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COMPARATIVE STUDY OF THE SCRATCHING BEHAVIOUR OF THE MATERIALS USED FOR MEDICAL ORTHOSES

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Abstract*: This paper presents a comparative study on the scratching behaviour of materials commonly utilized in the production of medical orthoses. Medical orthoses play a critical role in providing support and corrective functions for patients with musculoskeletal conditions. The research focuses on assessing the scratch resistance of various materials, considering factors such as hardness, surface finish, and durability. Through comprehensive comparative analyses, including tribological testing, the study aims to identify optimal materials for orthotic applications. Insights gained from this investigation contribute to the enhancement of orthoses design, ensuring the longevity and performance of these devices in the medical field, ultimately benefiting patients and healthcare practitioners alike.*

Key words: *Ankle-Foot Orthosis, 3D printing, polypropylene, medical rehabilitation, scratching behaviour.*

1. INTRODUCTION

Navigating the complexities of Ankle-Foot Orthosis (AFO) construction, this research dives into a comparative evaluation of various materials, tailored to address the challenges of neurologic spastic foot conditions. Stemming from diverse medical origins like stroke, multiple sclerosis, spinal cord injuries, and traumatic cranio-cervical events, these conditions manifest in a pronounced spastic state across specific muscles. Such manifestations not only disrupt gait but also impede life quality, influence bone alignment, and dictate the health of muscles and tendons. Left unchecked, these conditions can escalate, giving rise to tendon shortening, muscle retraction, altered sensibility, and the onset of pressure sores.

Orthosis is an artificial device that assists externally to support the spine or limbs and to avert any unnecessary movement by the patient. The difference of the orthosis form prostheses is that prostheses completely replaces the part of the body, which is hurt or missing. In contrast, the orthosis helps limbs to recuperate from the injury and to strengthen the proper functionality of them, [1]. Usually, the Ankle-foot orthosis is designed in the form of “L”, where the vertical part is placed in the rear side of the calf, and the horizontal component is joined to the sole, [2]. In the comparative analysis of materials used for medical orthoses, particularly Ankle-Foot Orthosis (AFO), three materials stand out for their distinct properties and performance in scratch tests: Carbon Filament Polyethylene Terephthalate Glycol (PETG), ABS Smart Filament, and polypropylene (PP). Each material offers unique advantages that are pivotal in determining their suitability for orthotic applications. Regarding the printing, Carbon Filament PETG and ABS Smart Filament were both printed in two modes: Hexagonal and Triangle infill pattern with infill percentage of 15% and on the other hand, polypropylene (PP)

Polypropylene (PP), a synthetic resin developed through the polymerisation of propylene, [3], is widely utilised in orthosis workshops. Its attributes include semi-rigidity, translucency, chemical resistance, toughness, good fatigue resistance, hinge properties, and elevated heat resistance, [4]. Moreover, PP has a robust electrical and chemical resistance at higher temperatures and is not susceptible to stress-cracking.

ABS Smart Filament - Acrylonitrile butadiene styrene (ABS) is another thermoplastic filament, impact-resistant, recognised for its resilience under physical stress, making it a preferred choice in the manufacturing sector, [3]. Is easily processed through injection moulding, extrusion and 3D printing. It resists many chemicals, making it suitable for diverse industrial uses.

Carbon Filament Polyethylene Terephthalate Glycol (PETG) - is a thermoplastic polyester that offers a good balance of properties, including clarity, toughness, and chemical resistance by incorporating carbon fibre, the material gains enhanced strength and stiffness compared to standard PETG. This material is often used in applications where strength and lightweight characteristics are essential, such as in aerospace, medical components, or high-performance engineering.

By utilising the CETR UMT experimental tribometer, this study aims to assess whether 3D printed AFOs can potentially replace conventional polypropylene devices. By testing attributes such as elasticity resistance and deformation patterns of the materials, this research seeks to identify the optimal material for orthosis applications. The study's findings will provide insights into the most suitable material for AFOs and its potential implications on scar risk.

2. CLINICAL IMPLICATIONS OF THE MATERIALS, BIOCOMPATIBILITY AND PATIENT COMFORT.

The clinical implications of the material choice in the construction of Ankle-Foot Orthoses (AFOs) are significant, considering the diverse needs of patients with musculoskeletal conditions. The materials studied - Carbon Filament Polyethylene Terephthalate Glycol (PETG), ABS Smart Filament, and polypropylene (PP) - each have distinct characteristics that impact their performance in a clinical setting.

