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Design, Fabrication, and Performance Testing of PMMA Interference Screws Prepared by 3D Printing Methods

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ABSTRACT

The Interference screws are one type of device that is often used in ACL reconstruction surgery. These devices are made of strong materials such as titanium or bioabsorbable materials. However, the use of PMMA (polymethyl methacrylate) as a material for the production of interference screws has not been widely explored. PMMA is commonly used in biomedical applications such as orthopedics and bone tissue engineering. Therefore, the aim of this study was to assess the structural integrity and performance characteristics of PMMA-based interference screws fabricated by utilizing three-dimensional (3D) printing techniques. The interference screw fabrication was carried out by adjusting the nozzle temperature, bed temperature, and print speed on the 3D printing machine to 240^oC, 100^oC, and 30 mm/s, respectively. The tests conducted in this study include torque, density, and fracture surface analysis. This study found that the density of the PMMA and commercial interference screws met the density requirements for cortical bone. However, the PMMA interference screw had a lower density than the commercial interference screw. The PMMA and commercial interference screws had densities (g/cm^3) of 1.10 and 1.31, respectively. The mechanical properties of interference screws increase with increasing density. The PMMA interference screw achieved only 41% of the PFT (peak failure torque) exhibited by the commercial interference screw. In addition, the PMMA interference screw only meets the clamping criteria, while the commercial interference screw has met the good clamping criteria. The results of surface fracture analysis showed that the PMMA and commercial interference screws had ductile and brittle properties.

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1. Introduction

The ACL (Anterior Cruciate Ligament) is a ligament in the knee that helps support the knee. An ACL injury is a type of knee injury that damages the ACL tendon, which links the femur and tibia bones. ACL injuries are common in sports and even in everyday activities. Sports that include quick movements and stops, such as football, basketball, and volleyball, can increase the risk of an ACL injury. Furthermore, overweight, muscle exhaustion, a lack of pre-exercise warm-up, muscle imbalance around the knee, wearing improper shoes, direct impact on the knee, and heredity can all raise the chance of ACL injury [1-8]. The pain caused by an ACL injury may vary depending on the severity of the injury and individual factors. Some common symptoms that may be reported when an ACL injury occurs are pain in or around the knee, inflammation and swelling in the knee area, difficulty or instability when walking or standing. In addition, an ACL injury can cause difficulty in fully bending or straightening the knee, and a "pop" sound when an ACL injury occurs [9,10].

Treatment of ACL injuries require a comprehensive and personalized approach that should be tailored to each patient's unique needs and condition. The doctor or healthcare professional may recommend several treatment options suited to the situation, such as physical therapy, the use of a knee brace, the use of painkillers, and surgery. In cases of severe ACL injuries, such as additional damage to other structures within the knee, surgery may be required. The surgical procedure may involve repairing or reconstructing the damaged ACL ligament [11-13]. An interference screw is one type of device that is often used in ACL reconstruction surgery. ACL reconstruction aims to replace the damaged ACL ligament using a graft (replacement tissue) to restore knee stability. Interference screws are used in the graft fixation stage, which is to secure the end of the graft into the bone. These devices are made of strong materials such as titanium or are bioabsorbable materials (biodegradable by the body) [14,15].

Materials commonly used to make interference screws include polyetheretherketone (PEEK), titanium, magnesium, polylactic acid polymer, Poly-L-lactic acid (PLLA), biocomposite of Poly-L-lactic acid (PLLA) and beta-tricalcium phosphate, poly-D, L-Lactide (PDLLA), PLLA/hydroxyapatite (HA) biocomposite, polylactide carbonate (PLC), and PLA/PCL/HA biocomposites [14-22]. The investigation of PMMA as a material for the production of interference screws has not been extensively explored. PMMA (Polymethyl Methacrylate) is a synthetic polymer that is commonly used in biomedical applications that demand durable and mechanically stable constructions, such as orthopaedics and bone tissue engineering. This polymer is created by polymerizing methyl methacrylate. Lightweight, cheap cost, non-toxicity, excellent stability and durability, excellent biocompatibility and hemocompatibility, high transparency, chemical stability, aesthetics, simple manipulation, high Young's modulus, and adjustable mechanical properties are some of the general advantages of PMMA [23-26]. Hence, additional investigation is necessary regarding the application of PMMA as a material for fabricating interference screws.

