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APPLICATION OF ADDITIVE MANUFACTURING TECHNOLOGIES FOR MEDICAL PURPOSES

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Abstract: This study examines the metrology of 3D printed parts, focusing on surface roughness and hardness to evaluate the performance of various 3D printers including the Ender 3 V2, Stratasys F370, and Stratasys J835. Initial calibration of the Ender 3 V2 was conducted followed by the printing of plastic plates whose surface roughness and hardness were meticulously analyzed. Similar tests were conducted on milled steel plates for comparative purposes. The objective is to assess how different printing materials and technologies affect the final product's mechanical properties, particularly focusing on their practical implications in industrial and medical applications. By integrating both surface roughness and hardness measurements, the study provides comprehensive insights into optimizing 3D printing processes to enhance the functional quality of printed components.
Keywords: Additive Manufacturing, 3D Printing, Medical Prosthetics, Tissue Engineering, Customized Implants

INTRODUCTION

The emergence of additive manufacturing (AM), commonly referred to as 3D printing, has heralded a transformative era in manufacturing and engineering.

This groundbreaking technology, defined by its capability to construct objects layer by layer, has extended far beyond its original industrial applications, making substantial advancements in the field of medicine.

The objective of this study is to explore the applications, advancements, and implications of AM technologies within medical science domain where precision, customization, and innovation are not merely advantageous but indispensable.

While the widespread adoption of additive manufacturing in medicine may seem recent, its origins date back to the 1980s with the advent of stereolithography.

Over the past few decades, AM has undergone remarkable evolution, significantly expanding its capabilities and diversifying the range of materials it employs. These materials now include not only plastics and metals but also bio–inks and living cells, paving the way for groundbreaking advancements in medical science and patient care.

In healthcare, AM is being utilized in numerous innovative ways, including the production of patient–specific prosthetics, orthopedic implants, and the development of bioprinting techniques for creating biological tissues. These applications underscore the versatility and transformative potential of AM technologies, illustrating their profound impact on patient outcomes and medical research.

The ability to tailor solutions to individual needs has positioned AM as a critical tool in advancing personalized healthcare and surgical precision. This study explores the various uses of AM in healthcare, emphasizing its potential to redefine patient care and medical innovation.

The study emphasizes the achievements and challenges associated with applying AM in clinical settings by looking at case studies and recent research. This paper also discusses the technical, ethical, and legal issues that arise when AM is used into medical procedures.

This study intends to shed light on how additive manufacturing (AM) technologies are changing healthcare and propelling upcoming advancements in medical research and treatments by examining the nexus between AM and medical science.

STATE OF ART

The integration of 3D printing technology into medical practices, particularly in knee replacement surgeries, marks a significant leap toward personalized healthcare solutions.

This literature review examines the transformative role of additive manufacturing (AM) in enhancing surgical precision, customizing prosthetic designs, and potentially reducing patient recovery times. By analyzing key studies, this review explores the advancements, challenges, and future implications of AM in knee arthroplasty, contributing to the evolving landscape of orthopedic surgery.

Smith and Doe conducted a comprehensive systematic review to evaluate the long–term outcomes of total knee arthroplasty. Their analysis consolidated data from diverse clinical studies, offering a nuanced understanding of both the clinical and functional impacts of knee replacement surgeries over extended periods [1].

Revilla–Leon and Ozcan highlighted the utility of additive manufacturing technologies in dentistry, particularly focusing on 3D metal printing for dental implants and prostheses. Their work underscores the broad applicability of AM beyond orthopedics, demonstrating its role in producing precise, patient–specific solutions [2].

Johnson and Roberts explored the impact of preoperative physical therapy on the postoperative recovery of total knee arthroplasty patients. Their findings reveal that early physical intervention significantly enhances recovery speeds, reduces rehabilitation periods, and improves long–term functional outcomes.

This study emphasizes the importance of incorporating preoperative protocols into surgical care [3]. Lee, Park, and Kim conducted a comparative analysis of various 3D printing materials for use in medical implants, assessing their mechanical properties, biocompatibility, and potential to enhance patient–specific outcomes. Their research provides critical insights into selecting optimal materials for AM–based medical solutions [4].