Carbon Filament PETG, enhanced with carbon fibre, offers superior strength and stiffness, which are advantageous in creating orthoses that require high mechanical strength. Given its unique characteristic as a biomaterial, PETG has been utilized and is being actively researched in tissue engineering, dental, optometry related, cardiovascular, orthopedics, neurological, gynecological, drug delivery, anti-bacterial, as well as surgical and medical imaging related applications, [5]. This material's toughness and resistance to chemical degradation make it suitable for patients who are more active or require orthoses that can withstand rigorous use. Additionally, the clarity of PETG might be beneficial for aesthetic purposes, which can be an important consideration for patient acceptance and satisfaction. PETG demonstrates the optimum mix of processing parameters, mechanical qualities, and low cost; PETG displays mechanical properties that were more suited for the application (for example, toughness), [6]. However, the increased stiffness of PETG might limit its use in cases where greater flexibility is required for comfort or functionality. With its low carbon footprint, PETG contributes to sustainable development while offering innovative solutions for industries such as car interiors, medical devices, and electronic components, [7].

ABS Smart Filament, known for its resilience and impact resistance, is well-suited for patients who need a durable and robust orthotic device. Its ability to withstand physical stress ensures that the orthoses remain functional under various conditions, including those involving dynamic and repetitive movements. Due to its amorphous nature, ABS lacks a defined melting point compared to other common polymers, ABS has advantageous mechanical characteristics such impact resistance, and stiffness, [8]. The versatility in processing ABS, particularly its compatibility with 3D printing, allows for the creation of custom-fit orthoses, which can significantly enhance patient comfort and device effectiveness. Customisation is crucial in orthotic devices as it ensures a better fit, which is essential for the correct alignment and support of the affected limb.

Polypropylene (PP) is a widely used material in orthotic workshops due to its balance of semi-rigidity and flexibility. This balance is vital for patient comfort, especially in conditions where prolonged wear of the orthosis is required. PP's good fatigue resistance and hinge properties make it suitable for orthoses that need to provide consistent support while allowing some degree of movement. Moreover, its resistance to chemical degradation and heat adds to its longevity, making it a practical choice for orthoses intended for long-term use.

In clinical applications, the choice of material for AFOs significantly influences the orthosis's effectiveness, durability, and patient comfort. While PETG and ABS offer high strength and the potential for customisation through 3D printing, PP provides a well-established solution with its balance of flexibility and support. The decision should be based on a thorough understanding of the patient's specific condition, activity level, and personal preferences. This tailored approach in material selection is crucial for optimizing the therapeutic outcomes of orthoses, ensuring that they not only provide the necessary support and correction but also enhance the overall quality of life for the patient.

The biocompatibility and patient comfort associated with the materials used in Ankle-Foot Orthoses (AFOs) are crucial factors that significantly influence their clinical efficacy and patient compliance. In this context, the materials under consideration - Carbon Filament Polyethylene Terephthalate Glycol (PETG), ABS Smart Filament, and Polypropylene (PP) - each present unique aspects of biocompatibility and comfort, which are essential for patient-centred orthotic design. The ankle functions biomechanically as a modified hinge joint to allow motion of the shank and foot segments, [9]. An AFO that effectively restricts ankle motion should be made from materials with sufficient stiffness to withstand motion in the shank and foot segments of the limb, as well as motion of the ankle joint itself, [10].

Carbon Filament PETG, particularly when reinforced with carbon fibre, offers a robust composition that ensures durability. However, its biocompatibility is a critical factor, especially since these devices are in prolonged contact with the skin. While PETG is generally considered safe and non-irritating, the addition of carbon fibre necessitates careful consideration of any potential skin sensitivities or allergic reactions. Comfort-wise, PETG's rigidity, while beneficial for strength, might limit its flexibility, potentially affecting comfort during extended wear. Therefore, while PETG is suitable for applications demanding high strength, its rigidity and biocompatibility aspects must be carefully evaluated in the context of patient-specific requirements.

ABS Smart Filament is noted for its resilience and is commonly used in various consumer products, is recognized for its robustness, durability, and heat resistance, is an excellent option for automotive applications, pipes, and protective enclosures, [11]. In terms of biocompatibility, ABS must be assessed for any potential irritants, especially for patients with sensitive skin. The material's durability and resilience are advantageous, but similar to PETG, the comfort level of ABS in orthotic devices depends significantly on the device's design and the degree of customisation achieved. ABS is a strong, rigid material that can be easily produced by injection molding, extrusion, and thermoforming, [12]. When comparing ABS to other thermoplastics, there are various benefits such as exceptional toughness even at low temperatures, [13].

The ability to 3D print ABS allows for tailored orthotic solutions that can enhance comfort by providing a precise fit, which is essential in reducing pressure points and improving overall wearability. Also, ABS demonstrated greater elongation and flexural strength prior to breaking, [14].

