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Estudio de maquinabilidad de 3 biomateriales diferentes utilizados en la fabricación de implantes

Machinability study of 3 different biomaterials used in implant manufacturing

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Guillermo Alfredo Mosquera Canchingre

DIRECTOR DEL TRABAJO DE TITULACIÓN

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1 INTRODUCTION

With the increased awareness of the health and well-being of pets, there is a growing interest in the development of advanced surgical techniques and medical devices for the treatment of diseases and injuries in animals.

In small animal clinical practice, one of the most common signs in orthopedic consultations is lameness, with hindlimb lameness being the most frequent. Among the hindlimb pathologies that manifest with lameness is cranial cruciate ligament rupture (CCLR), which occurs acutely, generally in patients who exercise frequently and are somewhat overweight, although poor joint movement in a light dog will also cause this type of injury. In a study conducted in Chile, it was reported that, of the patients who presented hindlimb lameness, with clinical signs of injury to the cranial cruciate ligament (CCL), 28% of them were positive for CCLR [1].

There are few studies of the anatomy of the CCL of canines, however, it is highlighted that its structure plays an important role in its complex behavior due to the arrangement of collagen fibrils, which due to their undulation contribute to their biomechanical properties [2].

Therefore, the TTA (Tibial Tuberosity Advancement) implant is used in veterinary orthopedic surgery to treat cranial cruciate ligament disease in dogs and according to experts, it is specified that it is the most advanced orthopedic and traumatological technique in the treatment of CCLR in dogs. It is designed to restore stability to the affected knee joint by altering the biomechanics of the joint [1]. The implant modifies the relationship between the tibia and the femur, thereby reducing stress on the injured cranial cruciate ligament and promoting healing [3].

The use of implants in animals has a long history that has evolved in parallel with advances in veterinary medicine and orthopedic surgery. The first records of the use of implants date back to rudimentary techniques applied to animals to correct fractures and bone defects, using natural materials such as wood or bones from other animals. These practices, although primitive, marked the beginning of a search for structural solutions that would restore the functionality of the limbs and improve the quality of life of affected animals [4].

With the development of modern surgery in the late 19th and early 20th centuries, metal implants such as pins and plates began to be used in orthopedic procedures in both humans and animals. During this period, advances in surgical asepsis and the availability of stronger and more biocompatible materials such as stainless steel allowed significant improvements in clinical outcomes. During the first decades of the 20th century, internal fixation techniques such as intramedullary pinning with metal plates became standard methods in the treatment of fractures in animals [4].

Figure 1 illustrates the complexity of the knee joint, highlighting the various structures that comprise it. These include bones (the femur, tibia, and patella), ligaments (lateral and medial collateral ligaments), cruciate ligaments (cranial and caudal), tendons (such as the patellar tendon), menisci, the joint capsule, infrapatellar fat, and synovial membranes [2],[5].

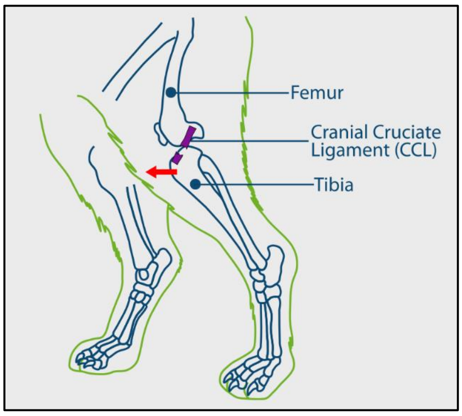


Figure 1. Unbraced CCL tear

This ligament plays a key role in the stability of the knee joint (femorotibial joint), especially in the distribution of forces and the control of movements. The biomechanics of the cranial cruciate ligament (CCL) in dogs is essential for the proper functioning of the knee and therefore for the animals to be able to walk can walk, run and perform physical activities efficiently, distributing forces evenly and protecting joint structures [2].

When the cranial cruciate ligament (CCL) ruptures, it causes a significant disruption in the knee's biomechanics. The tibia moves abnormally forward relative to the femur, a motion known as "cranial drawer." This results in a loss of knee stability, leading to pain, inflammation, and lameness. The menisci, which help distribute forces within the joint, become overloaded and are at risk of injury, further aggravating the condition. Weight distribution is altered, causing an irregular gait and compensatory stress on the other limbs, increasing the risk of secondary injuries [6]. Dogs with a ruptured CCL cannot bear weight properly on the affected limb, severely limiting their ability to walk, run, or jump.

The biomechanics of the knee are severely affected, requiring surgical intervention, such as the TTA or TPLO technique, to restore its function and allow the dog to regain a stable gait.

The Tibial Tuberosity Advancement (TTA) technique was introduced in 2002 as a treatment for cranial cruciate ligament (CCL) disease in dogs, consists of modifying the anatomy of the knee so that the cruciate ligament is not necessary. This procedure has shown excellent outcomes, achieving limb function recovery within a short postoperative period [7]. The following figure illustrates the different Tibial Tuberosity Advancement Techniques (TTAT):

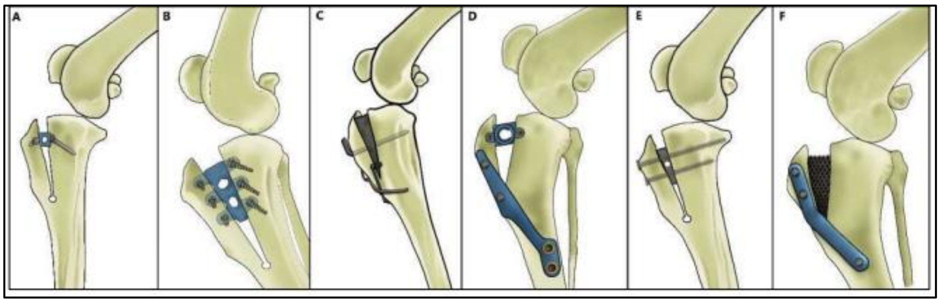


Figure 2. Graphic Illustrations of TTAT

In Figure 2. The following TTA techniques are illustrated:

- **(A)** Modified Maquet technique (MMT)
- (**B**) TTA rapid
- (**C**) Modified Maquet procedure (MMP)
- (**D**) Modified Maquet tibial tuberosity advancement (mTTA)
- (**E**) Tibial tuberosity advancement with cranial fixation (TTA-CF)
- (**F**) Porous TTA.

Among the options mentioned, *TTA rapid* has gained popularity in the market due to its simplicity and lower invasiveness compared to traditional techniques. Its design allows for faster recovery and fewer postoperative complications, making it a preferred choice for many veterinary surgeons [8]. This method simplifies the original procedure by eliminating the need for plates, pins, nails or wires. It uses a special cage that provides immediate stability and facilitates osseointegration. Its benefits include lower invasiveness and faster recovery times. However, additional studies are required to fully evaluate its efficacy and complication rates [9].

Various surgical options have been described for stabilization of the cranial cruciate ligament deficient stifle. Whilst these have typically focused on the medium, large and giant breeds, only a few studies exist regarding the optimal management of the condition in small dog breeds [10].

Small breeds have thinner cortical bones and lower bone density compared to larger dogs, which makes them more prone to fractures or implant failure if standard implants are used. Accurate preoperative planning, including precise measurement of the tibial plateau angle (TPA), is essential to ensure proper alignment and to neutralize cranial tibial thrust effectively during the TTA procedure [11].

The selection of appropriately scaled implants is critical for small breeds, as oversized implants can cause excessive stress on the tibia, leading to complications such as fractures, implant migration, or delayed healing. Modified implants, like TTA Rapid or customized solutions, have shown promise in reducing surgical trauma and improving stability for smaller dogs. Despite these challenges, studies have reported favorable clinical outcomes when proper techniques and tailored implants are used, with dogs regaining functional limb use and experiencing a low rate of complications. Postoperative care and monitoring are equally important to address any issues that may arise due to the smaller bone structure of these animals [12].

