

Vibration Analysis on Biomechanical Behaviour of Spacer Implant Post Total Knee Arthroplasty

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Abstract

Post total knee arthroplasty (TKA) surgery, knee spacer of poly-methyl-methacrylate (PMMA) material undergoes compressive loading condition while movement of knee joint. Through vibration analysis reliability of knee joint is studied along with the similar boundary conditions that a knee spacer implant undergoes in actual conditions. In order to carry out this study knee spacer 3D model in MIMICS and solidworks software is generated by utilizing the CT scan report. After generation of 3D model of TKA spacer it is physically developed by additive manufacturing process and is utilised for carrying out experimental analysis of vibration under Vibrometer. This study explains the reliability of implant under loading condition and can be useful for improvement in performance of implants life under loading conditions. Through this study failure of implant can be predicted and analysis can be utilised for improvement of life and quality of implant.

1. Introduction

The knee joint has a complex functionality and is a synovial joint as it exhibits multiple degree of freedom (DOF) during the lower extremities movement and load carrying conditions [1]. The ground reaction while movement of knee joint is counterbalanced by cartilages, meniscus and bundles of tendons and ligaments under static and dynamics conditions [2]. Functionality of knee joint under different loading condition results on tear of cartilages and meniscus which cause pain and restrict the person from proper gait movement [3]. This reduces the effectiveness and performance in activities of a person under vertical loading conditions, mainly hip and knee joints [4]. Even though meniscus, ligaments and cartilages have their own self-healing property but is limited

due to their behaviour of non-vascularization [5]. But for osteoarthritis the relief from pain is achieved through surgical procedures [6]. TKA (Total Knee Arthroplasty) has been considered as most effective and suitable solution for person suffering osteoarthritis, this procedure includes replacing the human knee joint with non-metallic and metallic implants for restoration of functionality of joint. Life span of the joint depends on working conditions of joint and reliability and durability of implants under it [7]. Finite element technique is often adopted for better understanding of knee joint operations under loading conditions [8]. It is often observed that person undergoing knee replacement surgery remain unsatisfied with the functionality of joint and it takes long rehabilitation and physiotherapy sessions for attaining proper gait [9]. Post TKA surgery the lower extremities of body is heavily impacted by artificial joints as in varies tension among ligaments, enhances pressure on patella and may cause pain in movement of joint [10][11][12]. In long run of implant there is loosening of implants which further lead to damage of cartilages and ligaments [13]. The objective of this work is to get better understanding of stresses generated in TKA spacer during static loading condition and to predict its failure under similar working conditions.

2. Materials and Methods

Under similar boundary conditions and load a biomechanical study is conducted to examine first mode frequency of TKA component [14]. All side simply supported boundary condition is used to carry out the experimental study. The experimental analysis for TKA spacer is carried out with the similar dimensions of real spacer, for this spacer is developed through additive manufacturing with fused deposition modelling (FDM), and the impact of vibration on it is studied. The biocompatible material is used for manufacturing the spacer is PMMA, which is a and widely used in implants [15][16]. The first mode frequency of the TKA spacer implant component is obtained [17].

2. Finite Element 3D Models

Multiple images were collected from computerised tomography (CT) scan for development of 3D model of knee joint. Slice thickness if 1.5mm was kept and scan is performed. The person undergoing scanning was kept as supine position, complete extension if knee and hip joint were patella facing toward ceiling. DICOM (The Digital Imaging and Communications in Medicine) images files were generated and are MIMICS (Materialise's Interactive Medical Image Control System, Materialise-Belgium) software to generate 3D models of the bones. To generate accurate 3D model of bone components, region growth and segmentation operation is performed.

2.1 Material, Mesh Properties and Boundary Conditions

For study, the TKA spacer is considered to be linear elastic, isotropic, and homogeneous in nature [18][19][20][21]. The material properties for the TKA spacer

component are referred from the Poly-methylmethacrylate (PMMA) filament,[22] as shown below:-

Table 1: The material properties of TKA spacer model under simulation

Implant Component	Assigned material	Young modulus E (MPa)	Poisson's ratio ν	Density d (Kg/m ³)
3D TKA spacer	PMMA	2944	0.375	1150

PMMA orthopaedic implants are used where high strength is not required, and they are non-biodegradable and lightweight [23][24]. The TKA spacer 3D model has been imported into the Ansys workbench, static structural and modal analysis for carrying out computational analysis simultaneously. Quadratic tetrahedral mesh is selected, geometry with irregular and complex shapes [25][26]. The contact surface region between the contact surfaces are further refined for better results. Moreover, a convergence test was carried out to ensure accurate results, and final meshed implant model is shown in Fig 1 [27].