Green and Brown investigated postoperative pain management strategies and their influence on patient satisfaction following knee arthroplasty. By analyzing patient feedback and clinical outcomes, their study highlighted the critical role of effective pain control in improving overall surgical experiences and recovery outcomes [5]. Patel and Singh conducted a meta–analysis to evaluate the efficacy of computer–assisted surgery (CAS) in total knee arthroplasty. Their results demonstrate that CAS significantly enhances implant placement accuracy, leading to better alignment, improved surgical outcomes, and according to the methodology part of the research article, the primary goal of developing 3D–printed knee replacement prototypes is to evaluate heightened patient satisfaction compared to traditional techniques [6].

Murphy and Schwartz examined the advancements in robotic–assisted knee arthroplasty, focusing on its precision and ability to improve recovery times. Their study underscores the transformative impact of robotics in achieving higher surgical accuracy and patient satisfaction [7].

O'Neil and Hughes analyzed the role of evolving surgical techniques and postoperative rehabilitation strategies in knee replacement surgeries. Their findings highlight the importance of integrated approaches to improving recovery rates and overall patient functionality [8].

Zhang and Wong explored the potential of nanostructured materials in orthopedic implants. Their study emphasizes the superior properties of these materials in promoting implant integration and enhancing bone healing [9].

Gupta and Keshav investigated the role of patient education in improving surgical outcomes for knee replacement procedures. Their research highlights that well–informed patients exhibit better postoperative recovery rates and higher satisfaction levels, showcasing the value of comprehensive preoperative education programs [10].

Norris and Anderson reviewed advancements in minimally invasive surgical (MIS) techniques for knee arthroplasty, detailing their benefits in reducing recovery times, minimizing postoperative pain, and improving patient outcomes.

Their decade–long analysis offers valuable insights into the evolution of MIS and its implications for modern surgical practices [11].

Smith and Doe also conducted a longitudinal study comparing minimally invasive surgery to traditional approaches in knee arthroplasty. Their findings indicate that MIS significantly enhances patient recovery experiences, reduces pain, and improves long–term outcomes, making it a preferred choice in specific scenarios [12].

Lee and Patel examined the integration of 3D printing technologies in customizing knee implants. Their research illustrates how these innovations have revolutionized implant design, offering personalized solutions that align with patient–specific anatomical needs [13].

Chen and Kumar performed a comparative analysis of cemented versus cementless knee prostheses, evaluating their relative advantages in terms of implant longevity, patient recovery, and overall satisfaction. Their findings contribute to the ongoing debate over the most effective fixation techniques in knee arthroplasty [14].

Garcia and Thompson investigated various rehabilitation protocols to facilitate recovery after total knee replacement surgeries. Their study highlights the critical role of tailored rehabilitation programs in pain management, mobility restoration, and overall patient satisfaction [15].

Sanadhya et al. provided a comprehensive review of 3D printing's transformative role in healthcare, focusing on its applications in custom prosthetics, implants, and educational models. Their work underscores the broader impact of AM in personalizing medical treatments and improving patient care [16].

Mika Salmi et al. explored the efficiency of 3D printing technologies in creating personalized medical solutions, emphasizing their potential to streamline production processes while maintaining high precision [17].

Bo Sun et al. presented an overview of additive manufacturing advancements in medical applications, detailing the challenges and innovations involved in producing customized medical devices. Their study highlights AM's potential to address complex medical needs through tailored solutions [18].

Javaid and Haleem examined the role of 3D printing in revolutionizing medical treatments, particularly in the development of custom prosthetics and anatomical models, showcasing the technology's capacity for personalized patient care [19].

Thieringer, Honigmann, and Sharma explored the pivotal role of AM in creating bespoke surgical tools and implants, demonstrating how these technologies enhance surgical outcomes and optimize patient care [20]

METHODOLOGY OF RESEARCH

The primary goal of developing 3D–printed knee replacement prototypes was to evaluate the use of additive manufacturing (AM) in the fabrication of anatomically realistic and functionally feasible medical models.

These prototypes are designed to investigate the benefits of 3D printing technology in personalizing implants to improve patient–specific results in knee replacement procedures. The selection criteria for the 3D printers included their capacity to manufacture complex shapes, the resolution and precision they provide compatibility with biocompatible materials, and their proven ability to produce medical–grade prototypes.

The Stratasys F370, known for its precision and material variety; the Stratasys J835, recognized for its multi–material and full–color capabilities; and the Ender 3 V2, appreciated for its cost–effectiveness and accessibility, selected for this study.

