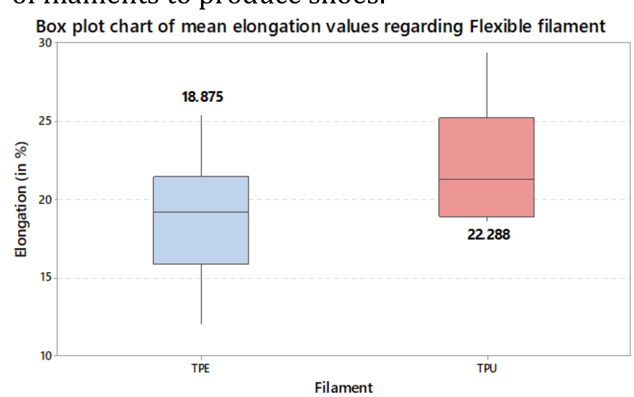

Fig. 19.Box plot chart of mean elongation values regarding Flexible filament.

TABLE VIII. ELONGATION TEST STATISTICS REGARDING FILAMENT

Filament	N	Mean	Std. Deviation	Std. Error Mean
TPU	8	22.288	1.361	3.850
TPE	8	18.875	1.454	4.112

Infill Density (B). Table XII and Fig. 20 show the results of the T-test (P≥0.795), when applying the percentage of filler: 5% and 12% regarding elongation performance of the shoes. The outcome shows that the percentage of filler does not vary significantly in the production of shoes, i.e. at 12% of filler, elongation is equal to 5% of filler.

TABLE IX. ELONGATION TEST STATISTICS REGARDING INFILL PERCENTAGE

% Infill	N	Mean	Std. Deviation	Std. Error Mean
5%	8	22.463	3.861	1.365
12%	8	18.700	3.922	1.387

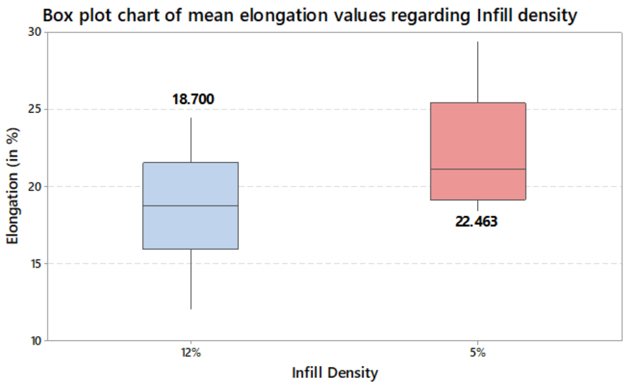

Fig. 20.Box plot chart of mean elongation values regarding Infill density.

Printer. Table XVI. and Fig. 21 shows the T-test result (P≥0.082) for elongation test. It is observed that the Anet A8 printer does not vary statistically compared to the M3D Crane Quad printer.

TABLE X. ELONGATION TEST STATISTICS REGARDING 3D PRINTER

3D Print	N	Mean	Std. Deviation	Std. Error Mean
Anet A8	8	22.612	5.104	1.805
M3D Crane Quad	8	18.550	1.703	0.602

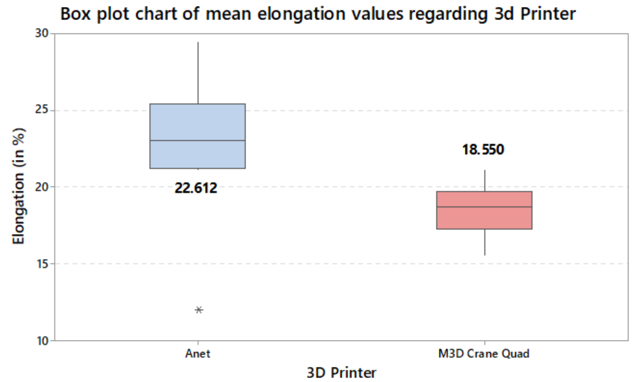

Fig. 21.Grafica de caja de medias en la prueba de elongacion respecto a la impresora 3D.

Process Type. Table XVII. and Fig. 22 show the results of the T-test (P≥0.179), when applying the type of process: Software Design and 3D Scanner to the performance of footwear elongation. The outcome states that there is no statistical difference between both processes: Software Design and 3D Scanner.