Polypropylene (PP) is widely regarded for its biocompatibility and has been extensively used in medical applications. Its non-irritating nature and low risk of allergic reactions make it a safe choice for prolonged skin contact. PP's semi-rigidity offers a balance between support and flexibility, which is crucial for patient comfort. This balance allows orthoses made from PP to provide necessary support while adapting to the body's contours, reducing discomfort during movement. Furthermore, PP's resistance to moisture and chemicals ensures that the orthosis maintains its integrity and comfort over time, even under varying environmental conditions and during regular cleaning.

In summary, while all three materials have properties that make them suitable for use in AFOs, their biocompatibility and comfort levels vary. PETG and ABS offer high strength and customisation possibilities but require careful consideration of biocompatibility and rigidity. In contrast, PP stands out for its proven biocompatibility and optimal balance of flexibility and support, enhancing patient comfort for prolonged use. The ultimate choice of material should be guided by a thorough understanding of the patient's specific needs, skin sensitivities, and the required mechanical properties of the orthosis, ensuring that the device is not only effective in its therapeutic function but also comfortable and safe for long-term wear.

3. DETERMINATION OF THE PROFILE OF PLASTIC-DEFORMED SURFACES USING THE SCRATCHING METHOD.

Plastic deformation is a crucial aspect in understanding material response to mechanical stress. This research focuses on examining the plastic deformation characteristics of materials subjected to mechanical scratching. By varying the applied load and the nature of the substrate material, the study aims to delineate the deformation profiles of these materials. The study aims to provide valuable insights into the material's plastic response under controlled conditions, contributing to a deeper understanding of surface behaviour. Such knowledge is essential for optimising manufacturing processes, enhancing material durability, and improving the overall performance of engineered components subject to plastic deformation.

In the figure 1 there are the notations:

F_y is the tangential (translational) component of the scratching force,

x – component in the x direction of the deformed material.

A – the point of contact of the roughness of the rigid cone with the viscoelastic material corresponding to the maximum level of indentation (penetration).

BC - roughness diameter - rigid cone

V(x_v, y_v) the top of the parabola formed by the bordered material;

x_0, x_f – the start and end coordinates of the edging in the x direction.

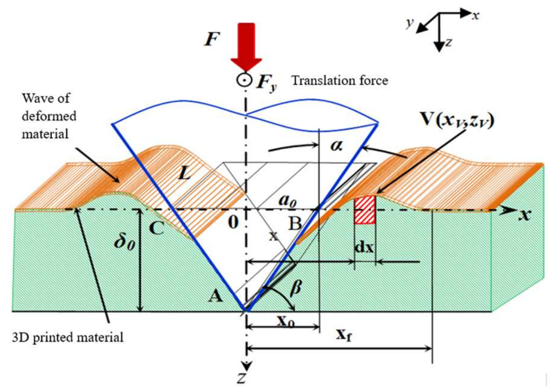

Fig. 1 Scratch contact, [9]

It is assumed that the section of the bordered material has the parabolic shape given by the relation:

$$z = m \cdot x^2 + n \cdot x + p \qquad (1)$$

The parameters m, n, and p are determined from the condition that, the volume of the prismatic crater with the section of a triangle having the base equal with $\mathbf{2a_0}$ and height $\boldsymbol{\delta_0}$ is equal to the volume of the paraboloid with the same length as the prism.

$$\frac{1}{2} \cdot a_0 \cdot \delta_0 \cdot L = L \cdot \int_{x_0}^{x_f} z\, dx \qquad (2)$$

where **L** is the length of the trace.

The parabola has a derivative equal to the cone's angle of attack, **β**, and it is zero for $\boldsymbol{z = 0, x = a_0, x = x_f}$.

$$\begin{cases} m = \dfrac{\tan\beta}{a_0 - x_f} \\ n = \tan\beta - 2a_0 m \\ p = -ma_0^2 - na_0 \\ z = mx^2 + nx + p \end{cases} \qquad (3)$$

The condition for the conservation of the volume of plastically deformed material is:

$$\frac{1}{3}\pi a_0^2 \delta_0 = \int_{x_0}^{x_f} 2\pi xz\, dx \qquad (4)$$

$$\int_{x_0}^{x_f} 2\pi xz\, dx = 2\pi\left[m\frac{x_f^4 - x_0^4}{4} + n\frac{x_f^3 - x_0^3}{3}\; p\frac{x_f^2 - x_0^2}{2}\right] \qquad (5)$$

