International Journal of Engineering & Technology, 7 (4.26) (2018) 70-72

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Mechanics of Total Ankle Replacement During Flexion in Relation to Geometrical Design: a Finite Element Study

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Abstract

Total ankle replacement (TAR) procedure is carried out to reduce the pain due to arthritis and trauma in patients. The failure of TAR implants occurs through various wear mechanisms in the polyethylene due to high ankle load, leads to instability as well as loosening problem. The objective of this project is to assess the performance of Salto Talaris (TAR) implants before and after design modification. In the present study, the computational model of Salto Talaris and the modified design was developed using CATIA V5R20 while the finite element analysis (FEA) was performed in ANSYS V18. The results have shown that the maximum von Mises stress induced in the polyethylene insert for Salto Talaris and the new design were 13.9 MPa and 8.7 MPa, respectively, with applied 880 N of axial ankle load. The modified version exhibited better performance due to elimination of edge loading with good contact area. Design modification is essential to lower the stress induced at PE insert, hence reduce the failure of TAR prosthesis.

Keywords: *Total ankle replacement; polyethylene insert; finite element analysis; von Mises stress*

1. Introduction

Total ankle replacement (TAR) is said to be an option for end-stage arthritis surgical treatment. However, the survival rates of TAR implants are way lower than those being attained by total hip replacement (THR) and knee arthroplasty (TKA) due to high complication and revision rates [1]. TAR is a procedure which is carried out to reduce the pain due to arthritis and trauma in patients. Wear in polyethylene (PE) insert is one of the most common failure modes even though the implants fail by various mechanisms [1]. Existing TAR lasts only about 5 to 8 years and its longevity would be decreased due to active lifestyle or overweight patient [1]. Currently, ankle implants are primarily used in older peoples[7]. The advantages of ankle arthroplasty include substantial pain relief and retained mobility of patients.

Intact human ankle consists of three bones which are the tibia, the fibula and the talus [2]. At each end of these bones are articular cartilage that covers them and combined to form joints. The ankle joint allows foot to dorsiflex and plantar flex. Healthy cartilage helps easier movement of joints and allows the bones to move smoothly against each other with minimal friction[3]. Damage of the cartilage can decrease joint function causes the bones to grind on each other which lead to pain and inflammation.

The first total joint arthroplasty is considered to be hip arthroplasty performed in 1890. Arthroplasty of the knee and shoulder followed shortly afterwards[2], [4], [6], [7]. It took almost 100 years until Buchholz (in the early 1970's) performed what is today considered to be the first total ankle arthroplasty[5]. Later, a modified version of this implant was used in Buchholzís own diseased ankle. In the mid-1970's, short-term reports on clinical performance of ankle implants showed promising results, with a success rate of 80% to 85%[5]. The first and second generation of ankle replacement implants were cemented and constrained. Hence, those implants recorded higher failure rates [7]. The preference of third generation of ankle implants increases by continuous design improvement with less constraints [7]. There are still some complications that the surgeon should treat carefully which is loosening of prosthesis, periprosthetic fracture, and infection[8].

TAR prosthesis is made up of two metallic components; the tibial and the talar component [4]. Between those two components is an insert which is a biocompatible plastic called polyethylene (PE) to imitate the function of articular cartilage. There are only 5 second generation total ankle replacements (TARs) namely Agility, Topaz (Inbone), Salto Talaris, Eclipse and Scandinavian Total Ankle Replacement (STAR) which are approved by the US Food and Drug Administration (FDA) [5]. TAR involves high costs and difficulties in experimental studies which result in slow progressing of TAR prostheses development [8],[9]. Therefore, CAD engineers have found a more promising approach in ankle arthroplasty by developing artificial ankle prosthesis model using finite element simulation[10]. The mechanical performance was analysed and the outcomes were documented for future enhancements in TAR systems[10]. However, to the best of our literature study, there is limited number of finite element study on TAR implants.

The ultimate goal of this study is to investigate the effect of TAR implant geometrical design on the mechanics of PE insert through finite element simulation. In this study, Salto Talaris TAR prosthesis was analysed. Then, the geometrical design was modified and the biomechanical behavior of PE insert was further observed.

2. Methods and Analysis

Figure 1 shows the geometrical design of Salto Talaris TAR prosthesis and the modified version. Salto Talaris has a flat-on-flat interface between PE insert and talar component while in the modified design, the articulation has been improved by curve-on-curve interface at both lateral and medial condyles. The CAD models were developed using CATIA V5R20 software while finite element analysis was performed in ANSYS V18 environment.