Many standard TTA systems are not specifically designed for smaller dogs, which has led to the development of variants tailored to this group. The TTA Jump!, seen in Figure 3, is an innovative implant designed to treat cranial cruciate ligament (CCL) rupture in dogs using the Tibial Tuberosity Advancement (TTA) technique [13]. Similar as the TTA rapid design, this system stands out due to its monoblock design, which integrates the plate and spacer into a single piece. This design simplifies the surgical procedure and enhances the stability of the fixation.

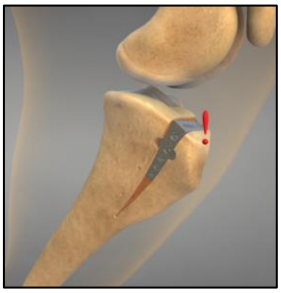


Figure 3. TTA Jump! Implant applied

Thanks to its adaptability to various sizes, as shown in Figure 4, the TTA Jump! is particularly beneficial for small breeds. Its compact structure and reduced surgical trauma contribute to a faster and safer recovery. However, the lack of published studies analyzing its specific clinical outcomes limits the full evaluation of its performance compared to other traditional TTA implants.

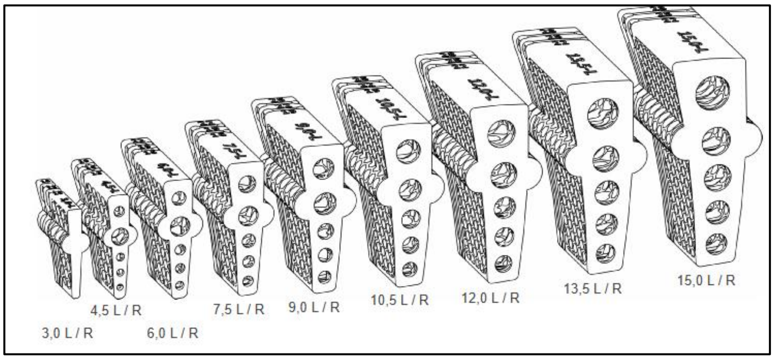


Figure 4. TTA Jump! Implant in different sizes

After the procedure Tibial Tuberosity Advancement (TTA), one common issue involves surgical site infections and inflammatory responses, which can compromise both healing and implant stability. Contributing factors include the surgical technique, the material of the implant, and the quality of postoperative care. Infection rates following TTA vary, with some studies indicating incidences as high as 15.4% in specific populations [14].

Traditionally, titanium implants have been preferred due to their strength and biocompatibility. However, in certain cases, these implants have been associated with complications such as infection, implant rejection, and inflammatory reactions, all of which can negatively affect the animal's recovery process. These challenges highlight the importance of selecting appropriate implant materials and ensuring meticulous surgical technique and postoperative care to optimize patient outcomes [15].

While mechanical characteristics such as strength and stability are critical for TTA implants, the material is equally, if not more, important for ensuring biocompatibility and minimizing complications. By selecting appropriate biomaterials, the procedure can achieve better outcomes, particularly in terms of implant longevity, reduced complications, and improved patient recovery [16]. These factors emphasize the need for careful material selection in combination with meticulous surgical planning and postoperative care to optimize the success of TTA surgeries in dogs.

Alloplastic materials represent a diverse category of synthetic biomaterials characterized by their varied structures, compositions, and mechanical and biological properties. These inorganic, biocompatible materials are widely employed as bone graft substitutes, with common examples including hydroxyapatite (HA), tricalcium phosphate (β-TCP), polymers, and bioactive glasses. However, recent histological studies suggest that synthetic grafts primarily serve as space fillers, offering limited contribution to bone and connective tissue regeneration [17].

The application of biomaterials in orthopedic and veterinary medicine has advanced significantly to address the requirements for biomechanical performance, biocompatibility, and tissue regeneration. This study focuses on three innovative biomaterials—dental resin, nylon reinforced with hydroxyapatite, and resin combined with bovine bone powder—that show great potential for improving surgical outcomes in Tibial Tuberosity Advancement (TTA) procedures for dogs.

Hydroxyapatite, a previously mentioned alloplastic material, can be derived from various animal and plant sources, including mammalian bones, bird eggshells, coral remains, and fish bones or scales [18]. Its osteoconductive properties enable surrounding bone tissue to grow on its surface, ensuring stable and durable fixation in medical applications. Being chemically inert, HA minimizes adverse reactions while providing essential structural support for bone regeneration. These qualities make HA a popular choice for dental and orthopedic implants, as well as bone substitutes.

Moreover, hydroxyapatite is often combined with other materials to enhance its mechanical and biological properties. For instance, its integration with polymers such as nylon or resins produces hybrid composites that balance elasticity, strength, and osteoconductive capabilities [19].

Bovine bone is another material extensively utilized in biomaterial engineering due to its chemical composition and structural similarity to human and animal bone tissue. As a natural alloplastic material, it undergoes specific treatments to ensure safety, reduce disease transmission risks, and enhance its efficacy in medical applications [20]. Bovine bone exhibits osteoconductive properties and, in certain cases, *osteoinductive* capabilities, enabling the formation of new bone in areas lacking bone tissue through active biological stimulation. Its accessibility, adaptability to various shapes, and straightforward preparation processes make it highly practical. However, its limited mechanical strength in its pure form can restrict its use in high-load applications.

To overcome these limitations, bovine bone is often combined with polymers, ceramics, or bioactive composites. These combinations enhance its mechanical properties, such as strength and stability, making it suitable for high-load applications. Additionally, hybrid approaches allow customization of mechanical and biological properties to meet specific patient needs. However, this involves more complex preparation methods and potentially higher costs due to additional components [21].

Resins are widely used alloplastic polymers in medical applications due to their biocompatibility, mechanical strength, and customizability. Acrylic and epoxy resins, in particular, are valued for their chemical stability and wear resistance, making them ideal for primary or supporting components in orthopedic devices. When combined with bioactive materials like bovine bone powder, resins gain improved mechanical and biological properties, making them suitable for implants requiring both structural integrity and integration with surrounding bone tissue [21].

Resins offer numerous advantages, including moldability, which allows for the production of customized implants tailored to a patient's anatomy. Their lightweight nature reduces mechanical stress on surrounding tissues, facilitating faster recovery. Furthermore, resins are compatible with advanced manufacturing technologies like 3D printing, enabling the creation of precise implants in shorter timeframes [23].

Nylon, a thermoplastic polymer from the polyamide family, is another alloplastic material extensively used in biomedical applications for its mechanical strength, elasticity, and biocompatibility. Its flexibility makes it ideal for withstanding dynamic loads, while its wear resistance ensures durability in applications such as orthopedic implants and joint prostheses [24]. Additionally, nylon's moldability allows for the creation of implants that fit perfectly to a patient's anatomy, and its biocompatibility reduces the risk of adverse reactions, making it a safe choice for long-term medical use.

The combination of nylon with hydroxyapatite (HA), a calcium phosphate that constitutes the main mineral component of bone, facilitates the integration of the implant with the surrounding bone tissue. By incorporating HA into the nylon matrix, a composite material is obtained that combines the flexibility and resistance of the polymer with the osteoconductive capacity of ceramic, promoting better osteointegration and accelerating bone formation around the implant [25].

Among the most prominent techniques for manufacturing medical implants are milling and 3D printing, each with unique characteristics that respond to diverse clinical and design needs. These technologies allow working with a wide variety of materials, from metals to polymers, ensuring precision and adaptability. Both techniques are explored below.

Milling is a machining process widely used in the manufacturing of medical implants, including orthopedic and dental implants, due to its ability to create precise, high-quality parts. This process involves the controlled removal of material from a solid block using a rotating tool (milling cutter), allowing complex geometries to be obtained with exact tolerances.