From this condition, the abscissa of the parabola, x_f, is determined. The abscissa x_f is the solution to the cubic equation and is dimensionless with respect to: a^0

$$x_{af} = \frac{x_f}{a_0}$$

$$x_{af}^3 - x_{af}^2 - x_{af} - 1 = 0 \qquad (6)$$

The nondimensional coordinates of the parabola's vertex, under the assumption of volume conservation for the deformed material, become:

$$V: \begin{cases} x_{av} = \frac{1 + x_{af\,2}}{2} = 1.42 \\ z_{av}(\beta) = \frac{1}{4} \cdot \tan\beta (x_{af\,2} - 1) \\ z_{av}\left(\frac{\pi}{10}\right) = 0.068 \end{cases} \qquad (7)$$

4. EXPERIMENT DESCRIPTION AND RESULTS

The experiment was carried out by employing the CETR-UMT2 Tribometer, part of the

Tribology Laboratory within the Department of Machine Elements and Tribology from POLITEHNICA University. The schematic of the setup used in this study is shown below. It can provide rotational translational or reciprocating motions with speeds ranging from 0.1 µm/s up to 10 m/s.

The load is applied to the sample by the carriage using F_z for a close-loop feed-back mechanism for stability and accuracy and can be kept constant or linearly increasing from as low as 1 mN to as high as 1 kN. Friction force (F_x), normal load (F_z), penetration depth and tangential force are measured and recorded at a total sampling rate of 20k Hz. To perform the measurements, the tribometer was equipped with the DFH-20 2-axis sensor, capable of measuring forces of up to 200N with a resolution of 10 mN and with the L-Drive L20HE-0292 for translational motion The configuration below is the setup used for the experiments presented in this paper, [15].

The experiment script consists of three stages during which a scratch of 20 mm length is produced. The indenter will move at a speed of 1 mm/s over a specified time of 20 seconds. For scratching, a diamond steel indenter with a cone tip angle of 120° and a radius of 12.5 µm, depicted in Figure 2, was used.

Fig. 2 Indenter

Prior to applying the load, the test samples were cleaned with isopropyl alcohol. Figure 3 presents the spent specimens. A total of five scratch tests were made with loads of 5N, 10N, 20N, 50N and 100N, respectively.

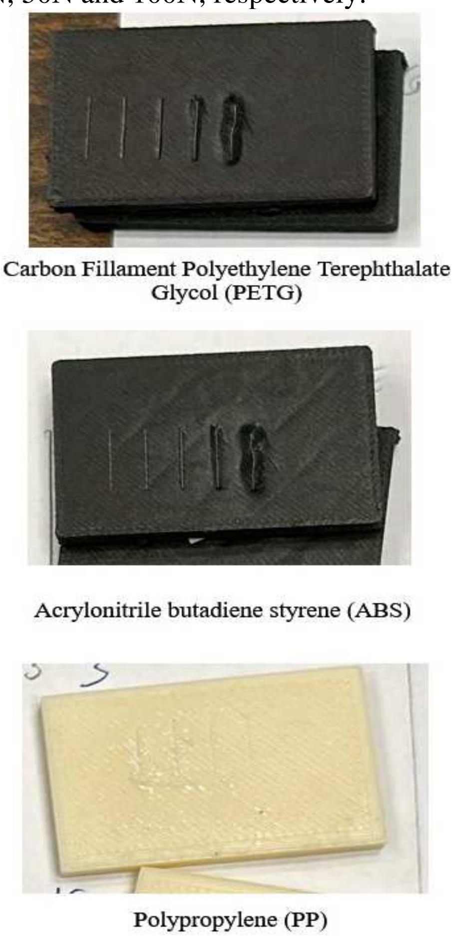

Fig. 3 Specimens

To secure the specimens in place, a robust clamping system, as depicted in Figure 4, was employed. This carefully designed clamping mechanism ensures the stable positioning of the specimens during testing, facilitating accurate and reliable force measurements.

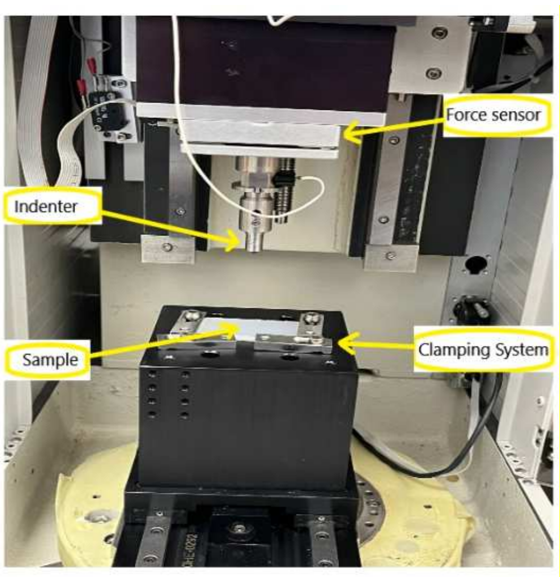

Fig. 4 Force sensor, Clamping System, Intender, Sample

The experimental results, obtained through rigorous testing, are captured using an acquisition system can be seen in Figure 5. This system records and compiles comprehensive data sets, encompassing various parameters and responses such as forces in the vertical axis and driving direction, 3 axis orthogonal positioning and velocities measured in the same 3 axis is depicted in (Fig.6).