TABLE XI. INDEPENDENT SAMPLE T-TEST FOR ELONGATION TEST REGARDING FLEXIBLE FILAMENTS

	Levene's Test for Equality of Variances		T-test for Equality of Means						
								95% Confidence Interval of the Difference	
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Equal variances assumed	.001	.971	1.714	14.000	.109	3.413	1.991	-.859	7.684
Equal variances not assumed			1.714	13.940	.109	3.413	1.991	-.860	7.685

TABLE XII. INDEPENDENT SAMPLE T-TEST FOR ELONGATION TEST REGARDING INFILL DENSITY

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	.070	.795	1.934	14.000	.074	3.762	1.946	-.411	7.936
Equal variances not assumed			1.934	13.997	.074	3.762	1.946	-.411	7.936

TABLE XIII. ELONGATION TEST STATISTICS REGARDING PROCESS TYPE

Process	N	Mean	Std. Deviation	Std. Error Mean
Software Design	8	21.025	5.417	1.915
3D Scanning	8	20.138	2.931	1.036

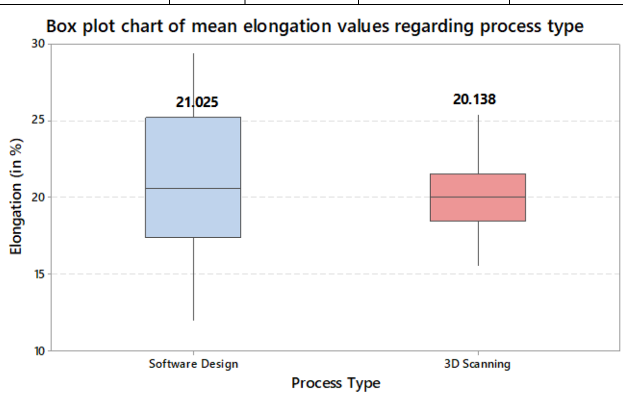

Fig. 22.Box plot chart of mean elongation values regarding process type.

B. Tensile Strength

Table XIV shows the data obtained during the tensile test. This experiment was conducted to have a reference of the amount of force (N) that can be applied to the sole.

TABLE XIV. TENSILE STRENGTH TEST DATA

Filament	Process	3D Printer			
		A8 Anet		*M3D Crane Quad*	
		5%	*12%*	*5%*	*12%*
TPU	Software Design	142.83	132.84	151.95	142.95
	3D Scanning	136.38	139.95	121.61	152.92
TPE	Software Design	133.22	162.20	141.14	146.36
	3D Scanning	112.03	143.03	127.67	128.64

Table XV shows the results of the analysis of variance. The model is not significant and therefore is not applicable to the factors: filament and infill percentage. Each factor is described in the followings.

TABLE XV. ANALYSIS OF VARIANCE - TENSILE STRENGTH TEST

Source	df	Sum of Squares	Mean Square	F	Sig.
Filament (A)	1	46.036	46.036	0.321	0.581
% Infill (B)	1	420.865	420.865	2.936	0.112
A x B	1	158.005	158.005	1.102	0.314
Error	12	1720.392	143.366		
Total	**15**	**2345.298**			

- Filament (A). - The value of the filament equality contrast statistic, F = 0.321 leaves a p-value =0.581, greater than the 5% significance level. The effectiveness of this design does not depend on the filament type and does not have a significant effect; therefore, the design is not effective and the inclusion of the filament type factor in the model is not accurate. Thus, the production of the footwear does not depend on filament type
- Infill Density % (B). - The value of the test condition equality contrast statistic, F = 2.936 leaves a p-value= 0.112, greater than the 5% significance level. It means that the test condition does not influence shoe production. In other words, there is no significant difference in footwear production between the two test

conditions for traction (tensile) in shoes.

- A x B. - The interaction between filament type and test condition, with a value F=1.102 is not significant. It can be concluded that there is sufficient evidence to state that there is no interaction between filament type and test condition, i.e., the study factors are not dependent on each other.

