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Finite element analysis on femur subjected to knee joint forces during incline-decline walking

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Abstract

Walking is one of the activities that produce a significant magnitude to joint reaction forces and stresses of human bone. Walking on different ground surfaces contributes to the different loads and stresses, particularly on femur bone. Other than uneven surfaces, walking on certain slope surfaces could also affect the magnitude of joint forces. Therefore, finite element analysis (FEA) was employed in this study to simulate the effect of walking on different slope angles for both incline-decline towards stress and strain responses of the femur bone. A three dimensional (3D) geometrical model of the femur was developed and converted to 3D finite element model. The loading conditions and constraints that reflect to walking on different sloped surfaces were applied on femoral head and patellar surface. Failure risk, stress-strain distribution and maximum stress-strain on femur were obtained from the simulation. The results show that the increase of sloped angles contributes to the increase of von Mises stress and strain as well as maximum principal stress and strain. The study provides an additional insight on the risk of injury due to incline-decline walking for certain angle of slopes.

Keywords

Femur, Knee Joint, Joint reaction force, Finite element analysis, Incline walking.

1.Introduction

Walking is a movement from one location to another location by raising and dropping each foot in turn at a regular pace. Work is produced at lower limb joint in order to move from one place to another over different pieces of lands. The lower limb joints, including the hip, knee and ankle, not require to ingest an expanded power as the foot lands [1]. Incline-decline walking on different angles of slopes contribute to the different reaction loads and stresses on femur bone. Hip joint function in the frontal plane leads to regulating the pelvis and trunk against gravitational forces to 23 percent of the overall hip work [2]. The gravitational forces demanded will increase while performing incline-decline walking. In regulating the pelvis and trunk against this requirement, hip frontal work will be highly relevant [3].

In contrast, walking on a horizontal surface to incline-decline surface, different motor pattern in the lower boundary is required [4]. Increasing of torque happened on hip and ankle musculature as the muscle stabilises each joint and drive the mass of the body upward. The report shows that increase in lower boundary joint loading in addition of slope collated to level surface step. Relative to a horizontal surface, greater movement of excursion of the centre of mass while walking on incline-decline slopes [5]. Walking on different types or uneven surfaces contributes to different ground reaction force responses [6]. Different ground reaction force generates different magnitude of joint forces. Incline-decline walking increases the workload and stress on the lower limb joints [7]. In decreasing walking, the demand against the powers of gravitation will raise and hip frontal work is going to be extremely critical in regulating the pelvis and trunk against this greater need.

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Although there are numerous studies [8−12] on the effect of slope surface activities either walking and running on joint reaction forces have been conducted, however investigation up to joint stresses and strains relatively very little. Finite element analysis (FEA) is a common computational tool to investigate the stress and strain response, including for porous materials [13] and bone mechanics [14]. Hence, this study was undertaken to investigate the effect of knee joint reaction forces due to incline-decline walking on the stresses and strains of the femur bone. Finite element method was employed to model the human bone that subjected to various loading conditions which reflect to the incline-decline walking activities.

The outline of this paper is as follows: Section 2 highlighted the review of published works that related to the present study. The methods used to develop the finite element models of femur bone were then discussed in section 3. Sections 4 and 5 present the remarkable results and significant discussion of the study, respectively. Conclusion and recommendation for future works are described in section 6.

2.Literature review

Since the surface topography varies in terms of irregularity and slope, outdoor surfaces are typically not level. The unevenness may be the result of unavoidable human error in man-made work or an environmental effect, such as ramps used to reach buildings or pavement on slopes, respectively [15]. There has been an increase in research on the effects of incline surfaces, while standing [16, 17−20] moving around while running [12, 18], walking [19, 20], or doing both [20, 21], in recent years. For example, kinematics [22, 23], kinetics, muscle response [24], protheses, and pathological cases [25] have all been studied in relation to incline walking.

Inclined surfaces are also recognised to have a variety of health advantages. Walking on surfaces with varying gradients has become a well-liked form of exercise that is frequently advised for rehabilitation purposes, especially for patients who have difficulty navigating stairs [26]. However, walking on sloped surfaces poses a greater risk of injury and falling than on level ground [27]. According to Leroux et al. [28] and McIntosh et al. [29], incline walking affects the stability of the body during walking and changes the lower extremity's ability to exert force and expand joint range of motion. Although impact peak, which includes force production, has frequently been investigated, relatively little is known about its association to injury [30]. Every time an external force damages biological tissue and causes an injury, the internal load's magnitude is increased. While jogging, external ground response forces are about 2.5 times as strong as internal joint contact forces, which range from 8 to 15 times as much weight [31]. Since the external ground force is simply a proxy for internal loading and will understate the real force experienced by the body, it is crucial to explore the joint reaction forces in gait [30].

