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Optimization total deformation of knee implants made Ti6Al4V material

Djoko Kustono[1*], *Retno* Wulandari[1], *Andoko*[1], *Poppy* Puspitasari[1], *Galih Adhi* Kurniawan[1], and *Agus Dwi* Putra[1]

[1]Department of Mechanical Engineering, Faculty of Engineering Universitas Negeri Malang, 65145 Malang Indonesia

Abstract. Bones play an integral role in human survival. Damage to the knee joint has prompted orthopaedic specialists to develop implants as one of the solutions. In this study, Ti6Al4V as the implant material was optimised to determine and achieve the optimum implant condition based on the loading applied and the total deformation occurred. The optimisation results showed that the activity of walking downstairs resulted in the highest average of total deformation (19345 mm), followed by walking (15984 mm) and jumping (2.94 mm).

1 Introduction

Data shows that, among other bone joints, the knee is the most commonly injured joint suffered by both adults (55%) and children (40%) [1]. It is estimated that by the end of 2030, the number of total hip replacements will increase by 174% (572,000 procedures) and the number total knee arthroplasty surgeries will rise by 673% [2]. The key to overcoming the damage to the knee joint is by developing bone implants out of materials that match the characteristics of the human body. Most implant materials are derived from biomaterials. Biomaterials play a supporting role in medical applications. The use of biomaterials in medical applications should be meticulously formulated to achieve the most appropriate structure [3].

Ti6Al4V has been extensively used in medical equipment, such as in human bone implants, due to its excellent properties including chemical stability, low Young's modulus, low thermal conductivity and biocompatibility [4]. The ANOVA method was used to optimise the ability of the knee implants made of Ti6Al4V to perform various human activities (walking, walking downstairs and jumping) considering the total deformation. The software used for optimisation was SPSS 22.

* Corresponding author: djoko.kustono.ft@um.ac.id

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2 Literature review

2.1 Implant

An implant is a medical device designed to replace a biological structure. The surface of the implant in contact with the body can be made of biomedical materials such as titanium, silicon and other implant materials. In the orthopaedics field, an implant refers to a device used as a bone substitute to support the fractured bone. Implants can be placed inside the body (internal) or outside the body (external). A previous study found that aseptic, osteolysis and infection are the most common causes of total knee arthroplasty (TKA) failure. The study examined the role of implant design features and stems in resisting loosening, and explored the sensitivity of the implants to a loose surgical instrument due to oscillation [5].

As widely recognised, the fixation method (cemented or cementless) and implant configurations (stemmed or stemless) can have a major effect on the movement between bone and implant. Also, recent studies have shown that implant design features, such as the size and placement of the distal femoral pegs, the anteroposterior slope of the femoral component, and the angle of the implant, may have a substantial role in the long-term durability of prosthesis [5]. There are many different types of knee arthroplasty implants depending on the number of knee compartments to be replaced and the stability of the ligaments. The purpose of total knee replacement is to sustain normal knee alignment, unlike unicompartmental arthroplasty. The main feature that distinguishes between different types of implants is the presence or absence of a physical connection between the femoral and tibial components. Therefore, there are two major groups of implants: hinged or constraint implants and non-constraints implants [6].

2.2 Titanium

Titanium is a chemical element in the periodic table represented by the symbol Ti and atomic number 22. This metal is light, lustrous, strong and corrosion-resistant (i.e. resistance to aqua regia, sea water and chlorine) with a silvery-white-metallic colour. A titanium plate is widely used for cranioplasty since it is considered safe for human implantation. It is also one of the most common biomaterials for calvarial reconstruction or fixation in Japan. The degree of infection related to the use of titanium plates in many different neurosurgeries is about 5% of all the cases. The utilisation of titanium mesh cranioplasty is becoming increasingly popular as it minimises the vulnerability of unprotected brain tissue, avoids cosmetic deformity, and reduces the risks and costs related to additional procedures [7].

Titanium alloy, including Ti6Al4V, is widely used in medical devices (e.g. orthopaedic and dental implants) due to its excellent properties including low Young's modulus, chemical stability, low thermal conductivity and biocompatibility. Ideally, an implant should meet the following criteria: biocompatibility, anti-infective efficiency, long-lasting anti-infective efficiency, good mechanical properties and antibacterial coating stability [7].

Titanium is well-known for being used successfully as an implant material, and the success is credited to its excellent biocompatibility as a result of the formation of stable oxide layers on its surface [7]. Titanium is, in fact, the metal of choice in medicine (e.g. surgical instruments, orthopaedic pins and implants). The characteristic of not reacting directly with tissue makes it a great benefit in the medical field [8].

2.3 Finite Element method

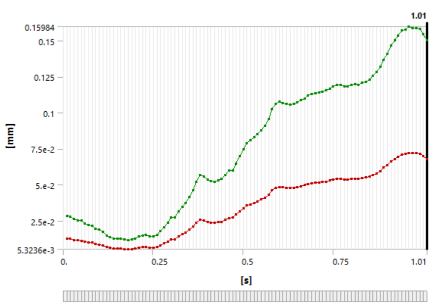
Finite element method (FEM) is a mathematical technique for managing and solving systems of partial (or integral) differential equations. In technique, the finite element method is used to divide unpredictable systems using closed form equations into small pieces, or elements, whose solution is known or can be estimated [9].