Surface roughness was measured to evaluate the quality of the surfaces produced by the three printers using three key parameters: arithmetic mean roughness (R_a) root mean square roughness (R_q) and maximum height of the profile (R_z). These parameters are calculated using the following equations:

Arithmetic Mean Roughness (R_a):

$$R_a = \frac{1}{L}\int_0^L |y(x)|dx \qquad (1)$$

where: L: Length of the surface profile, y(x): Deviation of the surface profile from the mean line.

1. Root Mean Square Roughness R_q:

$$R_q = \sqrt{\frac{1}{L}\int_0^L y^2(x)dx} \qquad (2)$$

2. Maximum height of the profile (R_q):

$$R_z = R_p + R_v \qquad (3)$$

where: R_p: Maximum peak height, R_v: Maximum valley depth.

Hardness Analysis

Shore D hardness testing was conducted to evaluate the mechanical properties of the printed parts. Using the Hartip 3000 tool, the hardness values were correlated with material properties, such as Young's modulus (E), using the empirical relationship:

$$E = K \cdot H \qquad (4)$$

Where: E: Young's modulus (MPa), H: Shore D hardness value, K: Material – specific constant, determined experimentally.

This analysis provided insights into the durability and wear resistance of the prototypes, ensuring they could withstand the mechanical demands of medical applications.

3D Printer Specifications

- Stratasys F370: Part of the F123 series, known for its versatility and precision, with a build size of 355 x 254 x 355 mm and a layer thickness of 0.127 mm. Materials include ABS, ASA, and TPU for creating durable prototypes.
- Stratasys J835: A PolyJet printer capable of multi–material and full–color printing, with a

minimum layer thickness of 14 microns. Ideal for producing models with diverse material properties.

— Ender 3 V2: A consumer–grade printer with a build volume of 220 x 220 x 250 mm and a layer resolution of 0.1 mm, commonly used with PLA and ABS materials for conceptual models and fit testing.

For the prototypes in question, the materials were chosen based on the desired properties of the final product. The Stratasys F370 and J835 likely used advanced materials such as ABS–M30 for its mechanical strength and PC–ABS for its heat resistance, while the Ender 3 V2 likely used PLA due to its ease of printing and good surface finish.

Each material selection was aligned with the intended use of the prototype, whether for structural demonstration, functional testing, or patient and practitioner education.

Design Process

Using SolidWorks, patient–specific anatomical data is used to design knee replacement prototypes with high precision. The CAD models underwent iterative refinement for optimal biomechanical performance. The final STL files were printed, and post–processing is performed to enhance structural integrity. The settings for each printer are tailored based on the material properties and intended application of the prototypes.

Stratasys F370: Layer height of 0.254 mm, infill percentage tailored to structural requirements (20%–60%), and bed adhesion enhanced with temperature adjustments.

— Stratasys J835: Layer height of 0.014 mm for intricate details, with UV exposure fine–tuned for multi–material curing.

— Ender 3 V2: Layer height of 0.2 mm, standard infill of 20%, with adhesion aids like glue or rafts. The described methodology effectively illustrates the use of 3D printing technology in the fabrication of personalized knee replacement prototypes, demonstrating the entire process from design to final print across several printers.

This holistic approach not only meets the study's aims by emphasizing the practical uses of additive manufacturing in orthopedics, but it also establishes a foundation for future research.

This chapter ensures research reproducibility by providing a transparent and detailed account of the experimental procedures, emphasizing the importance of 3D printing in the advancement of personalized medical devices.

RESULTS AND DISCUSSIONS

The distinct characteristics of each printer made a substantial contribution to the project by providing information about the real–world uses and constraints of contemporary 3D printing technologies in the medical industry, especially with regard to the creation of orthopedic solution

Stratasys F370 results

Components that need to pass rigorous functioning and stress resistance testing can be manufactured more easily thanks to the F370's versatility in using a variety of materials.

This flexibility is essential for creating durable medical equipment tailored to individual patient requirements, highlighting the role additive manufacturing plays in advancing the creation of reliable and personalized healthcare solutions. The Stratasys F370 pieces are shown in Figure 1.

Figure 1. Knee replacement parts printed in F370

Stratasys J835 results

At the forefront of color and multi–material 3D printing, the Stratasys J835 printer can produce intricate models that accurately mimic the various densities and textures of actual tissues. This enhanced functionality gives surgeons a more complete visualization tool, which is essential for pre–surgical planning.