TABLE XVI. INDEPENDENT SAMPLE T-TEST FOR ELONGATION TEST REGARDING 3D PRINTER

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	3.516	.082	2.136	14.000	.051	4.062	1.902	-.018	8.143
Equal variances not assumed			2.136	8.539	.063	4.062	1.902	-.276	8.401

TABLE XVII. INDEPENDENT SAMPLE T-TEST FOR ELONGATION TEST REGARDING PROCESS TYPE

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	2.006	.179	.408	14.000	.690	.888	2.177	-3.783	5.558
Equal variances not assumed			.408	10.774	.692	.888	2.177	-3.917	5.692

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- Experimental Error. - This row shows the variances of the dependent variable, which is the traction of the product, not explained by the model.

- Total. - This row shows the variability observed in the dependent variable due to all causes

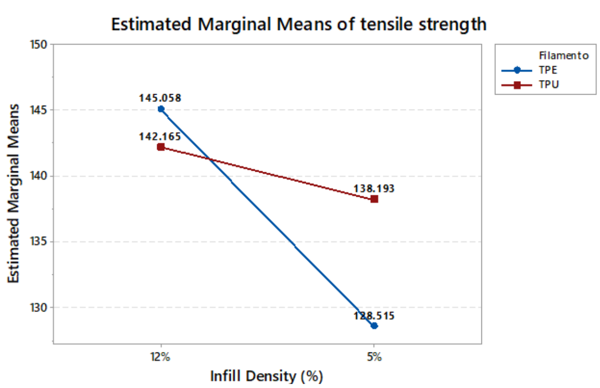

Fig. 23.Estimated Marginal Means of tensile strength.

However, the analysis of variance does not allow to determine which treatment has the greatest average increase. To do this, a test of difference of means (T-test) must be performed for the factors: Filament (A) and Infill density (B).

Filament (A). Table XXI and Fig. 24 show the t-test (P≥0.322), when applying the type of filament: TPE and TPU in the tensile performance of the footwear. The results state that the type of filament: TPE and TPU do not statistical differ in the production of footwear.

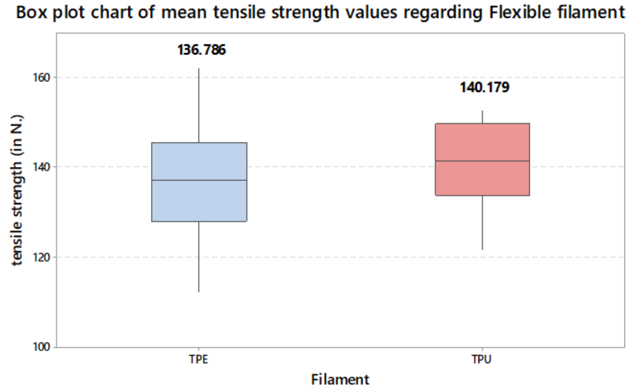

Fig. 24.Box plot chart of mean tensile strength values regarding Flexible filament.

TABLE XVIII. TENSILE TEST STATISTICS REGARDING FLEXIBLE FILAMENT

Filament	N	Mean	Std. Deviation	Std. Error Mean
TPU	8	140.179	10.203	3.607
TPE	8	136.786	14.979	5.296

Infill Density % (B). Table XXIII and Fig. 25 shows the t-test (P≥0.569), when applying the percentage of filler: 5% and 12% respectively to the traction performance of the shoes. The result states that the percentage of filler does not differ significantly in the production of shoes, i.e. at 12% filler the traction is equal compared to 5% filler.

TABLE XIX. TENSILE TEST STATISTICS REGARDING INFILL PERCENTAGE

% Infill	N	Mean	Std. Deviation	Std. Error Mean
5%	8	133.354	12.707	4.493
12%	8	143.611	10.651	3.766

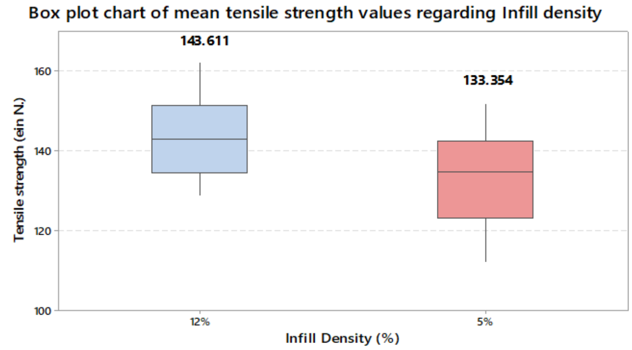

Fig. 25.Box plot chart of mean tensile strength values regarding Infill density.