3 Processing and method

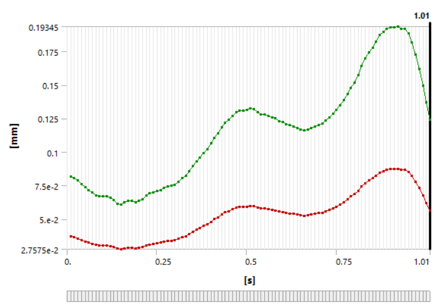
In this study, time and load of human activities varied from 0 to 1,01 seconds with a multiple of 0.01 seconds. The ANOVA method was used to optimise the ability of the knee implants made of Ti6Al4V to perform various human activities (walking, walking downstairs and jumping) considering the total deformation. The ANOVA test facilitates the analysis of several different sample groups with the smallest risk of error.

3.1 Total deformation simulation

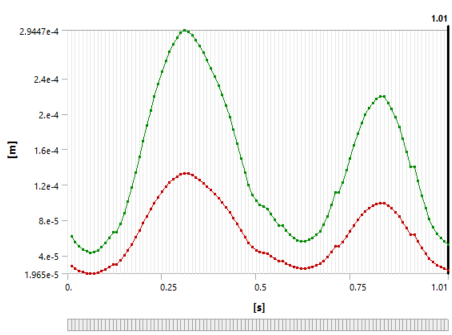
The simulation results of the total deformation based on various human activities are presented in Figure 1.



(a)



(b)



(c)

Fig. 1. (a) Total deformation in walking activity; (b) total deformation in walking downstairs activity; (c) total deformation in jumping activity.

Notes: …………. : maximum deformation
………….. : minimum deformation

The simulation aimed to investigate the total deformation of implants due to various human activities (walking, walking downstairs and jumping). The simulation was performed using ANSYS 18.1.

3.2 Optimisation

The optimisation results showed the total deformation of knee implants after various human activities (walking, walking downstairs and jumping). The optimisation was done using the ANOVA method with SPSS 22 software. The data were analysed by one-way ANOVA test with Tukey's post hoc testing and a sig. level of 0.05. The optimisation analysis included the descriptive analysis, ANOVA and multiple comparisons. These results became the basis for determining the optimum implant condition based on the total deformation occurred.

4 Result and discussion

Data generated from knee implant optimisation consist of the results of the descriptive analysis, ANOVA analysis and multiple comparisons analysis.

4.1 Descriptive analysis

Table 1. Descriptives.

Total_deformation

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Walking	101	5157,0807	6122,85291	609,24664	3948,3527	6365,8087	14,86	15984,00
Walking downstrairs	101	8462,9727	7090,84535	705,56548	7063,1509	9862,7945	60,96	19345,00
Jumping	101	1,3046	,84705	,08428	1,1374	1,4718	,04	2,94
Total	303	4540,4527	6420,76973	368,86358	3814,5844	5266,3209	,04	19345,00

The results of the descriptive analysis showed the mean of total deformation due to loading from the three human activities. Walking resulted in an average deformation of 5157.0807 mm, with the highest value of 15984 mm. Walking downstairs resulted in an average deformation of 8462.9727 mm, with the highest value of 19345 mm. Jumping resulted in an average deformation of 1.3046 mm, with the highest value of 2.94 mm.

4.2 ANOVA test

Total_deformation

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3673396101	2	1836698051	62,779	,000
Within Groups	8776941626	300	29256472,09		
Total	1,245E+10	302			

The ANOVA test results showed a sig. value of 0.000, meaning that there was a significant difference in total deformation as a result of the applied loading from three different human activities (independent variables), i.e. walking, walking downstairs and jumping.

4.3 Multiple comparison analysis

Table 3. Multiple comparisons.

Dependent Variable: Total_deformation

Tukey HSD

(I) Aktivitas	(J) Aktivitas	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Walking	Walking downstrairs	-3305,89198*	761,14130	,000	-5098,6888	-1513,0951
	Jumping	5155,77609*	761,14130	,000	3362,9792	6948,5729
Walking downstrairs	Walking	3305,89198*	761,14130	,000	1513,0951	5098,6888
	Jumping	8461,66807*	761,14130	,000	6668,8712	10254,4649
Jumping	Walking	-5155,77609*	761,14130	,000	-6948,5729	-3362,9792
	Walking downstrairs	-8461,66807*	761,14130	,000	-10254,4649	-6668,8712

Table 3 shows the mean difference of total deformation after the three physical activities (walking, walking downstairs and jumping). The activity of walking downstairs resulted in the highest average of total deformation, followed by the walking activity and the jumping activity.

5 Conclusion

The results of optimisation with ANOVA on the implants made of Ti6Al4V showed that the activity of walking downstairs resulted in the highest average deformation of 8462.9727 mm, with the highest value of 19345 mm. Walking resulted in an average deformation of 6122.85291 mm, with the highest value of 15984 mm. Jumping was the activity that resulted in the lowest deformation, 1.3046 mm on average and 2.94 mm as the highest value.

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