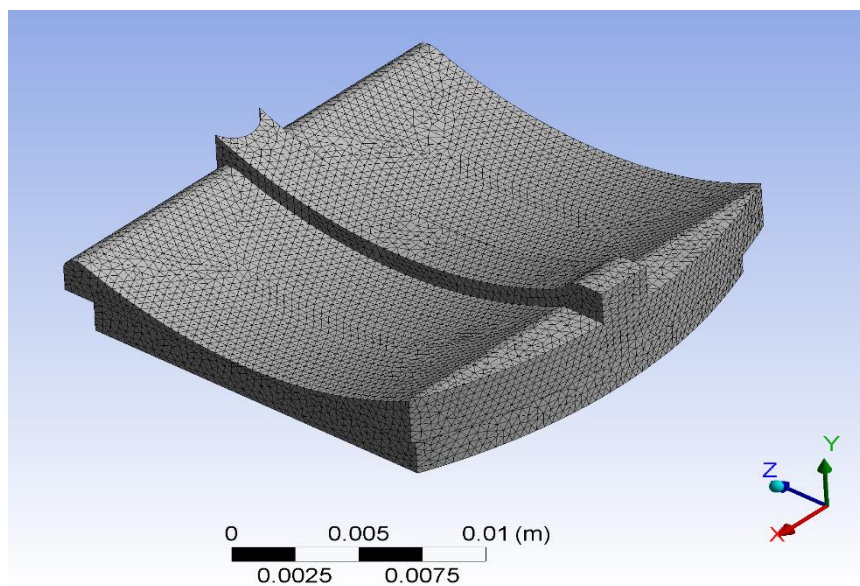


Figure 1: TKA knee spacer implant meshed model

All sides simply supported (SSSS) boundary conditions is provided to represent a post TKA surgical simulation of the spacer implant. The TKA spacer simulates full knee extension and upright standing movement biomechanics loading condition. For full extension, the center axis of the lower extremities is subjected to a compressive loading along the axis. The bottom of the tibia is fixed, to restrict movement and the simulation

process is carried out for this study, exhibiting all sides simply supported (SSSS) conditions on the spacer [28][29].

3. Computational Investigation

The SSSS boundary condition is provided for analysis Ansys software is used to perform computational modal analysis of PMMA implant. Homogeneous behaviour and linear characteristics is considered for the analysis implant material to have. From this study, the failure of the implant deformation can be seen on the central part. As shown in Fig 4 the first mode frequency is 10712 Hz for PMMA spacer implant shown in fig 2. The analysis provides an idea of the failure of the implant under directional stress caused by the movement of the TKA knee joint under action.

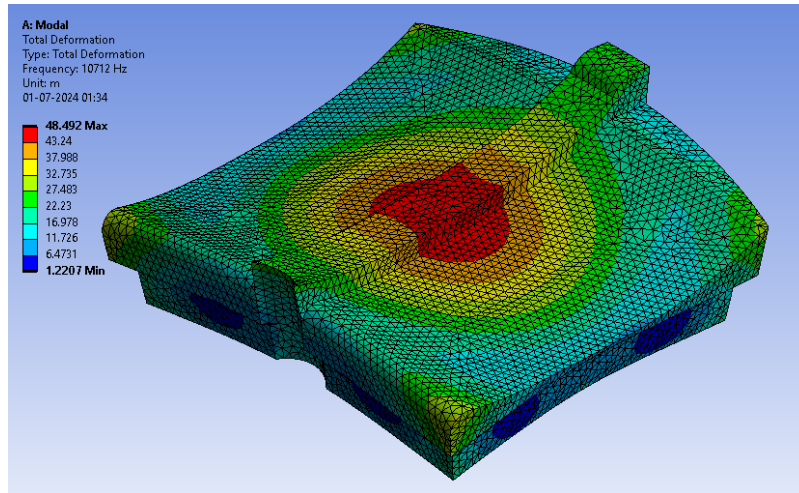


Figure 2: Total deformation of PMMA spacer under modal analysis

4. Experimental Investigation

The Laser Doppler Vibrometer (LDV), boundary conditions setup, an excitation impact hammer, a metal hammerhead, along with a PMMA spacer used for performing experiment. The authors utilized a PMMA TKA spacer manufactured by an additive manufacturing process, maintaining intact geometry. Spacers is arranged with all sides simply supported (SSSS) boundary conditions, and their first mode frequency is to be calculated to predict failure. A Polytech Laser Doppler Vibrometer (CLV 2534), shown in Fig 3 was used in a non-contact arrangement. This setup aimed to investigate the impact on the implant's lifespan under vibration caused by static and dynamic loading conditions. Polytech software for data acquisition, and a data acquisition system hardware were integrated, and values were obtained based on the defined arrangement.