Additionally, by providing a better understanding of surgical procedures and anticipated results, the lifelike models enhance patient education by facilitating improved decision–making and boosting patient involvement in their care.

A comprehensive knee replacement prototype made with the Stratasys J835 printer is depicted in figure 2, showcasing the remarkable accuracy and variety of materials that 3D printing technology offers to medical applications.

Major progress in the use of additive manufacturing technology in orthopedics is indicated by the thorough replication of human knee components, which highlights the possibility for customized treatment planning and educational purposes.

Figure 2. Knee replacement parts printed in Stratasys J835

Ender 3 V2 results

The utilization of the Ender 3 V2 in this study highlights the printer's ability to efficiently manufacture models at a surprising velocity, underscoring its crucial role in rapid prototyping. Faster iterations and necessary design adjustments are made possible by this efficiency, which significantly enhances the design–to–product workflow.

The Ender 3 V2 is an essential tool in the development of knee replacement devices because of its ability to quickly alter prototypes during the prototyping phase, underscoring its crucial role in promoting innovation and product improvement.

Parts produced in Ender 3 V2 are displayed in Figure 3.

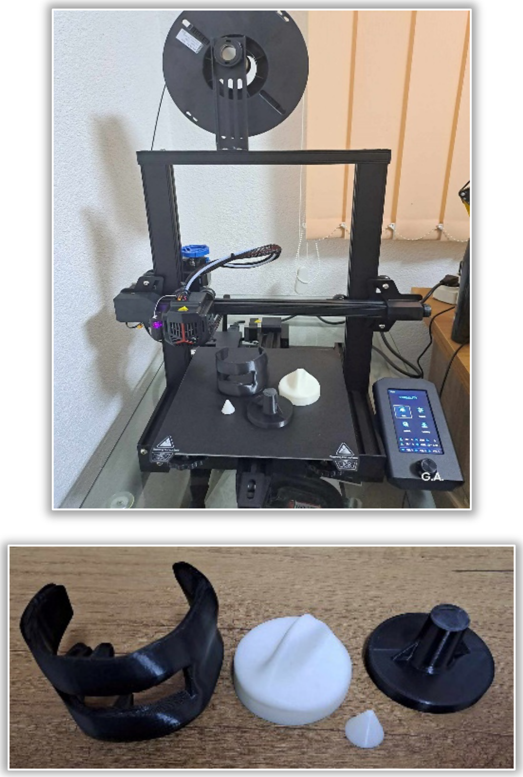

Figure 3. Knee replacement parts printed in Ender 3 V2.

Surface roughness was assessed using a comprehensive set of 28 metrics on 12 knee replacement components that were manufactured using three distinct 3D printers (Stratasys F370, J835, and Ender 3 V2, four pieces from each). Displayed a range of surface roughness values, from 6.29 for Ra min to 17.05.

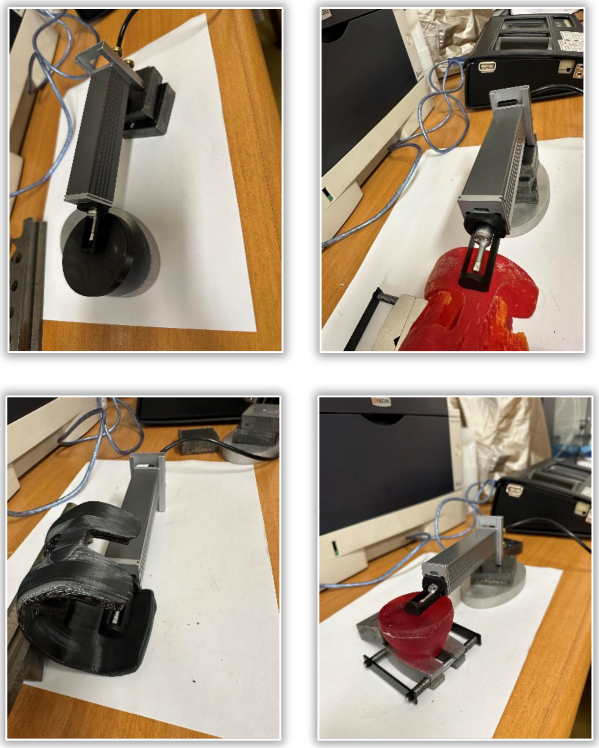

Figure 4. Roughness test for knee replacement parts

This difference demonstrates how different printing technologies can achieve surface qualities that are clinically acceptable, which is crucial for the success of medical implants.