High-precision implants can be manufactured using CAD/CAM assisted milling to meet specific clinical needs. This method is particularly useful for working with materials such as titanium, stainless steel, cobalt-chrome and polymers such as the previously mentioned resin and nylon. This machining method guarantees smooth surfaces and quality finishes.

However, because milling is a subtractive process, it can generate a higher volume of waste compared to methods such as 3D printing, and high-precision milling machines and dedicated cutting tools can be expensive, especially for low-volume production.

3D printing technology has revolutionized the manufacturing of implants, especially those made from resins. Its ability to create complex structures quickly and accurately makes it a key tool in personalized medicine and implant engineering. 3D printing makes it possible to design and produce devices tailored to the specific anatomical needs of each patient, optimizing both the functionality and integration of the implant.

This process offers an efficient and precise solution for the manufacture of resin implants, highlighting its ability to speed up the production process. Unlike traditional machining methods, this technology allows implants to be obtained in a matter of hours, which is particularly beneficial in clinical situations that require a rapid response. In addition, 3D printing minimizes material waste, since it uses only the amount necessary to create the implant, reducing the costs associated with waste.

Compatibility with bioactive materials also represents a key advantage of 3D printing in resin implants. The resins used can be combined with bioactive coatings to enhance osteoconduction, facilitating bone growth around the implant [23]. This versatility in the use of materials significantly expands the clinical applications of the technology, making it indispensable in the engineering of custom implants.

Although 3D printed resins are precise and customizable, their mechanical strength may be lower than that of other materials. There are even materials that cannot yet be manipulated with 3D printing, such as a resin mixed with bone powder or nylon with hydroxyapatite.

The 3D printers used for manufacturing the implants are the following:

- Anycubic Photon Mono SE
- Elegoo Mars 4 Ultra

In a study, the aim was to describe the postoperative results of the tibial tuberosity advancement (TTA) in canines with the cranial cruciate ligament (CCL) rupture. The treated animals presented positive results in the evaluation due to good stabilization of the knee, so the technique is considered an option to treat CCLR in canines [26].

Implants made from biocompatible materials, are less likely to be rejected by the recipient animal's body. This reduces the risk of complications and increases the likelihood of successful integration of the implant into the patient's biological tissue. In addition, it offers mechanical properties similar to those of natural bone, which can improve implant stability and durability [27].

Using materials derived from biomaterials may be a more sustainable and ethical option compared to other synthetic materials derived from non-renewable sources or with more intensive manufacturing processes. Evaluating the effectiveness of these materials in implants for the TTA technique could promote more sustainable practices in veterinary medicine.

The primary *objective* of this thesis is:

Study the machinability of 3 different biomaterials used in for implant manufacturing.

To ensure compliance with the general objective, the following *specific objectives* have been set:

- Define an implant to manufacture using the biomaterials.
- Find a process windows in which the implants can be machined using the 3 tested materials.
- Evaluate the machinability of the biomaterials to manufacture the specific implant selected.

2 METHODOLOGY

The methodology for this study was guided by specific functional and non-functional requirements to ensure the successful machining and evaluation of biomaterial implants. For the conceptual design of the investigation, the selection of biomaterials was performed, specifying the implant size and the machining tools required. The specific design of the study outlined the materials to be machined and detailed how these materials were acquired. Additionally, cutting parameters such as feed rate, spindle rate, cutting-in amount, path interval and finishing margin, were defined. The evaluation criteria for the results were established, focusing on machining time and overall performance of the implants.

2.1 REQUIREMENTS

2.1.1 FUNCTIONAL REQUIREMENTS

- ***Implant Comparison***: Comparison of machined implant dimensions. Ensure that dimensions such as length, diameter and geometric shapes are accurately measured.
- ***Simulation of Machining Process***: Simulate the machining process necessary for the preparation of implants, such as milling and 3D printing.

2.1.2 NON-FUNCTIONAL REQUIREMENTS

- ***Compatibility:*** Must be compatible with existing medical systems and devices used in the TTA technique.
- ***Optimal Sizing:*** optimal sizing of the implants, taking into account the characteristics of the type of implant to be machined.
- ***CNC machine:*** for machining it is necessary to take into account the characteristics of the milling machine to be used. In this case the approach is to use the MDX 40A. In the same way, the 3D printer that should be used must be determined.
- ***Evaluate quality:*** visual examinations of the obtained implants will be performed to evaluate the quality of the machined surface of the implant.

2.2 CONCEPTUAL DESIGN

2.2.1 SELECTION OF MATERIAL TYPES

- *Dental resin* was selected for this investigation due to its exceptional versatility and adaptability, making it an ideal material for implant machining. Its inherent properties, such as biocompatibility, moldability, and ease of processing, allow for the creation of highly precise and customized implants tailored to meet specific anatomical requirements. Additionally, dental resin offers excellent surface finish quality after machining, ensuring smooth and uniform surfaces that are essential for minimizing tissue irritation and enhancing implant integration. Its compatibility with advanced manufacturing technologies, such as CAD/CAM systems, facilitates efficient and accurate production, reducing lead times and ensuring consistent results. These features, combined with its ability to integrate with bioactive materials like bovine bone powder, further support its selection, as it enables the development of implants that not only provide mechanical stability but also promote bone regeneration and integration with surrounding tissue [23].

- The use *of resin combined with bovine bone powder* in this investigation is justified by the synergistic benefits this composite material provides for implant machining and performance. Resin serves as a structural matrix, offering rigidity, moldability, and ease of processing, while bovine bone powder contributes bioactive properties essential for enhancing the implant's integration with the surrounding bone tissue.
  Bovine bone powder promotes osteoconduction, allowing bone cells to attach and grow on the implant's surface. In some cases, the material also exhibits osteoinductive properties, stimulating the formation of new bone tissue in areas where it might otherwise be absent. This makes the composite particularly valuable for applications requiring both mechanical support and biological activity [16].
  The resin ensures machinability and customization, enabling precise shaping of the implant to meet patient-specific anatomical needs. Meanwhile, the inclusion of bone powder enhances the bioactivity of the implant, improving integration and reducing the risk of implant failure. This hybrid approach addresses both the mechanical and biological requirements of modern implantology, making it a compelling choice for the study [21].

- *Hydroxyapatite combined with nylon* was chosen for its ability to effectively balance both mechanical and biological properties. Nylon, recognized for its flexibility and wear resistance, serves as a structural component that can withstand dynamic loads and adapt to the natural movements of the body. In contrast, hydroxyapatite is a bioactive ceramic that closely mimics the mineral structure of natural bone, offering outstanding osteoconductive properties. It promotes bone cell adhesion and stimulates bone growth, ensuring that the implant integrates seamlessly with the surrounding tissue [28]. Together, nylon provides the necessary strength and durability, while hydroxyapatite enhances the material's biological compatibility, fostering bone regeneration. This combination results in a composite that maintains mechanical stability while simultaneously supporting the body’s natural healing process. The synergy of these two materials effectively meets the functional and biological needs of orthopedic implants, making them an ideal choice for the study.

2.2.2 IMPLANT SIZING

Figure 5 shows the design of the implant with their respective dimensions to be machined.