Printer. Table XXIV and Fig. 26 shows the t-test outcome (P≥0.864) for tensile test. It is observed that the Anet A8 printer does not differ statistically compared to the M3D Crane Quad printer.

TABLE XX. TENSILE TEST STATISTICS REGARDING 3D PRINTER

3D Print	N	Mean	Std. Deviation	Std. Error Mean
Anet A8	8	137.810	13.961	4.936
M3D Crane Quad	8	139.155	11.794	4.170

TABLE XXI. INDEPENDENT SAMPLE T-TEST FOR TENSILE TEST REGARDING FLEXIBLE FILAMENT

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	1.055	.322	.529	14.000	.605	3.393	6.408	-10.351	17.136
Equal variances not assumed			.529	12.345	.606	3.393	6.408	-10.525	17.310

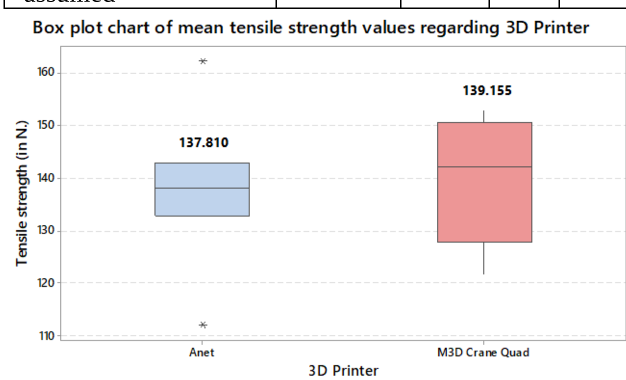

Fig. 26.Box plot chart of mean tensile strength values regarding 3D Printer.

Process Type. Table XXV. and Fig. 27 show the results of the T-test (P≥0.179), when applying the type of process: Software Design and 3D Scanner on the traction performance of the footwear. The outcome states that there is no statistical difference between both processes: Software Design and 3D Scanner.

TABLE XXII. TENSILE TEST STATISTICS REGARDING PROCESS TYPE

Process Type	N	Mean	Std. Deviation	Std. Error Mean
Software Design	8	144.186	9.645	3.410
3D Scanning	8	132.779	12.948	4.578

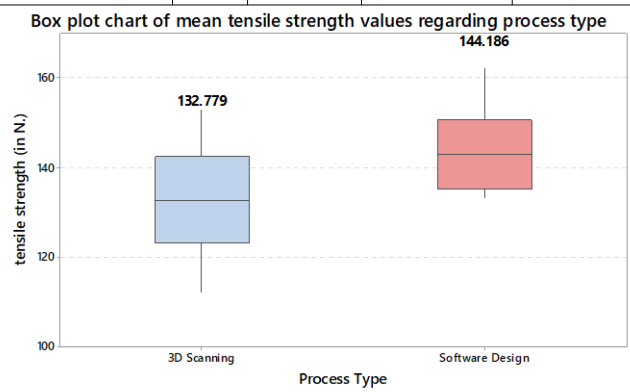

Fig. 27.Box plot chart of mean tensile strength values regarding process type.

DISCUSSIONS

The production of the sole was made in one single piece by both processes, which implies that the conducted tests determine the maximum percentage value of stretching (elongation), and strength to reach the rupture of the sole (traction).

The current study used TPU and TPE flexible filaments to produce the sole taking as reference the experiences stated in [1], [11] and [12]; In addition, the infill percentage (5% and 12%) was purposely determined by the researchers.

TABLE XXIII. INDEPENDENT SAMPLE T-TEST FOR TENSILE TEST REGARDING INFILL PERCENTAGE

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	Upper
Equal variances assumed	.340	.569	-1.750	14.000	.102	-10.257	5.862	-22.831	2.316
Equal variances not assumed			-1.750	13.585	.103	-10.257	5.862	-22.867	2.352

TABLE XXIV. INDEPENDENT SAMPLE T-TEST FOR TENSILE TEST REGARDING 3D PRINTER

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	Upper
Equal variances assumed	.031	.864	-.208	14.000	.838	-1.345	6.462	-15.204	12.514
Equal variances not assumed			-.208	13.620	.838	-1.345	6.462	-15.240	12.550

TABLE XXV. INDEPENDENT SAMPLE T-TEST FOR TENSILE TEST REGARDING PROCESS TYPE

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	1.041	.325	1.998	14.000	.065	11.407	5.708	-.836	23.651
Equal variances not assumed			1.998	12.939	.067	11.407	5.708	-.931	23.746

En [6], como primer proceso es realizar la simulación de la zapatilla para pasar a la etapa de la producción, que hasta ese parte del proceso coincide con nuestra investigación; sim embargo para Medina, el enfoque va por la simulación, producción 3D, y ecología; mientras que nuestra investigación se enfoca a las pruebas de procesos mecanizados (tracción y elongación).