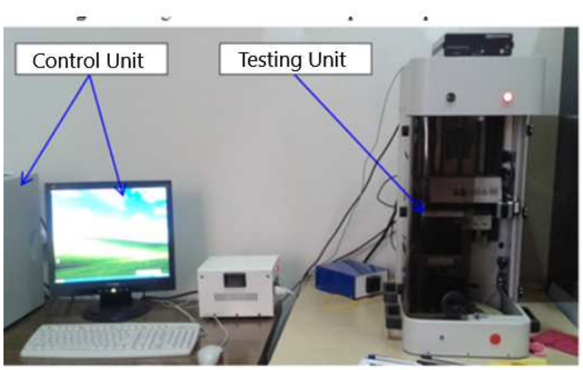

Fig. 5 Acquisition system

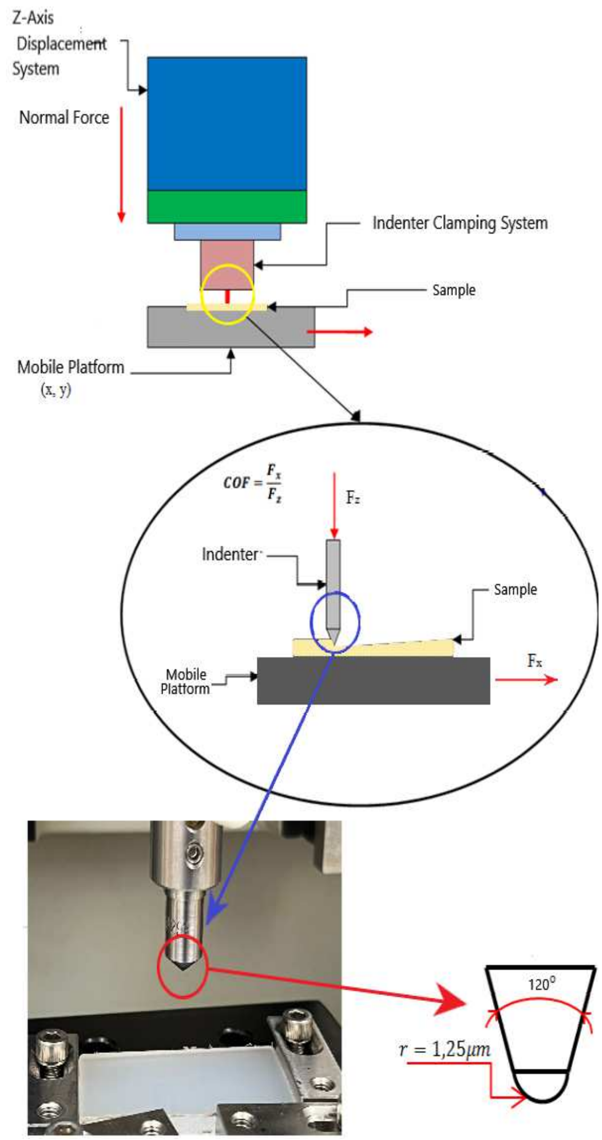

Fig. 6 Test exemplification

In the experiment, each of the three samples was subjected to five assessments. These assessments included measuring the normal force, the frictional or tangential force, and calculating a coefficient analogous to the coefficient of friction, which is determined as the ratio of the normal force to the tangential force referred as the friction coefficient from this point further. Values for this coefficient of friction can be observed in Figure 7, where a normal force of 20N was applied.