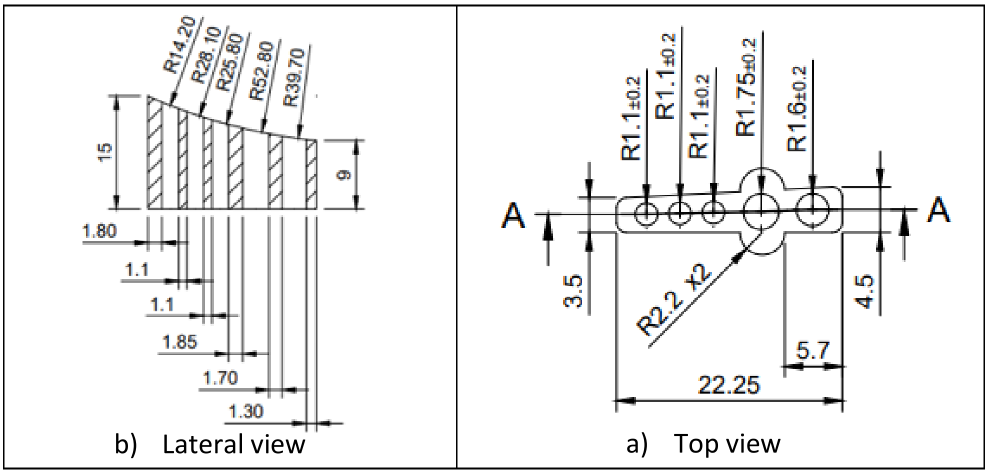


Figure 5. Implant dimensions

The implant contains a curved, anatomically aligned design. In comparison to a flat geometry, a curved shape creates additional radial directed forces when tensile forces are loaded. The radial directed forces creates pressure between tuberosity, TTA cage and tibia and stabilize the implant position. With the presence of multiple fixation holes it ensures better distribution of mechanical stress, which is key in small breeds where implant stability must compensate for lower natural bone strength The benefit of the screwless design is self-explaining and reduces the risk of fractures close to the screws [13].

The design of the implant was made to accurately match the anatomy of the dog's tibia and surrounding structures to minimize tissue trauma, promote proper healing, and optimize biomechanical function. The design of the implant allows for straightforward and precise surgical placement using standard TTA surgical techniques.

There is the possibility of customizing its dimensions and adapting it to each patient, since the implant will be manufactured using resins or nylon.

2.2.3 TOOLS FOR MACHINING

The machines in Figure 6 and Figure 7 were used for machining the implants.

- Modela MD40-A milling machine [29]:

Figure 6. Modela MDX-40A 3D Milling Machine

- Elliot U2 universal milling machine:

Figure 7. Elliot U2 universal milling maching

For machining, a 3.175 mm of diameter 2-flute cemented carbide cutter will be used, as shown in Figure 8:

Figure 8. 3.175 mm of diameter 2-flute cemented carbide cutter

This tool was chosen because cemented carbide (tungsten carbide) is an extremely hard and wear-resistant material, making it ideal for machining abrasive materials such as resins with reinforcements (bone powder or hydroxyapatite). Unlike high-speed steel (HSS), carbide maintains its edge for longer, which improves precision and machining quality.

The 2-edge configuration offers greater space for chip evacuation, which is essential when machining soft materials such as resins or polymers, avoiding excessive heating and the risk of melting or deformation.

For details and hole making, 1, 2 and 3 mm cemented carbide cutters will be used, as can be seen in Figure 9:

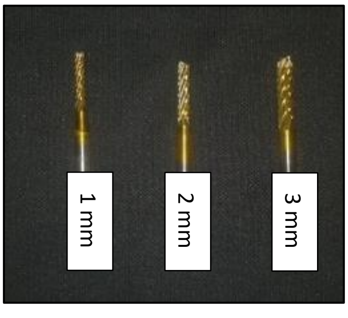


Figure 9. Cutters used for details

2.3 SPECIFIC DESIGN

2.3.1 MATERIALS TO BE MACHINED

A more detailed description of each material to be machined is given below:

- ***nylon + hydroxyapatite (HA)*** shown in Figure 10 is a block made of Nylon, which, despite being flexible, becomes more abrasive when combined with ceramic particles such as hydroxyapatite. In this case, a composition of 30% hydroxyapatite will be used, as this proportion ensures the material remains suitable for machining. A higher concentration of hydroxyapatite could increase brittleness or make the material more challenging to cut:

Figure 10. Block of nylon + hydroxyapatite

- ***Dental resin*** shown in Figure 11 is a dental resin named "Gingivial by Jamg He," which complies with ISO 10993, ensuring it does not cause adverse reactions such as toxicity, inflammation, or rejection. After printing and machining, a resin implant must undergo a series of treatment and curing processes to be considered a biomaterial suitable for medical and clinical applications. These processes enhance its biocompatibility, mechanical strength, and safety. In some cases, a combination of UV and thermal curing is used to maximize mechanical properties and chemical stability:

Figure 11. Block of resin

- ***Resin + bovine bone powder (BBP)*** shown in Figure 12, is a resin combined with bovine bone powder, an innovative composite material designed to integrate the mechanical properties of resin with the bioactivity of processed bovine bone. With a composition of 70% resin and 30% bone powder, this material achieves a balance between structural strength and osteoconductive capacity, making it ideal for orthopedic implants and bone regeneration. The resin serves as a matrix, ensuring dimensional stability and ease of machining, while the bovine bone powder—processed through demineralization and delipidization—promotes integration with surrounding bone tissue. This hybrid material enables the fabrication of customized implants that combine mechanical functionality with biological properties, optimizing clinical outcomes:

Figure 12. Block of resin + bovine bone powder

To obtain this block the following was done:

1 The volume of the mold (cylinder) that was used to create the mixture is calculated:
r = radius
h = height

$$V = \pi r^2 h$$
$$V = \pi * 2.25^2 * 2$$
$$V = 31.81\ cm^3$$

2 The percentage of resin and bone powder was determined with the following formulas:

$$(Resin)\ 70\ \% \ \rightarrow 0.7 * 31.81 = 22.26\ cm^3$$

$$(BBP) 30\% \rightarrow 0.3 * 31.81 = 9.54\ cm^3$$

3 In order for the resin to harden, a catalyst must be used, and this was calculated as follows:

- The resin usage factor to be used is 2:1
- Resin is element ***A***
- Catalyst is element ***B***

$$\frac{22.26}{1.5} = 14.84\ cm^3\ of\ element\ (A)$$
$$22.26 - 14.84 = 7.42\ cm^3\ of\ element\ (B)$$

4 Both components, resin and bovine bone powder, are mixed until a homogeneous composition is achieved, followed by a drying period of 72 hours at 25°C.

2.3.2 CUTTING PARAMETERS

In machining materials, such as in the manufacture of implants, it is essential to control certain parameters that directly affect the quality of the final product, the performance of the tool and the efficiency of the process.

- *Feed Rate:* is the speed at which the cutting tool advances through the material during the machining process (mm/min).
- *Spindle Speed:* refers to the rotation speed of the spindle, that is, the number of revolutions per minute (RPM) that the cutting tool performs.
- *Cutting-in Amount:* refers to the depth of material removed in one pass of the cutting tool (mm). This value can be adjusted depending on the type of material and the capabilities of the machine and tool.
- *Path Interval:* is the distance between consecutive tool paths during machining (mm). This parameter is crucial to achieve a uniform finish and avoid unmachined areas.
- *Finish Margin:* It is the amount of material that is intentionally left on the piece during the roughing process, with the aim of removing it in the final finishing operation (mm).

2.3.3 EVALUATION CRITERIA

The previously defined cutting parameters—feed rate, spindle speed, depth of cut, path interval, and finishing margin—were analyzed during the machining of the selected materials: pure dental resin, resin with bovine bone powder (70%-30%), and nylon with hydroxyapatite (70%-30%). Table 1 below presents the cutting parameters for each material.