The analysis highlights the significance of surface quality precision in meeting strict clinical criteria and offers valuable insights into enhancing additive manufacturing for medical devices. In Figure 4, is presented the test of roughness for knee replacement parts. As illustrated in Figure 4, roughness testing was conducted on several knee replacement parts using a standardized setup.

Figures 5, 6, and 7 present the certificates of inspection from the Mitutoyo SurfTest measurements, corresponding to different components assessed in this study.

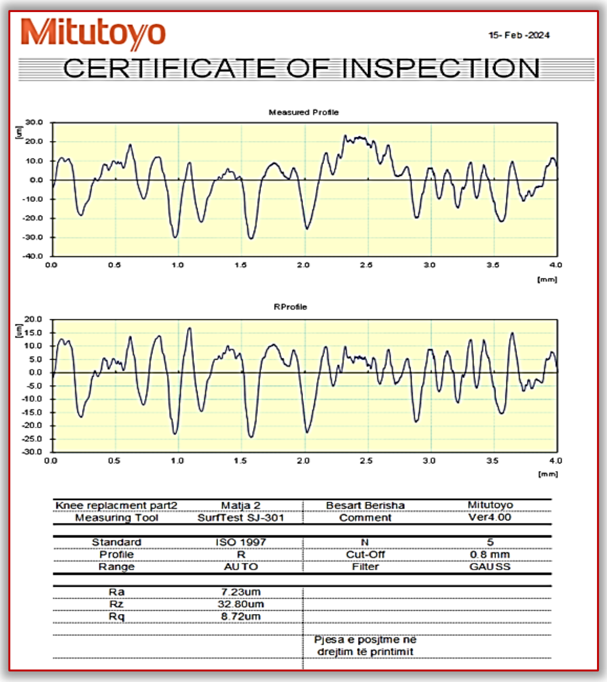

Figure 5. Certificate of inspection – Measurement 5

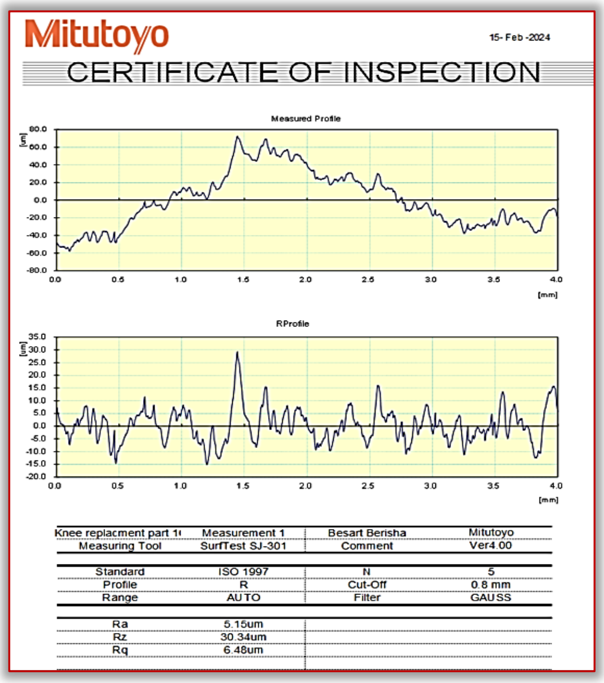

Figure 6. Certificate of inspection – Measurement 23

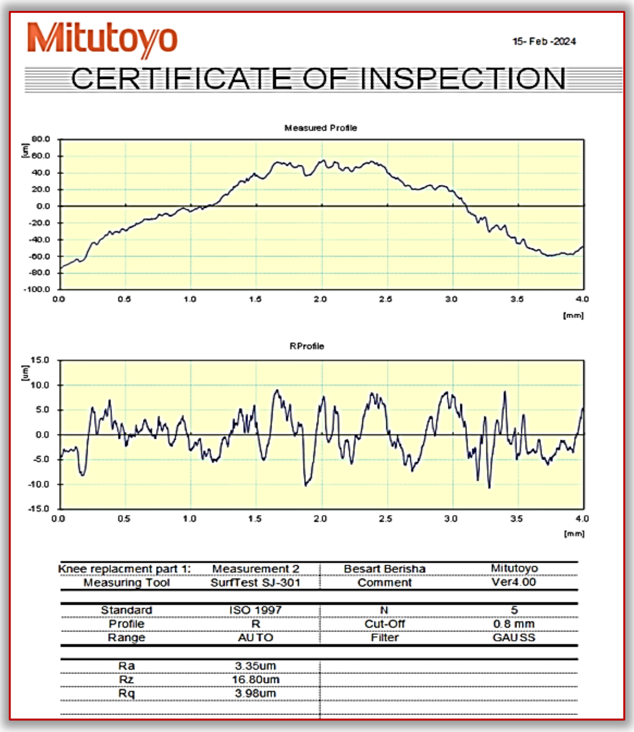

Figure 7. Certificate of inspection – Measurement 28

Table 1 presents the complete surface roughness results (*Ra*, *Rz*, *Rq*) for all parts that were inspected and certified through measurement.

Table 1. Results of all measurement Ra, Rz, Rq

No. of measurements	R_a [μm]	R_z [μm]	R_q [μm]
Measurement 1	14.11	59.80	16.56
Measurement 2	17.05	84.18	21.50
Measurement 3	13.58	60.01	16.05
Measurement 4	17.05	84.18	21.50
Measurement 5	7.23	32.80	8.72
Measurement 6	2.54	17.45	3.29
Measurement 7	14.59	64.45	17.16
Measurement 8	13.68	59.13	16.13
Measurement 9	8.93	39.40	10.48
Measurement 10	6.29	25.64	7.42