The objective of this research is to assess the structural integrity and performance characteristics of PMMA-based interference screws fabricated by the utilization of the three-dimensional (3D) printing technique. The screw utilized in this research refers to Ligafix Interference Screws manufactured by Science and Biomaterials (SBM), based in Lourdes, France.

2. Methodology

In this study, the Ender 3 Pro 3D printing machine manufactured by Creality 3D, Shenzhen, China, was used to convert PMMA filament into an interference screw. PMMA filament with a diameter of 1.75 mm was printed with nozzle temperature, bed temperature, and print speed settings of 240^{o}C, 100°C, and 30 mm/s, respectively. The print position was set in the vertical direction starting from the screw head as shown in Figure 1. The interference screw fabricated in this study has a screw diameter and length of 7 mm and 30 mm, respectively. The design details of the interference screw are shown in Figure 2.

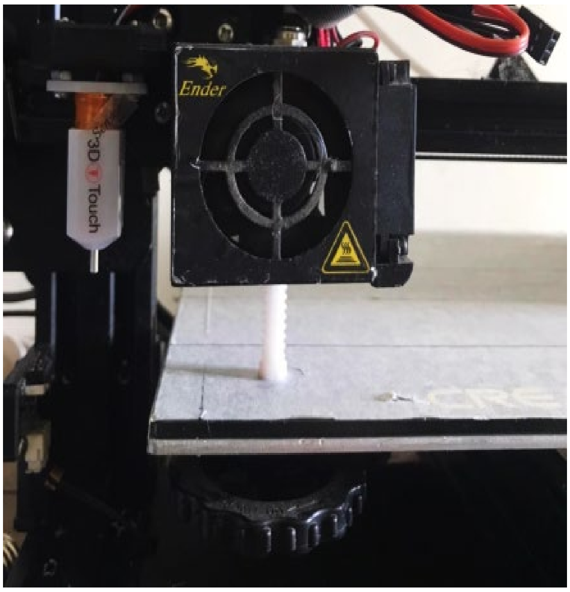


Fig. 1. 3D Printing process if interference screw using PMMA filament

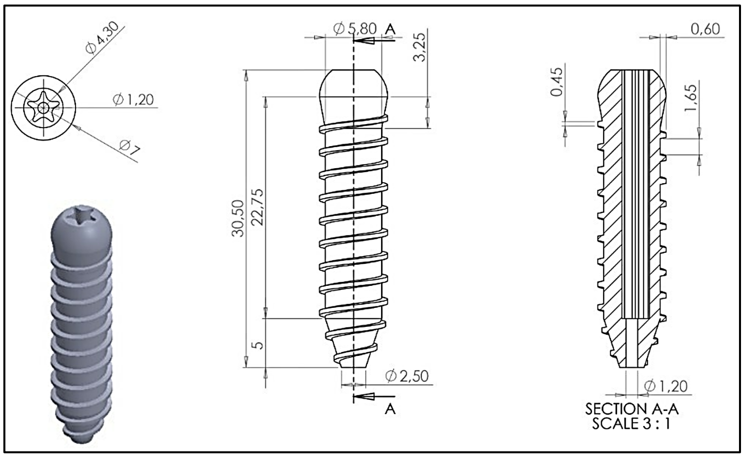


Fig. 2. Design if interference screw made from PMMA

The interference screws produced in this study (Figure 3) were then tested to evaluate their mechanical properties. The tests conducted in this study include torque, density, and fracture surface analysis. Torque testing was conducted according to ASTM F543 guidelines using an AWM Series Mini Digital Torque Wrench manufactured by Shenzhen Graigar Technology Co. Ltd., Shenzhen, People's Republic of China. In torsion testing, the interference screw is inserted into an artificial bone made of PMMA. The results of torque testing will obtain the threshold torque (TT) and peak failure torque (PFT) values, which will be used to determine peak clamping torque (PCT). PCT will be used to evaluate the clamping capability of the interference screw product. Fracture analysis was conducted by looking at the fracture model of the interference screw after the torsion test using an SD-30 Olympus Binocular Microscope (Olympus Corporation, Tokyo, Japan). Density testing was conducted using an electronic density meter (DME 220 series) from Vibra Canada Inc. (Mississauga, ON, USA) following the ASTM 792-08 standard. In this study, the Ligafix interference screw will also be tested for density and torque. The test results on the Ligafix interference screw will be used to evaluate the performance of the PMMA-based interference screw in 3D printing products.