Table 1. Cutting parameters for each material

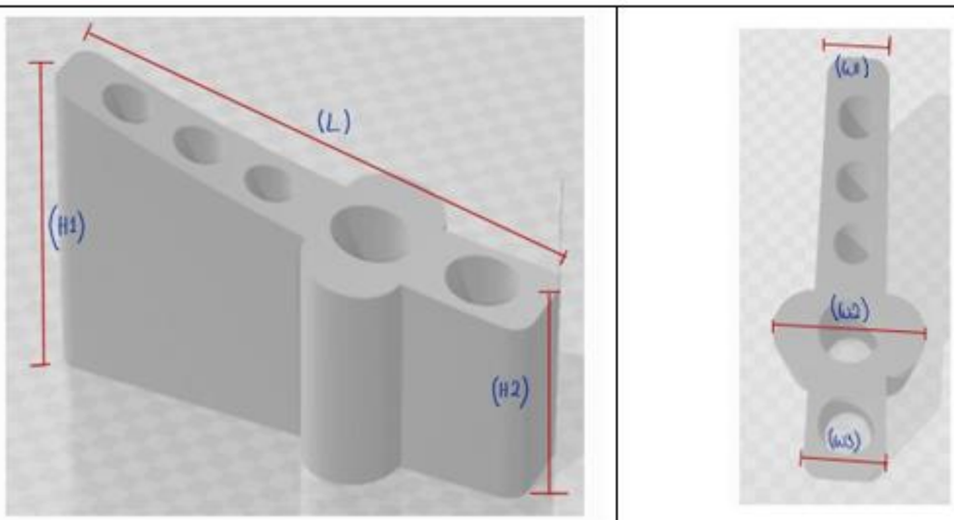
Material	Tool	Feed rate (mm/min)	Spindle (RPM)	Cutting-in Amount (mm)	Path Interval (mm)	Finish Margin (mm)	Machining time (hours)
Dental Resin	cemented carbide	540	8000	0.20	0.80	0.20	1.4
	cemented carbide	360	8000	0.20	0.80	0.20	1.6
	cemented carbide	340	8000	0.20	0.80	0.20	1.9
Resin + BBP	cemented carbide	540	8000	0.20	0.80	0.20	2.2
	cemented carbide	360	8000	0.20	0.80	0.20	2.9
	cemented carbide	340	8000	0.20	0.80	0.20	3.0
Nylon + HA	cemented carbide	540	8000	0.20	0.80	0.20	2.6
	cemented carbide	360	8000	0.20	0.80	0.20	3.0
	cemented carbide	340	8000	0.20	0.80	0.20	3.1

The influence of the type of material on the machining time will be evaluated under constant conditions for certain parameters and varying the feed rate.

3 RESULTS

Dimensional control in CNC parts is an essential process to ensure precision and quality in manufacturing. It involves the precise measurement of the dimensions of a part to ensure that it meets the specifications established in the design. This process is critical to detect and correct any deviation that may affect the functionality and quality of the final product.

Measurements were made using advanced metrology tools and equipment that guarantee high accuracy and repeatability. In this case, digital calipers were used, a tool used to measure specific dimensions with high precision. The following dimensional control shown in Figure 13 was carried out on the implants obtained by milling and 3D printing:



b) Lateral view

a) Top view

Figure 13. Dimensional control of the implant

Of the three samples obtained from each milling test, only the measurements of the *best-produced* piece will be considered. These measurements are presented in Table 2.

Table 2. Dimensional Control for each material compared to CAD design

Dimension Type (mm)	CAD design	Resin + BBP	Dental resin	Nylon + HA	3D print of Dental resin
Length (L)	22.5	21.8	22.3	22.4	22
Height bottom (H1)	15	14	14	15.1	14.6
Height top (H2)	9	8.5	9.1	8.9	9
Width bottom (W1)	3.5	3.9	3.8	4.2	3.5
Width center (W2)	8.5	9	9	9.1	8.4
Width top (W3)	4.5	4.9	4.7	4.5	4.4

- Machined Materials: Resin + BBP and Nylon + HA showed higher dimensional variations compared to the CAD design, especially in the dimensions related to width (W1, W2, W3). This can be attributed to the abrasive nature and heterogeneous distribution of their components. Dental Resin showed better agreement, with minor deviations in length and height.
- 3D Printed Model: The 3D printing of the dental resin showed consistent dimensional values but with minor deviations in length (-0.5 mm) and width (-0.1 mm in W3). These variations can be attributed to the printer resolution and shrinkage during curing.

The relationship between machining time and feed rate for Dental Resin was analyzed based on the data presented in Table 1. This analysis aimed to evaluate the impact of varying feed rates on the total machining time required to produce the implants. The results are illustrated in the corresponding Figure 14, which highlights the inverse relationship between feed rate and machining time.

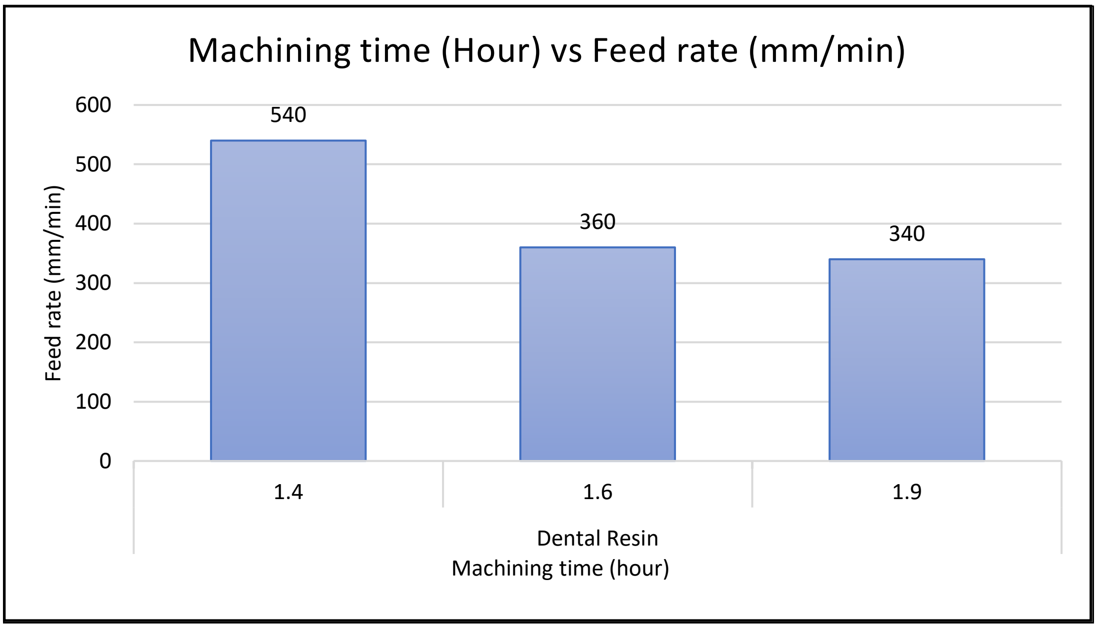


Figure 14. Machining time vs Feed rate (Dental Resin)

These results are consistent with the expected behavior of subtractive manufacturing processes, where higher feed rates allow the cutting tool to traverse the material more quickly, thereby reducing the overall machining time. However, achieving these results was possible due to the machinability of Dental Resin, which demonstrated a good balance between material removal rate and surface finish quality, even at varying feed rates. This characteristic makes it a suitable material for processes requiring precision and efficiency, as highlighted in the graph.

The relationship between machining time and feed rate was similarly analyzed for the composite material consisting of resin mixed with 30% bovine bone powder. The data presented in Table 1 was used to generate Figure 15 illustrating this relationship, which further highlights the inverse correlation between feed rate and machining time.