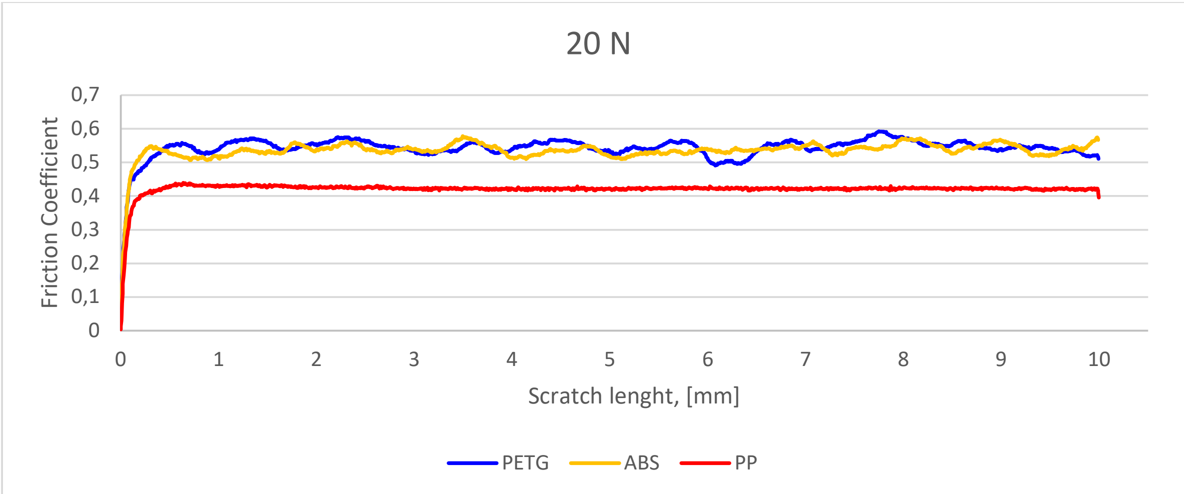

Fig. 7 Friction coefficient

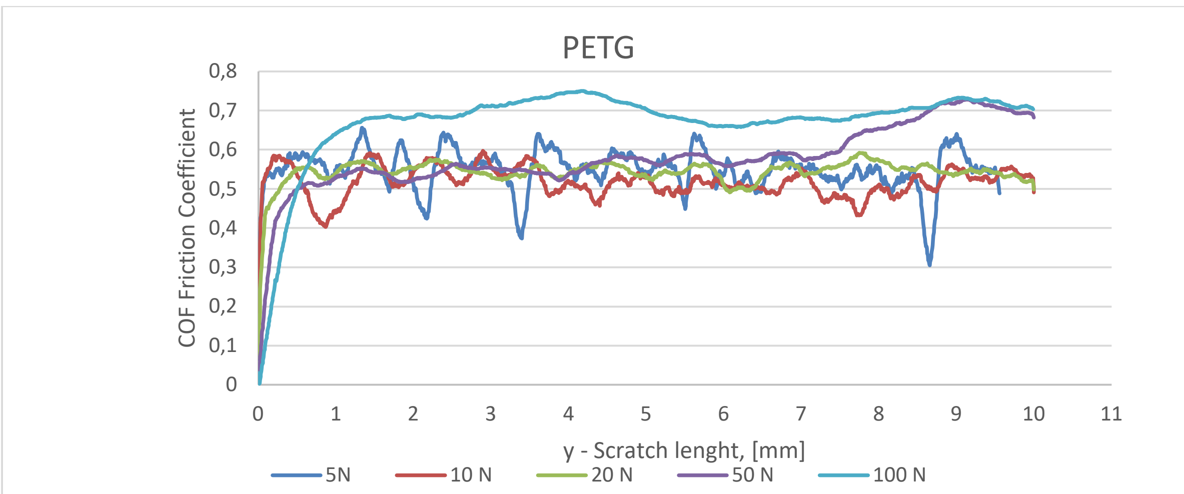

Fig. 8 PETG Friction Coefficient

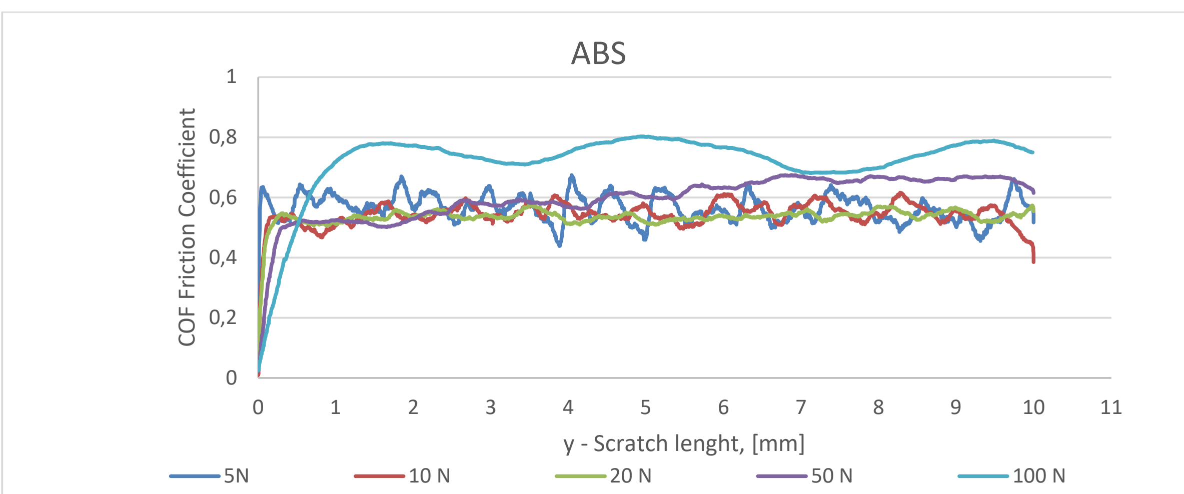

Fig. 9 ABS Friction Coefficient

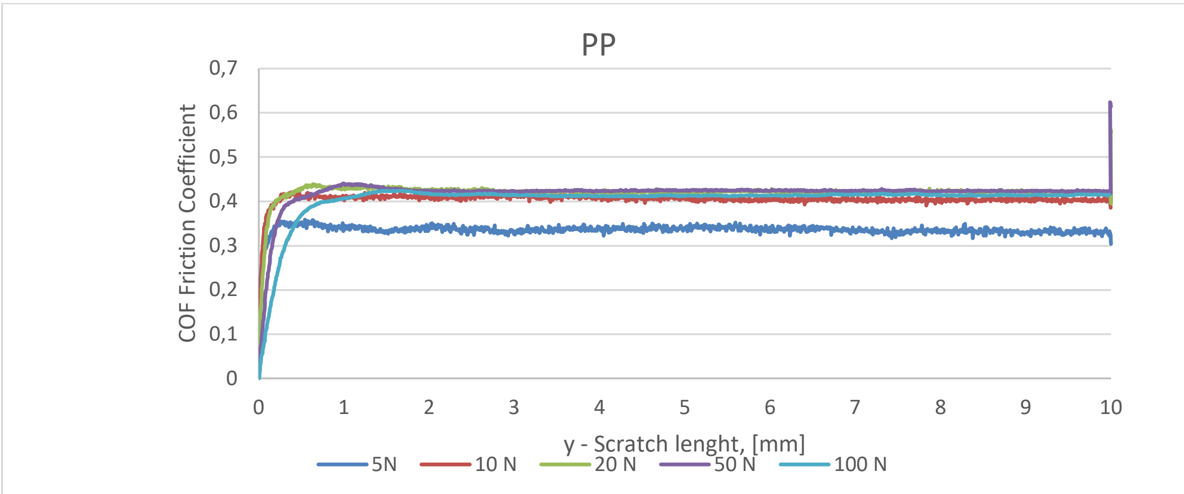

Fig. 10 PP Friction Coefficient

The subsequent diagrams provide a detailed sequential representation of the behaviour exhibited by three different materials - PETG (illustrated in Fig. 7), ABS (shown in Fig. 8), and PP (depicted in Fig. 9) - when subjected to a range of forces. Each diagram is designed to offer a clear visual perspective, illustrating how each of these materials responds when exposed to different load conditions. This visual representation is particularly valuable for gaining a deeper understanding of the tribological characteristics of each material. By examining the behaviour of PETG, ABS, and PP under various forces, we can gain insights that are crucial for their application in the manufacturing of foot orthoses. The diagrams aim to highlight the distinct mechanical properties and response patterns of these materials, thereby providing essential information that can guide the selection and optimisation of materials in the design and production of effective and durable foot orthoses. This understanding is vital in ensuring that the orthoses produced are not only functionally effective but also exhibit optimal wear resistance and mechanical compatibility with human biomechanical needs.

As a result of the scratching process, the tested surface deformed near the contact zone between the cone and the specimen.

4. CONCLUSION