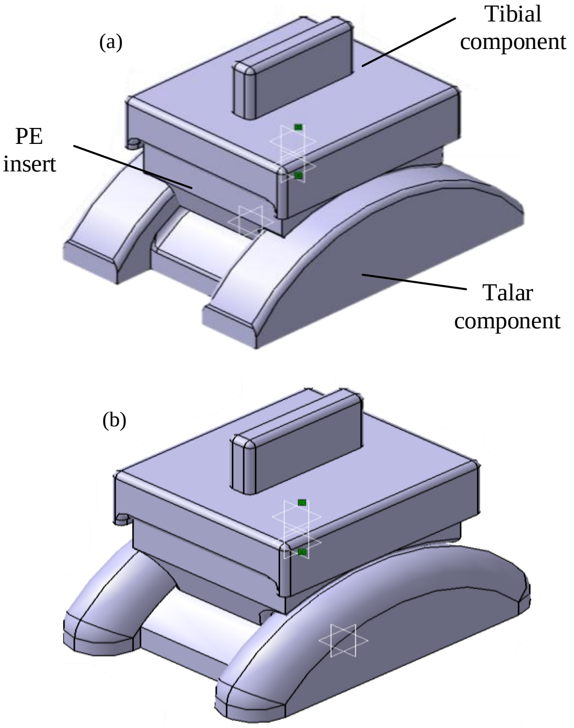

Fig. 1: TAR prostheses components for: (a) Salto Talaris and (b) Modified version.

Cobalt-chromium-molybdenum was selected as the material properties for the tibial and talar components for its high elastic modulus in comparison to titanium nitride [13]. The density, Young's modulus and Poisson's ratio of the Cobalt-chromium-molybdenum were 8.29 g/cm^3, 0.21 TPa, and 0.3, respectively, while the bulk and shear modulus were 0.175 TPa and 80.769 GPa, respectively. For the PE insert, ultra-high molecular weight polyethylene (UHMWPE) was selected because it is commonly used in most ankle arthroplasty [11]. The density, Young's modulus and Poisson's ratio of the UHMWPE were 0.951 g/cm^3, 557 MPa, and 0.46, respectively. The bulk and shear modulus of 21 MPa were defined for the insert material. Tetrahedron element was used for the FE model. The number of nodes generated for Salto Talaris and its modified version were 15,444 and 27,315 respectively.

Fixed support was set at the lower area of the talar component while the axial force of 880 N was applied at the top surface of the tibial component as shown in Figure 2, to represent the maximum ankle joint load during walking gait [8]. Tibial and talar components were set to have 0°, -10° and 30° angles to imitate the position during neutral, maximum dorsiflexion and maximum plantarflexion, respectively [13].

3. Results and Discussion

Figure 3 shows the von Mises stress distribution in the PE insert for modified version of Salto Talaris at 20° and 30° plantar flexion. The stress values obtained for both models and all ankle joint positions did not exceed the yield stress of UHMWPE (21MPa).

Figure 4 shows the von Mises stress at PE insert at different ankle flexion angles. Based on the results, it is clearly shown that the PE insert for both models experienced greater von Mises stress at flexion state compared to at neutral position. During ankle plantarflexion, the contact position changes from the centre to the posterior side which is the edge of PE condyle. The stress increases due to edge loading effect during such ankle joint position. The modified version has shown lower von Mises stress (8.6935 MPa) compared to Salto Talaris which was 13.891 MPa. This observation is due to the elemination of sharp edge at articulating interface without compromising decent contact area between PE insert and metallic talar component.

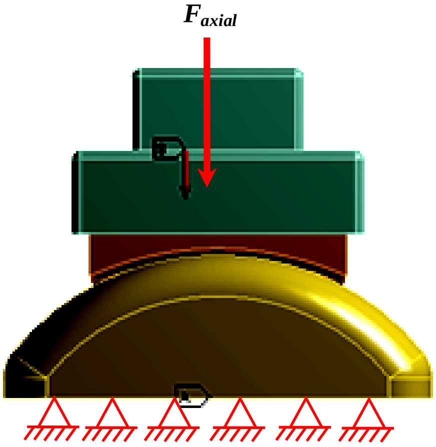

Fig. 2: Boundary conditions in finite element analysis.