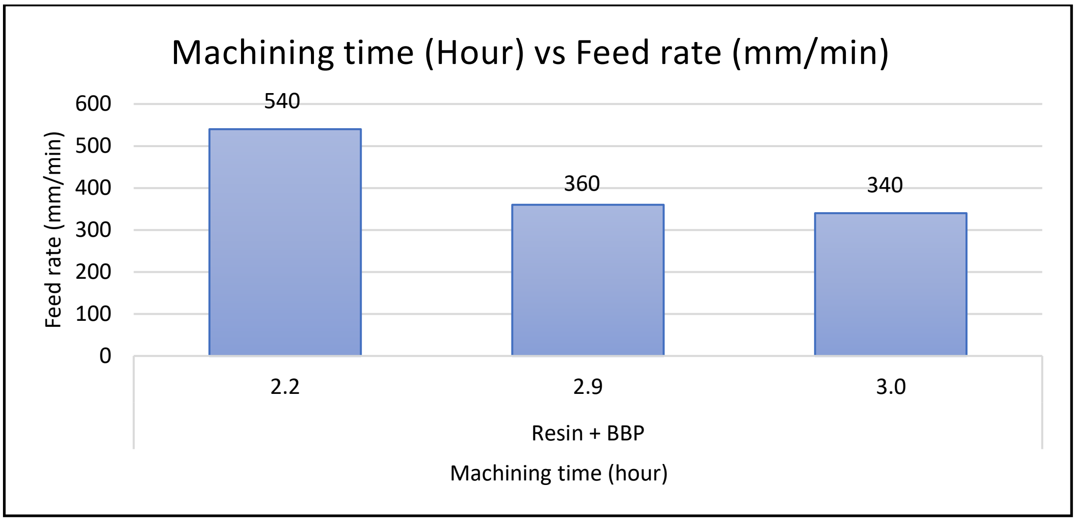


Figure 15. Machining time vs Feed rate (Resin+BBP)

Despite the increased machining times, the composite material demonstrated good machinability, balancing mechanical properties with biocompatibility. This suggests that resin combined with bovine bone powder is a viable option for implant manufacturing, provided that process parameters such as feed rate are carefully optimized to meet production efficiency and quality standards, as depicted in the graph.

The analysis of machining time versus feed rate was also conducted for the composite material consisting of nylon with 30% hydroxyapatite. Using the data in Table 1, Figure 16 was generated to visualize this relationship, further confirming the inverse correlation between feed rate and machining time.

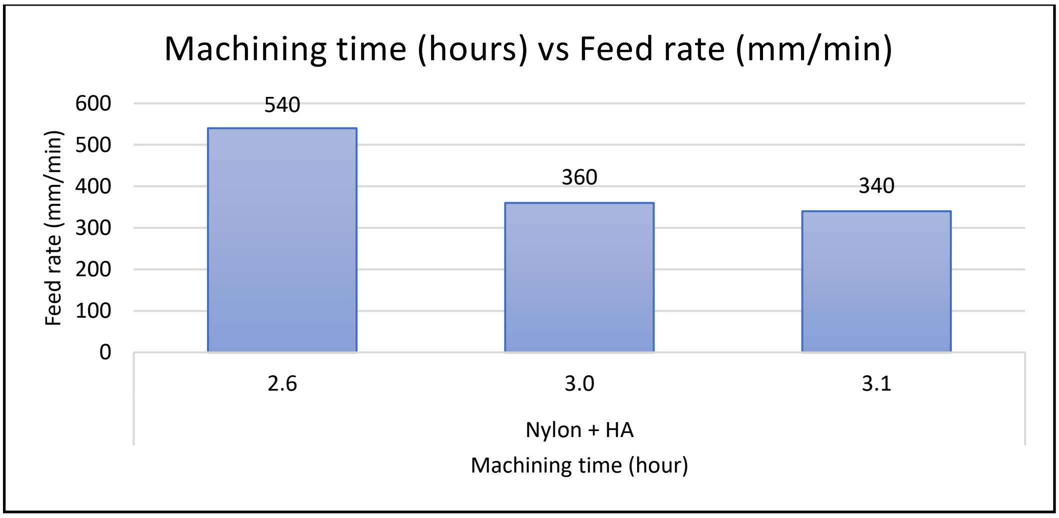


Figure 16. Machining time vs Feed rate (Nylon+HA)

The longer machining times compared to the other materials analyzed can be attributed to the unique combination of nylon's flexibility and hydroxyapatite's ceramic-like hardness. This combination makes the composite more resistant to material removal, particularly at lower feed rates, where tool engagement with the harder hydroxyapatite particles is more pronounced.

Despite these increased machining times, the nylon-hydroxyapatite composite offers a balanced blend of mechanical flexibility and osteoconductive properties, making it a strong candidate for orthopedic implants.

At the highest feed rate (540 mm/min), machining times were significantly reduced for all three materials. However, this came at the expense of surface finish quality, which was compromised due to the rapid material removal. Conversely, a lower feed rate (340 mm/min) resulted in superior surface finishes, but at the cost of extended machining times. The increased operating times also translate to higher energy consumption, greater tool wear, and elevated labor costs, which may impact the economic feasibility of mass production.

Among the tested materials, dental resin exhibited the shortest machining times across all feed rate combinations. This can be attributed to the material's lower mechanical resistance and abrasiveness, which reduce the tool's cutting effort and, consequently, the overall machining time.

In contrast, resin mixed with bovine bone powder and nylon combined with hydroxyapatite showed longer machining times. The inclusion of compounds derived from bovine bone and hydroxyapatite increased the abrasiveness of these composites, making them more challenging to machine. This heightened abrasiveness not only prolonged machining times but also contributed to increased tool wear.

These machining characteristics are further analyzed in Figure 17, which illustrates the dimensional deviations observed across different fabrication processes and materials compared to the original CAD design. The specific dimensional differences are summarized in Table 2, highlighting the impact of material properties and machining parameters on the precision of the manufactured implants.

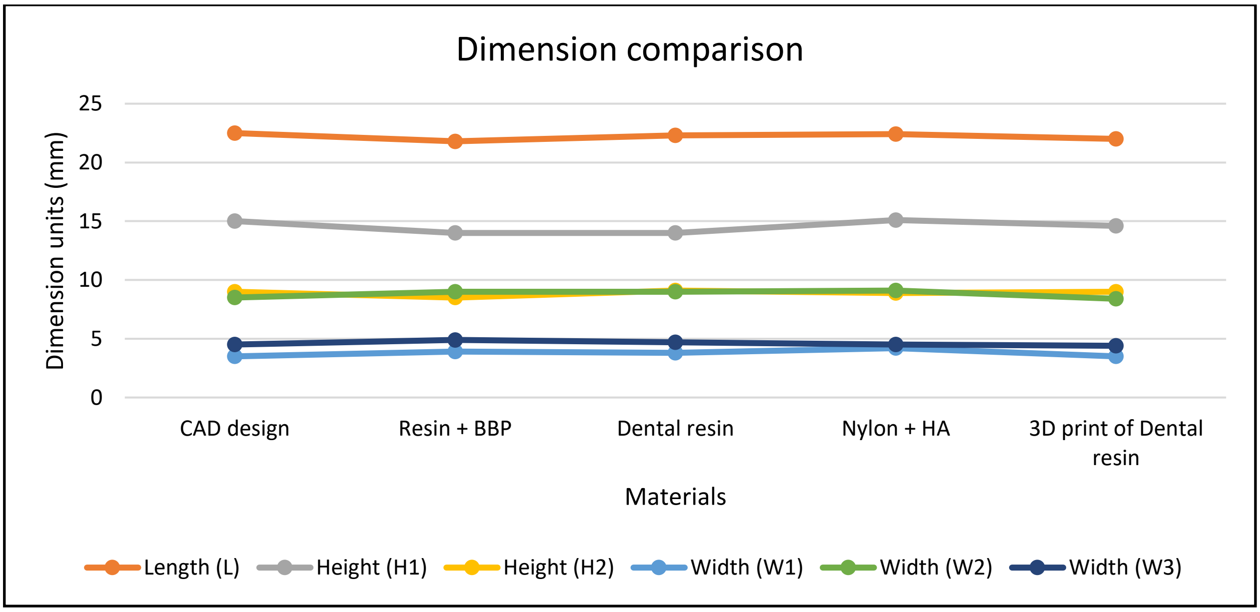


Figure 17. Dimensional differences in each studied material

The CAD design serves as a reference, representing the ideal dimensions. For Length (L), a slight reduction is observed in Resin + BBP (21.8 mm) compared to the CAD design (22.5 mm), while other materials show small positive or negative deviations. In the case of Height (H1), significant variations are present. Both Resin + BBP and Dental Resin fall below the CAD value (14 mm versus 15 mm), whereas Nylon + HA exceeds it slightly (15.1 mm). For Height (H2), the variations are minimal, with Dental resin being the closest to the original design.