During the scratching tests, the deformation of the tested surfaces near the contact zone between the cone and the specimen is a critical observation. This deformation is indicative of the material's response to localised stress and provides insights into its scratch resistance and overall durability. The nature and extent of deformation vary among the materials tested—Carbon Filament Polyethylene Terephthalate Glycol (PETG), ABS Smart Filament, and Polypropylene (PP)—reflecting their inherent mechanical properties.

All selected materials performed similarly, with PP being the material with the lowest coefficient of friction measured (0.35-0.4), as compared with the other materials (PETG – 0.3 to 0.75) (ABS – 0.45 to 0.8).

In the study, it was observed that the coefficient of friction remained consistent across all three tested materials, except in scenarios where a 100N force was applied. In these cases, the force was sufficient to plow through the surfaces of ABS and PETG materials, resulting in an increased coefficient of friction. Notably, the areas of increased friction coincided with the infill walls, suggesting a direct impact of the force application on the material's surface and internal structure.

Nonetheless, the examination of surface deformation characteristics in 3D printed polymer composites, including their scratch and wear resistance, remains largely unexplored. One study was identified that explores the scratch behavior of additively manufactured CF/PA6 composites by testing different fiber orientations and load-induced deformation modes, using a finite element model to assess the impact of fiber/matrix bonding and distribution on tribological performance, guiding the design of CFRPs in additive manufacturing, [16]. The results obtained in this study are of a different type, the only similarity with the presented study is the fact that matrix is affected in an analogous manner.