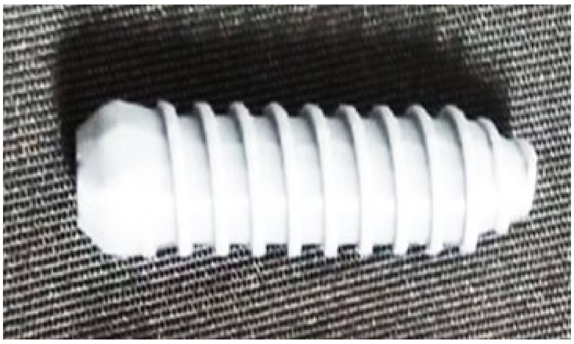


Fig. 3. Interference screw made from PMMA 3D printing product

3. Results

Density is one of the most essential properties of a material. Density measurements assist in determining and recording the material's density or weight per unit of volume. This information is essential for improved knowledge of the material's physical properties [27]. In this investigation, a PMMA interference screw and a commercial interference screw were used to measure density. The PMMA interference screw is tested four times, and the average value of the test results is then determined. Figure 4 depicts a comparison of the densities of PMMA interference screws and commercial interference screws. This study demonstrates that PMMA interference screws have a lower density than commercial interference screws. PMMA and commercial interference screws had densities (g/cm^3) of 1.10 and 1.31, respectively. The density of PMMA interference screws and commercial interference screws meets the density requirements for cortical bone. The density of PMMA and commercial interference screws falls within the range of cortical bone density, which is between 1.1 g/cm^3 and 1.3 g/cm^3. Because commercial interference screws are composed of PLLA/hydroxyapatite (HA) biocomposites, their high density is apparent. HA serves as a reinforcement in commercial interference screws, contributing to increased tensile strength, rigidity, fatigue resistance, impact resistance, dimensional stability, and shear strength [28-31]. The density of the composite increases as the hydroxyapatite content increases [27].

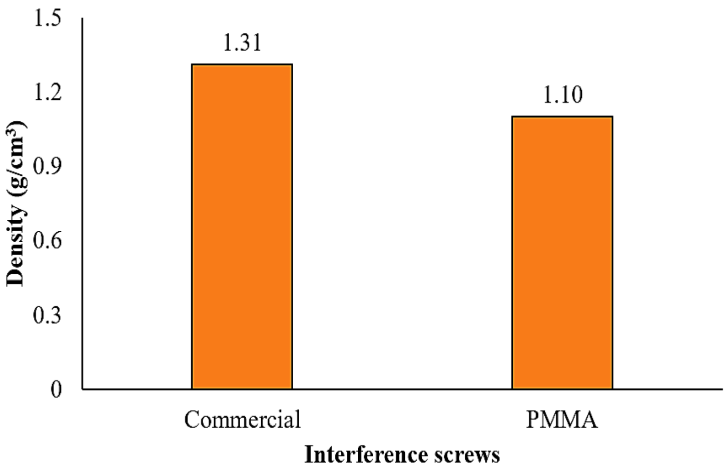


Fig. 4. Density of PMMA and commercial interference screw

Hydroxyapatite is a denser substance than most polymer matrices used in composites [32,33]. The presence of denser HA particles causes the final composite to become denser when hydroxyapatite and polymer are combined. Szustakiewicz *et al.,* [34] discovered that increasing the HA content in poly(L-lactide)/hydroxyapatite porous scaffolds resulted in an increase in density due to less porosity formation. The same results were also found in research conducted by Ismail *et al.,* [35]. Their research states that biocomposites with the addition of HA at 20 wt.% produce a higher density than other specimens. The density of a biocomposite increases as its HA concentration increases. Comparison of TT, PCT, and PFT on PMMA and commercial interference screws is shown in Figure 5. TT and PFT are obtained from the results of torque testing in accordance with ASTM F543. While PCT is obtained from calculations that refer to previous research [15,36].