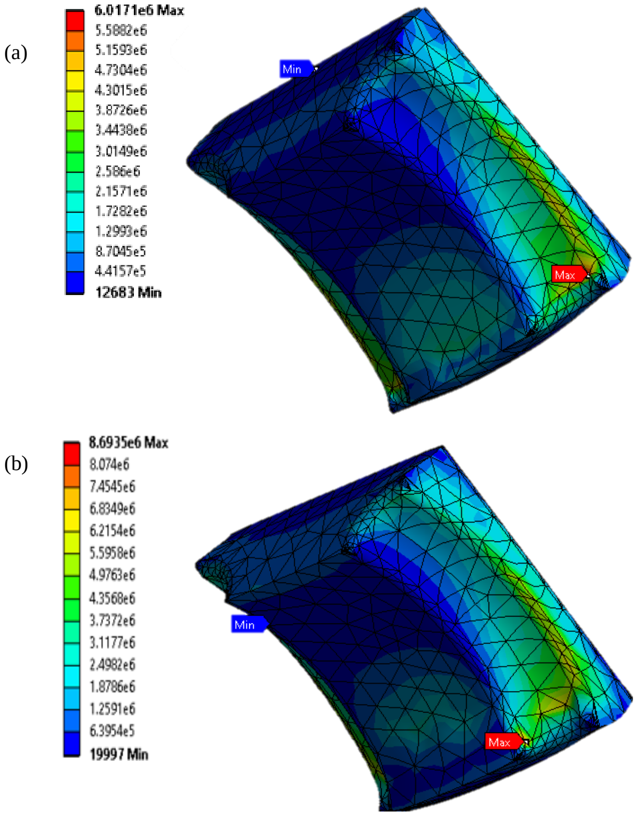

Fig. 3: Von Mises stress distribution at PE insert of modified version for (a) 20° and (b) 30° plantarflexion.

The results are in aggreement with the previous findings by B.J. Elliot et al.. In the study, characterization and methods to reduce wear were performed on Wright State University (WSU) patented TAR implants, and the researchers have reported that geometrical parameters are the major contributors in reducing stress at PE insert, thus lower the wear rates [8]. In total knee replacement (TKR) implant design, contact area at articulating interface plays the greatest role in contact stress that leads to PE insert failure [14]. A decent contact area can be achieved by optimizing the geometrical parameters between articular surface of PE insert and metallic condyle. However, there are some limitations of the present study. In assessing the mechanics performance of TAR implants, only axial force was applied in this FE analysis. In intact joint mechanics, human ankle undergoes more complex degree of freedom include internal and external rotation. This rotation will induce shear load at the joint articulation, leads to higher stress generated at PE insert. However, the axial joint load during walking gait was selected as walking is the most common activities among adults for both men and women [15]. Besides that, TAR implants were tested through a very limited number of geometrical parameters, hence the correlation between implant geometrical designs and von Mises stress couldn't be explained more significantly.

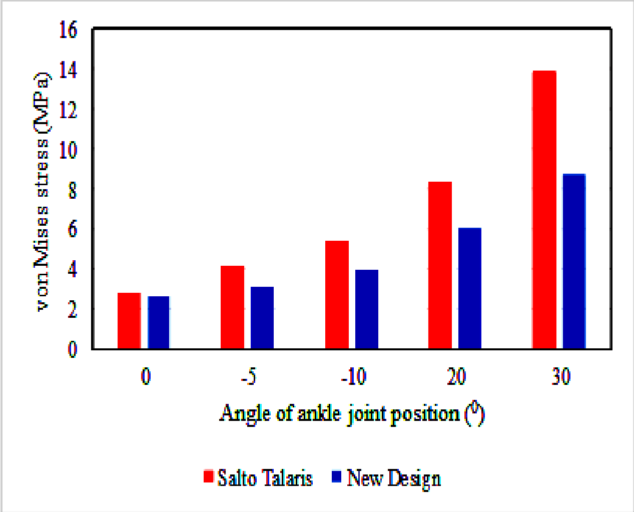

Fig. 4: The von Mises stress at PE insert versus ankle joint flexion angle.

4. Conclusion

Geometrical design modification is one of the best ways to lower the stress induced at PE insert, hence reduce the failure of TAR prosthesis. All the results obtained in this study have shown that the design modification has significantly improved the performance of TAR prosthesis. All the data from this study can be used by ankle-foot prostheses designers and provide comparative data to be assessed in future ankle joint prosthesis design.

Acknowledgement

This work was funded by Universiti Teknologi MARA (UiTM) under Bestari Perdana Research Grant (600-IRMI/DANA 5/3 BESTARI (P) (058/2018).

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