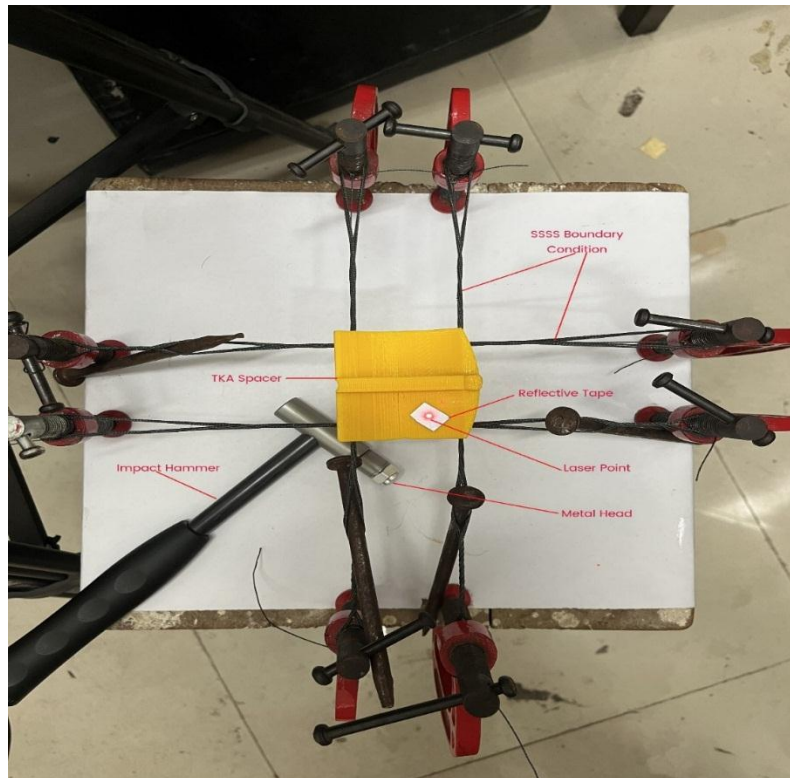


Figure 3: PMMA spacer under SSSS boundary conditions

Initial mode frequency along with numerous peaks are derived and based on generated data first mode frequency is illustrated in Fig4. Under this spectrum. The process is performed 3 times on the component and an average data is obtained by DAQs on screen by using Laser Doppler Vibrometer. An averaged result is obtained by averaging previous data.

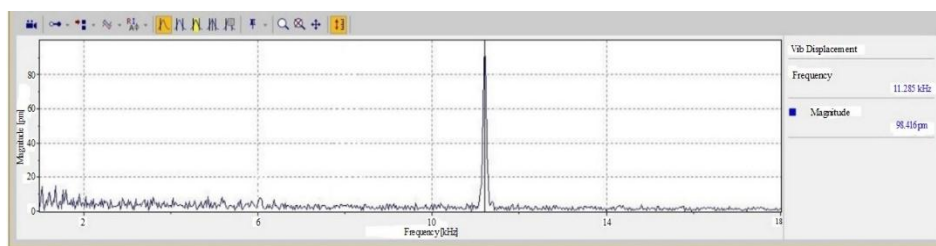


Figure 4: Frequency spectrum for PMMA spacer implant

5. Results

Under computational analysis of 3D PMMA spacer, satisfying all the boundary conditions and parameters modal analysis is performed successfully. For first mode frequency the results were obtained for the biomechanical response. The calculated first mode frequency of 3D spacer is 10712 Hz. whereas from experimental analysis first

mode frequency of PMMA spacer is 11285 Hz. The results under computational and experimental analysis has a variation of approximately 5% which lies under acceptance shown in table 2.

Table 2: Comparison between the computational and experimental results

Approach	Computational	Experimental	Variation	Variation %
Frequency	10712 Hz	11285 Hz	573 Hz	5%

6. Discussion

This study serves as the support element for performing experimental analysis and provides the result before carrying out anatomical human trials. This study will help in predicting the reliability and performance of implant under function. Also, these 3D-printed implants are useful for surgeons to access, patient-specific, surgical procedures. Thus, by this study the biocompatibility and functionality of implant increase and better tissue adhesion is promote for implant integration and regular performance. This research can be utilised to develop quality implants with more innovative and durable life which may lead better patient outcome.

7. Conclusion

In an engineering perspective, the aim for construction of biomaterial based TKA spacer implant is to study implant under vibration, extension and medial & lateral rotations while flexion. This study provides us better the impact of vibration of implant which undergoes loading condition during knee joint activity. The implant's mechanical performance is comparatively studied by FEA as well as experimental analysis including load conditions. This study illustrates a practical approach of computational finite element analysis and experimental analysis of 3D printed TKA spacer implants life under vibration.

The current study confirms scientific validation of life of implant under vibration during action and can be utilised to improve performance of implants. Further advancement in this study will setup path for innovation of more reliable and better quality implants for surgical applications.

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9. Conflict of interest

There are no conflicts of interest related to the manuscript.

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