The Width (W1, W2, W3) measurements exhibit greater dispersion. For instance, Nylon + HA and Resin + BBP show values exceeding the CAD design, suggesting dimensional accumulation or expansion, likely caused by the materials' abrasiveness and machining processes. On the other hand, 3D print of Dental resin tends to align more consistently with the CAD dimensions, though slight deviations are evident, particularly in Length (L) and Width (W3). These variations could result from the printer's resolution and material shrinkage during curing.

An analysis of the percentage variations highlights that 3D print of Dental Resin has the lowest average deviation (1.38%) across all dimensions, making it the most dimensionally accurate among the tested materials. This precision underscores the advantage of 3D printing in producing implants closely matching CAD specifications, even though minor deviations in Length (L) and Width (W3) reflect the inherent limitations of additive manufacturing processes. Conversely, Nylon + HA and Resin + BBP exhibit higher variations, particularly in Width dimensions, likely due to their composition and increased abrasiveness, which can influence tool wear and machining consistency. The findings suggest that while machined materials like Nylon + HA offer excellent mechanical properties, 3D printed Dental Resin provides superior dimensional accuracy, positioning it as a favorable option for applications requiring strict adherence to CAD designs.

Overall, the graph highlights how the material properties and fabrication method significantly influence the dimensional accuracy of the final product. While 3D printed model show better alignment with the CAD design, composite materials like Resin + BBP and Nylon + HA introduce challenges that affect dimensional precision due to their higher rigidity and abrasiveness.

Figure 18 demonstrates precise dimensional features, including uniform holes and smooth edges, highlighting the capability of 3D printing to achieve high geometric accuracy and a consistent surface finish. The well-defined structure aligns closely with the CAD design, making this method effective for producing intricate implant geometries.

Dental Resin (3D printing):

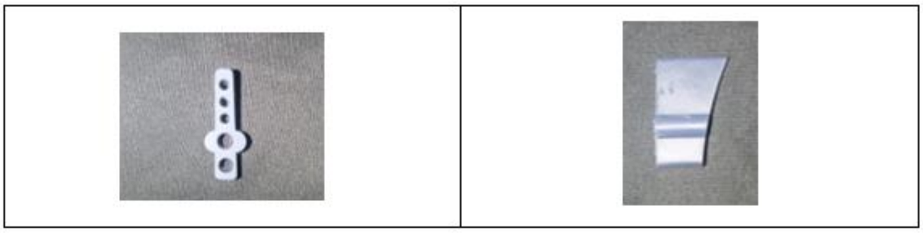


Figure 18. Dental resin (3D printing)

The analysis carried out in Table 2 took into account the best implants obtained by machining, that is, the elements that had a feed rate (mm/min) of 540 and 360. In the following images is shown how the dimensions resulted affected by the speed at which the cutting tool was established.

Dental Resin (mechanized):

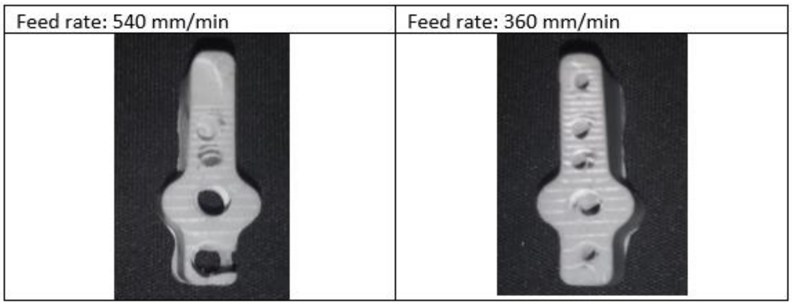


Figure 19. Dental Resin (mechanized) implants

It is a relatively brittle material with low impact resistance. If excessive cutting forces are applied, the resin may fracture, especially if it is not fully cured or contains internal defects. As shown in Figure 19, it was determined that at a feed rate of 540 mm/min, the piece did not achieve the expected characteristics. The material lacked sufficient resistance to the applied load, and details such as the holes were not properly formed.

Resin + BBP :

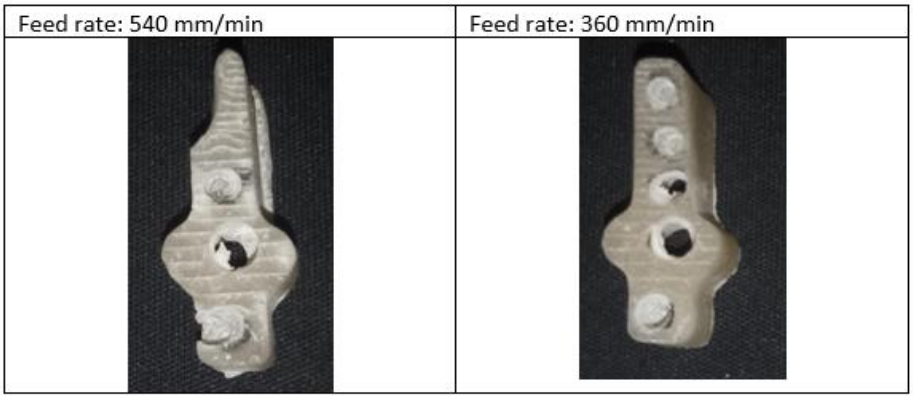


Figure 20. Resin + BBP implants

The addition of bovine bone powder introduces stiffness and abrasiveness, but can also generate weak zones in the material matrix. These zones are prone to fracture under mechanical loads during machining. In addition, uneven distribution of bone powder can lead to stress concentrations, increasing the likelihood of fracture. As shown in Figure 20, when using a feed rate of 540 mm/min and allowing the machine to develop minor details such as the holes in the upper and lower sections, the piece ended up breaking in those areas.

Nylon + HA:

Feed rate: 540 mm/min	Feed rate: 340 mm/min
	

Figure 21. Nylon+HA implants

Although nylon is stronger and more flexible, the addition of hydroxyapatite increases stiffness and abrasiveness, which can make the material less tolerant of errors in machining parameters. As shown in Figure 21, the piece had to be resized in certain areas, such as the height bottom (H1), the center (W2), and the width bottom (W1), according to the nomenclature in Table 2, to achieve results closer to expectations. Unlike the previous materials, it did not exhibit any breakage during machining, making it one of the materials that best adapted to the established feed rate.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

This study achieved its objectives of evaluating the machinability of three biomaterials for implant manufacturing, providing valuable insights into their performance under varying machining conditions.

Dental resin was highlighted as the most suitable material for manufacturing implants where the priority is to minimize machining times. Its low mechanical strength and abrasiveness facilitate the work of the tool and produce dimensional results closer to the original design. However, its fragility under high loads could limit its use in applications requiring high structural strength.

In contrast, Resin with Bovine Bone Powder and Nylon with Hydroxyapatite exhibited higher mechanical strength and bioactivity but presented greater challenges during machining. These materials' abrasiveness and stiffness significantly increased machining times, with Resin + Bone Powder requiring up to

3 hours at lower feed rates, compared to 1.6 hours for Dental Resin. Nylon with Hydroxyapatite also demonstrated prolonged machining durations, taking 2.6 to 3.1 hours depending on feed rate. These findings underscore the need for precise optimization of machining parameters to enhance production efficiency for these materials, particularly in mass production contexts.