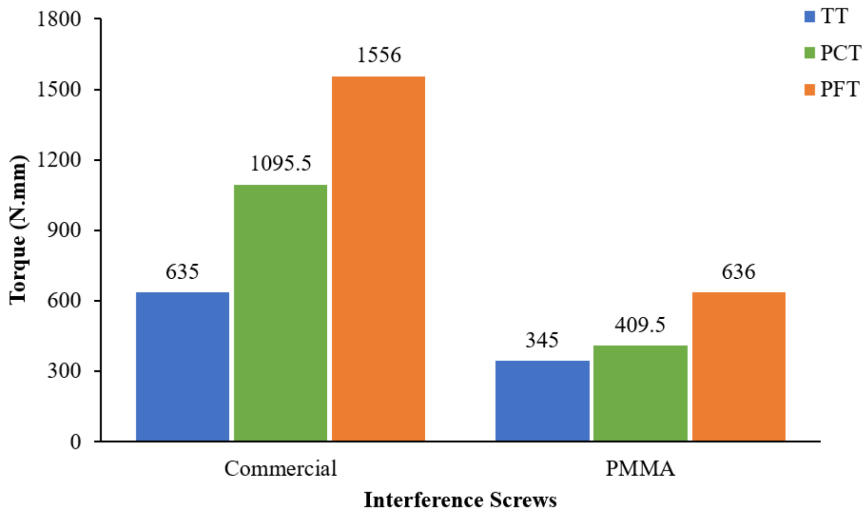
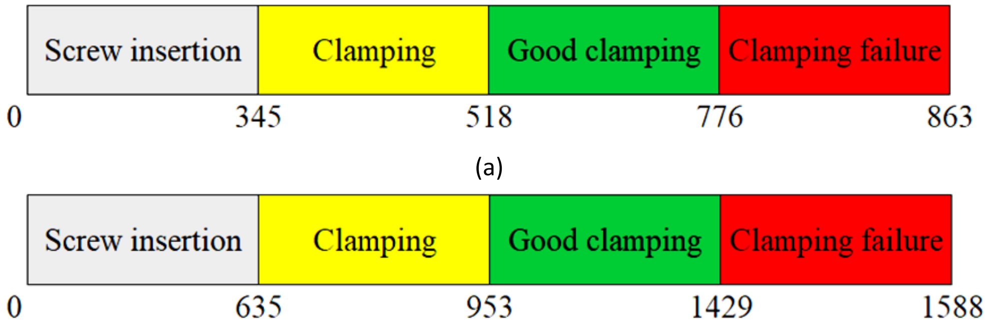


Fig. 5. Comparison of torque test results on interference screw made of PMMA and commercial interference screw

TT on interference screw made of PMMA and commercial interference screw are 345 N.mm and 635 N.mm, respectively. The results of this study show that inserting a commercial interference screw into the bone requires greater torque. This is because a high torsional threshold (TT) suggests an increased level of torque necessary for the successful insertion of an interference screw into the bone [15,36,37]. Furthermore, the torque test findings indicate that the peak failure torque (PFT) of the commercial interference screw surpasses that of the interference screw composed of polymethyl methacrylate (PMMA). This finding demonstrates that the commercial interference screw has superior resistance to torsional loads before experiencing fracture [15,36]. The peak failure torque (PFT) values for poly (methyl methacrylate) (PMMA) interference screws and commercial interference screws are 636 N.mm and 1556 N.mm, respectively. The 3D printing method for fabricating a PMMA interference screw only achieves 41% of the PFT exhibited by the commercial interference screw produced by Science and Biomaterials (SBM). The PCT on interference screws made of PMMA and commercial interference screws are 490.5 N.mm and 1095.5 N.mm, respectively. PCT was used to evaluate the clamping capability of the interference screw product.