In [7], the research includes the manufacture of the sole in 3D printing and shoe with polyester fabric. The filaments used were TPU and NYLON (flexible filaments), but also PLA (rigid filament) for the manufacture of the shoe last. In addition, the simulation and 3D printing of the shoe sole was done in pieces which differs to the current research, where the sole was printed in one single piece. Moreover, the work of Candel is based on the customization of the sole with 3D scanning, while this study has as core the mechanized tests of traction and elongation. Lastly, Candel suggests different tests to perform in the shoe, however, there is no evidence that he has applied those in his research work. Among the recommended tests, tensile strength and elongation stand out.

In [8], the approach is the additive manufacturing of water shoes. The author focused on the creation of footwear in one single piece, alike to the current research; however, the main difference lies in the design of the object. While Visier developed a non-fully solid shoe (the object is characterized by holes in the upper), the current work tested a sealed shoe. The process of simulation was made by software design and the filament used was elastomer (flexible) without clearly specifying the type (TPU or TPE). Finally, the economic cost of production was another aspect that Visier considered in his research, differing with the actual research where the testing of the shoes (traction and elongation) was the principal objective.

In [13] ,[15]; authors conducted traction tensile tests, however the filaments were rigid in nature such as PLA. There is no evidence of tensile tests on flexible filaments such as TPU or TPE.

In [13] ,[14]; the work described elongation tests using rigid filaments in nature such as PLA, HIPS (NYLON as exception); however, there was no data of tensile tests on flexible filaments such as TPU or TPE.

CONCLUSIONS

Among the digitization methods described in this research, it can be observed that there is no significant variation between the results obtained in the elongation test. The software design process obtained a higher performance (21.025%) than the 3D scanning process according to table N° XIII. The results show that both processes are eligible to manufacture footwear.

According to the statistical analysis, there is no significant variation among the filaments (TPU and TPE) regarding the elongation test. This shows that there is no interaction or dependence between the type of filament and the elongation value. In reference to the independent sample tests, the difference of infill density means (at 5% and 12%) for elongation test do not present a significant statistical difference. Likewise, there is no statistical difference between the M3D Crane Quad printer and ANET A8 regarding the elongation tests.

Regarding the tensile test, it is observed that among digitization processes, there is no significant variation in results. The software design digitization method obtained a higher performance (144.186N) compared to the 3D scanning process as stated in table No. XXII . The findings indicate that both processes are feasible for the manufacture of footwear. According to the statistical analysis (significance level of 0.05), there is no significant variation among filaments regarding the traction test. In other words, there is no interaction or dependence between the type of filament and the value of the tensile strength of the sole.

In reference to the independent sample tests, the difference of infill density means (at 5% and 12%) for tensile test do not present a significant statistical difference. Finally, there is no statistical difference between the M3D Crane Quad printer and ANET A8 for the traction test.

FUTURE WORK

It is necessary to extend research on sole and footwear manufacturing with respect to the type of filament employed. The authors propose NYLON and NINJAFLEX as filaments, in order to determine the most optimal for the manufacture of soles and footwear. In addition, there is little information about traction tests such as tensile and elongation. More information in this area might strengthen new research lines of industry 4.0, digital manufacturing and 3D printing.

Regarding the production of soles with 3D printers using digital additive manufacturing, it is necessary to research other elements that could directly influence the manufacture of the sole. The following highlight among the recommendations of authors: new filaments, time, cost, temperature, environment, GCODE generation software, 3D simulation software and others.

In addition, it is important to conduct research studies with different topics such as customer customization, comfort, and adaptability. Finally, another area of research might lead us to the manufacture of the sole by 3D printing regarding the color endurance to washing exposure, sun exposure, durability over time and other natural environmental factors

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