A feed rate of 360 mm/min emerged as an optimal balance between surface finish quality and machining time across all materials. This parameter reduced fracture risks in brittle materials like Dental Resin and minimized overheating and tool wear when machining abrasive composites like Resin + Bone Powder and Nylon + Hydroxyapatite.

During the preparation of Resin with Bovine Bone Powder, clusters of bone powder were observed in the composite matrix. These non-uniform agglomerations likely influenced the machining process, creating localized stress concentrations that affected tool performance and dimensional consistency. This highlights the importance of improving material homogenization techniques to enhance machining results and ensure uniform part quality.

Finally, while the addition of bone powder to the resin expanded the clinical applications of the implant by introducing bioactive properties, it also created weak zones in the matrix, increasing the risk of fractures during machining. The non-uniform distribution of the bone powder presented challenges in achieving dimensionally consistent parts. Despite these limitations, the combination of biological and mechanical properties in these materials offers promising opportunities for innovative implant designs that cater to diverse clinical needs.

4.2 RECOMMENDATIONS

Future research should investigate other biocompatible materials such as polyetheretherketone (PEEK) or titanium-reinforced composites, which have demonstrated high mechanical strength and biocompatibility. PEEK, for instance, offers excellent thermal stability and is lightweight, making it an ideal candidate for load-bearing implants. Titanium-reinforced composites, on the other hand, provide superior mechanical properties and osteointegration, which are essential for orthopedic applications. These materials could be tested in scenarios involving high-impact forces to determine their suitability in various clinical contexts.

Additionally, materials with tailored biodegradability, such as polylactic acid (PLA) or calcium phosphate composites, could be studied for temporary implants that gradually integrate with or dissolve into the host tissue. Such materials are particularly valuable in applications requiring temporary support, such as fracture fixation plates or scaffolds for bone regeneration. Exploring different processing techniques for these biodegradable materials, including additive manufacturing and controlled crystallization, could enhance their structural integrity while maintaining their bioactive properties.

Further studies could evaluate the impact of varying ratios of components (e.g., resin-to-bone powder or nylon-to-hydroxyapatite ratios) on machinability and implant performance. Adjusting these ratios could influence the material's mechanical properties, such as stiffness, tensile strength, and abrasion resistance, enabling customization for specific clinical applications. For instance, increasing the proportion of bone powder might enhance bioactivity but could also increase brittleness, necessitating a careful balance.

Testing additional reinforcing agents, such as silica particles or fiber reinforcements, could further improve strength and reduce dimensional deviations during machining. Silica particles could enhance hardness and wear resistance, while fibers might provide better toughness and crack propagation control. Experimental studies could focus on the dispersion quality of these reinforcements and their impact on both mechanical and thermal properties, ensuring optimal performance during and after machining.

To address challenges in precision and surface finish, high-speed milling (HSM) or micro-milling could be explored for machining smaller and more intricate implant geometries. HSM provides reduced cutting forces and better surface finishes, making it particularly suited for softer biomaterials like dental resin. Micro-milling, on the other hand, offers high precision, which is critical for implants requiring intricate features such as custom joint replacements or craniofacial structures.

Electrical discharge machining (EDM) or laser-assisted machining may also be considered for harder or more abrasive materials, reducing tool wear and thermal deformation. EDM is ideal for machining complex geometries in conductive materials like titanium composites, while laser-assisted machining can soften hard materials during the cutting process, improving machinability. Future studies could compare the cost, efficiency, and material compatibility of these techniques to determine their feasibility in large-scale manufacturing.

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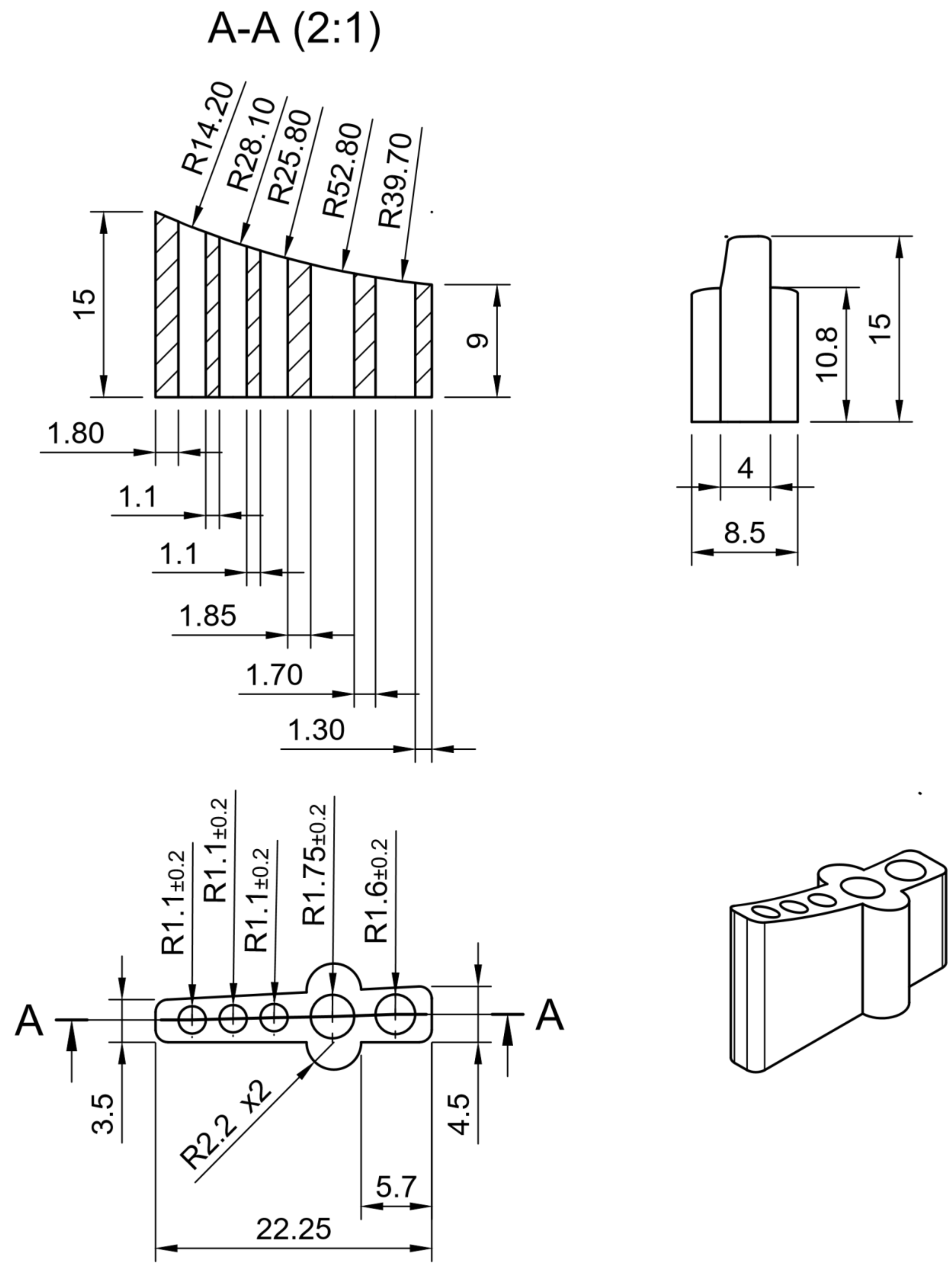

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UNIVERSIDAD INTERNACIONAL DEL ECUADOR

ESCUELA DE INGENIERIA MECATRONICA

PROYECTO/PROYECT: MACHINABILITY STUDY OF 3 DIFFERENT BIOMATERIALS USED IN IMPLANT MANUFACTURING

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