Measurement 11	16.16	69.80	19.11
Measurement 12	16.33	69.66	19.20
Measurement 13	7.53	39.30	9.65
Measurement 14	10.51	61.59	14.61
Measurement 15	7.53	39.30	9.65
Measurement 16	11.78	68.18	16.03
Measurement 17	13.57	41.02	14.83
Measurement 18	18.21	77.76	21.41
Measurement 19	10.99	64.25	15.45
Measurement 20	13.13	51.86	15.31
Measurement 21	23.46	119.90	28.49
Measurement 22	3.17	16.64	3.90
Measurement 23	5.15	30.34	6.48
Measurement 24	1.95	12.03	2.73
Measurement 25	1.39	9.47	1.85
Measurement 26	3.27	16.98	4.06
Measurement 27	2.96	17.83	3.73
Measurement 28	3.35	16.80	3.98

In addition to surface roughness, hardness tests were conducted on all parts using the Hartip 3000 tool. This further dimension of analysis enriches our understanding of the material properties imparted by each 3D printing process, offering insights into the durability and wear resistance of the knee replacement prototypes.

The integration of both roughness and hardness data provides a holistic view of the prototypes' suitability for medical application, emphasizing the multifaceted approach required to evaluate and optimize additive manufacturing for healthcare solutions.

In figure 8, upper photos shows measurement of hardness with the method of shore D which is special test for plastic parts, and on the bellow photos shows how has been carried out in the all 3D printed parts created by three different printers.