Figure 6(a) shows a visualization of the efficiency of torque on the interference screw made from PMMA. The PMMA-based interference screw has a Threshold Torque (TT) of 345 N.mm. The range of 345-518 N.mm is the starting clamping area obtained from the calculation of 1 TT-1.5 TT. At the next stage, the range 531-796 N.mm is the good clamping area obtained from the calculation of 1.5 TT-2.25 TT. The standard requirement for a good interference screw was that the resulting PCT must meet in the range of 1.5 TT-2.25 TT (good clamping criteria). The good clamping area describes the ability of the interference screw to bond well to the bone without any damage. Furthermore, if the PCT of the PMMA-based interference screw is in the range of 776-863 N.mm (2.5 TT-2.5 TT), clamping failure will occur during screw insertion. From the visualizations of torque efficiency, the interference screw made from PMMA only meets the clamping criteria. This is because the PCT (490.5 N.mm) produced by the PMMA interference screw is in the range of 345 - 518 N.mm (1TT-1.5 TT).



(b)

Fig. 6. The visualization of torque efficiency (a) PMMA (b) Commercial interference screw

Different results were found for the commercial interference screw. The commercial interference screw produced a TT of 635 N.mm. Furthermore, the PCT produced on the commercial interference screw of 1095.5 N.mm is in the range of 953-1429 N.mm (Figure 6(b)). The range is obtained from the calculation of 1.5 TT-2.25 TT and has fulfilled the criteria of good clamping. The results obtained in this study are the same as previous research. In the previous study, the interference screw made from PLA/PCL/HA [15] and PLA [36] printed using a 3D printing machine was only able to fulfil the clamping criteria. This happened because the PCT produced on the interference screw made from PLA/PCL/HA and PLA was in the range of 1TT-1.5 TT.

The image of the fracture after the torque test on the interference screw made of PMMA and the commercial interference screw is shown in Figure 7. The fracture surface of the PMMA interference screw shows a smooth and flat fracture surface. This fracture model indicates that the PMMA interference screw is ductile. Whereas in commercial interference screws, the fracture surface is rough because the surface is delaminated. Delamination is a localized separation by material bonding from the surface that reduces the toughness of the material. This fracture model shows that the commercial interference screw is brittle. The results of this study are in accordance with research conducted by Prapanca *et al.,* [38]. The results of their research show that the fracture that occurs in PP material with the addition of ABS by 10%, 20%, and 30% has ductile properties because it has a smooth and flat fracture surface. Meanwhile, the results of fractures in PP materials with the addition of ABS by 40% and 50% have more brittle properties because they have rough fractures due to delamination.

(a) (b)

Fig. 7. The fracture surfaces (a) PMMA (b) Commercial interference screw

4. Conclusions

The 3D printing technology has been successfully fabricating interference screws with PMMA filament. The interference screw fabrication was done by setting the nozzle temperature, bed temperature, and printing speed on the 3D printing machine at 240°C, 100°C, and 30 mm/s, respectively. This study found that PMMA interference screws have a lower density than commercial interference screws. The PMMA and commercial interference screws had densities (g/cm^3) of 1.10 and 1.31, respectively. The densities of the PMMA and commercial interference screws met the density requirements for cortical bone. The mechanical properties of the interference screws improved with increasing density.

This is evident from the torque test results of the commercial interference screws, which are better than the PMMA interference screws. The PMMA interference screw has a threshold torque (TT) of 345 N.mm and a peak failure torque (PFT) of 1556 N.mm. While the commercial interference screw had a TT of 635 N.mm and a PFT of 636 N.mm. The 3D printing method for fabricating PMMA interference screws achieves only 41% of the PFT exhibited by the commercial interference screw. In addition, PMMA interference screws only fulfil the clamping criteria because the PCT produced is in the range of 1 TT-1.5 TT. While the commercial interference screw has fulfilled the criteria of good clamping because the resulting PCT is in the range of 1.5 TT-2.25 TT.

The results of surface fracture analysis show that PMMA and commercial interference screws have ductile and brittle properties, respectively. This study concludes that PMMA is a promising material for manufacturing interference screws and further investigation is needed regarding the applicability of PMMA as a material for manufacturing interference screws.

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