In conclusion, the micro-scratch test results provide valuable insights into the mechanical properties of PETG, ABS, and PP, guiding the material selection process for AFOs. These findings are instrumental in developing orthotic devices that are not only functionally effective but also durable and comfortable for the patient, offering a promising direction for further research, optimising infill patterns and percentages.

5. REFERENCES

[1] Berry, D., 1981. *Composite materials for orthotics and prosthetics*. Orthot. Prosthet. 40:35–43

[2] Banerjee S., Singh P., Samanta S., *A critical evaluation of polypropylene impact copolymer morphology.* International Journal Of Polymer Science Vol 5, No. 2. 2019, doi: 10.37628

[3] Hazrat A., Smagulov Z., Otepbergenov T., *Finite element analysis of the CFRP-based 3D printed ankle-foot orthosis,* 2021, Procedia Computer Science Volume 179, 2021, Pages 55-62

[4] Meena Meena R., Wahab Hashmi A., Ahmad S., Yusuf M., *Influence of fly ash on thermo-mechanical and mechanical behavior of injection molded polypropylene matrix composites.* Chemosphere, Vol. 343, 130225

[5] Subramaniyan K., Thanigainathan S., Elumalai V., *Fabrication and mechanical behavior of structurally graded material (ceramic – reinforced polylactic acid/ polylactic- acid) for integrated engineering application.* - Proceedings of the Institution of Mechanical Engineers Part E. Journal of Process Mechanical Engineering. 2023

[6] Yan C., et al., . *PETG: Applications in Modern Medicine.* Engineered Regeneration, Vol. 5, Issue 1, 2024. Pages 45-55

[7] Redaelli D., et al., 15 oct *2020*, *3D printing orthopedic scoliosis braces: a test comparing FDM with thermoforming.* The International Journal of Advanced Manufacturing Technology, 2020, Vol. 11, pages 1707-1720.

[8] Santana D., 22-23, *PLA and PETG Applied to Extrusion-Based 3D Printed Snap-Fit Connections for Product Assembly.* From European Hournal of Applied Engineering and Scientific Research, 2020, Vol S1.

[9] Durga Rajesh K., Ganesh N., Tekkali M.,Teja Naidu S, *Experimental research on the mechanical characteristics of fused deposition modelled ABS, PLA and PETG specimens printed in 3D.* Materials today: Proceedings, 2023.

[10] Hovorka C., et al., Feb. *2021*, *Material properties and application of biomechanical principles provide significant motion control performance in experimental ankle foot-orthosis-footwear combination* Clinical Biomechanics Vol. 82, 2021

[11] Paritosh K., et al., *Investigation of mechanical properties of 3D printed sandwich structures using PLA and ABS* Materialstoday: Proceedings, 2023.

[12] Cress A., et al, *Effect of recycling on the mechanical behavior and structure of additively manufactured acrylonitrile butadiene styrene (ABS).* Journal of Cleaner Productions 279(4)123689

[13] Lee D., *Investigation of laser ablation on acrylonitrile butadiene styrene plastic used for 3D printing.* Journal of Welding and Joining, Vol 36(1), 2018

[14] Prakash A., et al., *An investigation of combined effect of infill pattern, density, and layer thickness on mechanical properties of 3D printed ABS by fused filament fabrication.* Helion, Vol. 9 Issue 6, 2023

[15] UMT Multi-Specimen Test System Hardware Installation & Applications Manual

[16] Ziyan M, Boyang W, Hongjian W, Qing L, Li C, *Experimental and numerical study on scratch performance of additively manufactured continuous carbon fibre reinforced polyamide 6 composites*, Composites Science and Technology, Volume 230, Part 2, 2022, 109314, ISSN 0266-3538,

Studiu comparativ al comportamentului privind testarea la zgâriere a materialelor utilizate pentru orteze medicale

Acest articol prezintă un studiu comparativ asupra comportamentului privind testarea la zgâriere a materialelor folosite în mod obișnuit în producția de orteze medicale. Ortezele medicale joacă un rol critic în furnizarea de suport și funcții corective pentru pacienții cu afecțiuni musculoscheletale. Cercetarea se concentrează pe evaluarea rezistenței la zgârieturi a diferitelor materiale, luând în considerare factori precum duritatea, finisajul suprafeței și durabilitatea. Prin analize comparative cuprinzătoare, inclusiv teste tribologice, studiul își propune să identifice materialele optime pentru aplicațiile ortotice. Informațiile obținute din această investigație contribuie la îmbunătățirea designului ortezelor, asigurând longevitatea și performanța acestor dispozitive în domeniul medical, beneficiind în final atât pacienții, cât și practicienii din domeniul sănătății.

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