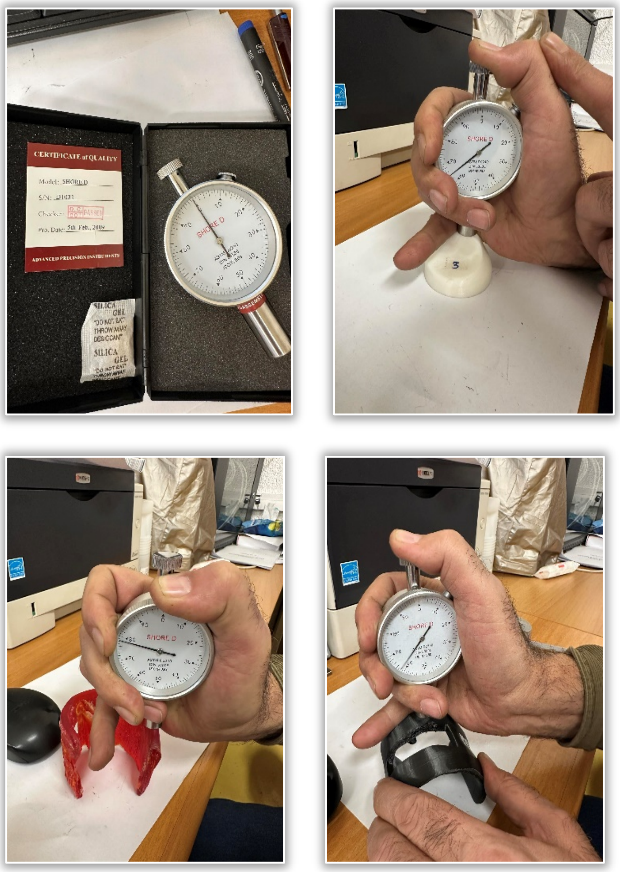

Figure 8. Hardness test with shore D

Table 2 presents the hardness measurements for twelve knee replacement parts, with four parts tested from each of the three different printers.

In Figure 9, presents a bar chart illustrating the average hardness measurements of 3D printed parts, categorized by part number. This visualization highlights the variations in hardness across the different parts, providing insights into the consistency and quality of the printing process

Table 2. Shore D Hardness Measurements for Knee Replacement Parts Produced by Stratasys F370, J835, and Ender 3 V2

Part 1		Part 2		Part 3		Part 4	
Measurement	Shore D	Measurement	Shore D	Measurement	Shore D	Measurement	Shore D
1	66	1	72	1	70.5	1	72.5
2	68	2	74	2	68	2	72
3	64	3	62	3	76	3	68
4	72	4	74	4	70	4	74
Main	67.8	Main	70.8	Main	70.3	Main	71.3
Part 5		**Part 6**		**Part 7**		**Part 8**	
Measurement	Shore D	Measurement	Shore D	Measurement	Shore D	Measurement	Shore D
1	66	1	65	1	71	1	71
2	68	2	68	2	70	2	70
3	65	3	63	3	72	3	73
4	63	4	72	4	68	4	74
Main	65.6	Main	66.8	Main	69.6	Main	71.2
Part 9		**Part 10**		**Part 11**		**Part 12``**	
Measurement	Shore D	Measurement	Shore D	Measurement	Shore D	Measurement	Shore D
1	62	1	73	1	79	1	67
2	60	2	75	2	81	2	66
3	75	3	79	3	78	3	64
4	70	4	81	4	79	4	65
Main	67.4	Main	76.2	Main	78.4	Main	66.2

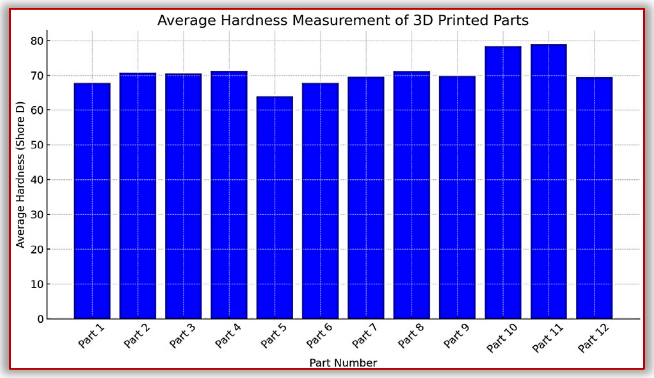

Figure 9. Average Hardness Measurement of 3D Printed Parts

CONCLUSION

This study has demonstrated the effectiveness of additive manufacturing in creating precise, patient–specific knee replacement prototypes using Stratasys F370, J835, and Ender 3 V2 printers. A strong emphasis on rigorous quality assessments, particularly roughness and hardness tests, confirms the suitability of these 3D–printed parts for medical use. Surface roughness tests verified that each part met the necessary smoothness criteria, which are crucial for patient comfort and implant durability, while hardness tests confirmed the strength of the materials under orthopedic stress. These tests are essential to ensure that the innovative solutions provided by 3D printing meet the stringent requirements of medical applications. The experimental results also demonstrated the versatility of 3D printing for medical devices, highlighting its potential to adapt and respond to the specific needs of patients.

The successful production of durable and precise parts indicates a promising direction for future research, focusing on refining printing processes and exploring new materials. As the field of additive manufacturing evolves, ongoing improvements in material properties and production accuracy will be critical for widespread adoption in clinical settings. This study provides a solid foundation for further exploration into the capabilities of 3D printing technology in healthcare.

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