Based on the overall review, there are not many researches that specifically use FEA to examine how uphill walking affects joint response forces and stresses. The majority of studies focus on cross-slope walking exercise [23, 32, 33]. In contrast to cross-slope surfaces, incline surfaces need to be researched because they are more frequently used for exercise or rehabilitation. Additionally, the majority of the earlier studies used treadmills rather than actual incline platforms to measure the surface angle [34−36]. The use of a treadmill may limit the generalizability of the results to walking activities, as noted by Huijben et al. [37], as gait on a treadmill tends to be less varied, more symmetric, and more stable. Hence, it is important to investigate the effect of incline walking on joint stresses based on the joint reaction forces that were obtained by experimentally on incline platforms.

3.Methods

The present study fully employed and utilised the established FEA software, namely, Ansys (Pennsylvania, United States). To obtain the stress response of femur bone during walking experimentally is almost impossible, especially to place the strain gauges on the bone surface. Hence, FEA is a useful computational tool that can be used to investigate the stress responses in this study. *Figure 1* shows the flowchart of the overall present study. First, the geometrical model of femur bone was edited using Catia (Dassault Systèmes, Massachusetts). Seven models of femur bone that reflect to incline-decline walking with different angles were developed. Then, the models were discretised in meshing process, where the convergence test was conducted to obtain the optimum element size. Next, boundary conditions were applied to simulate the incline-decline walking conditions. Stress or strain distribution, maximum principal stress and strain and failure risk of femur bone were then being analysed to complete the study.

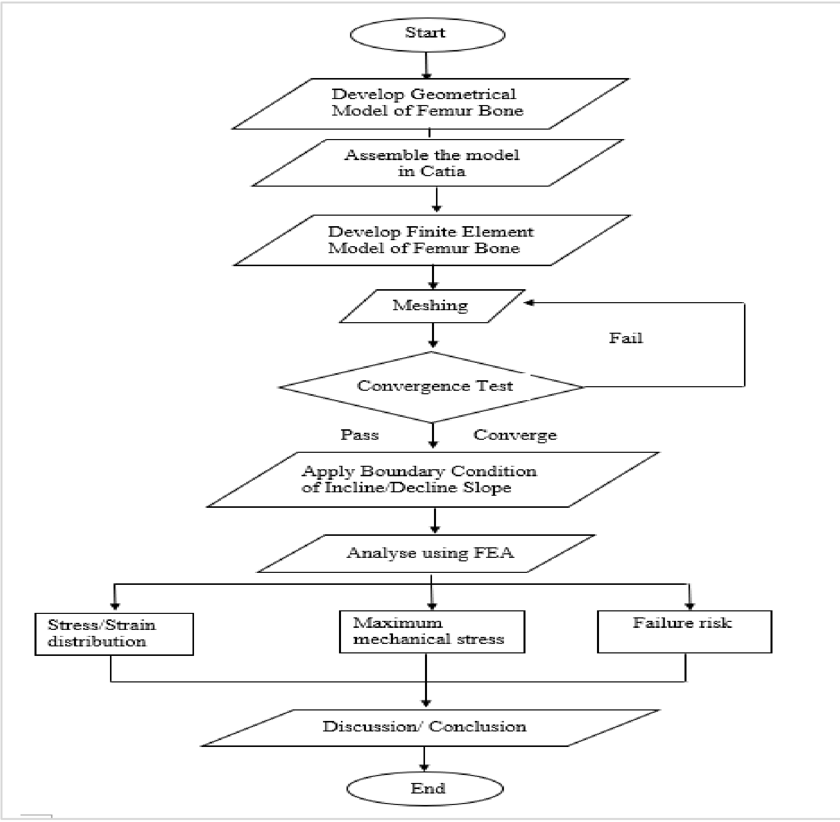


Figure 1 The flowchart of the present study

3.1Geometrical model of femur bone

The geometrical model of a standard femur bone was purchased from Turbosquid (Louisiana, United States) database. The model is a femur bone for normal adults. One end of the femur bone is connected to tibia bone, whereas other end is connected to pelvic bone. The dimension and geometrical was scaled up to fit the size of average young adults. The length of femoral bone is 440 mm. *Figure 2* shows the geometrical model of femur bone that was imported and edited in computer-aided design (CAD) software, namely Catia. Then, the model was exported to finite element software (Ansys) for the numerical simulation.

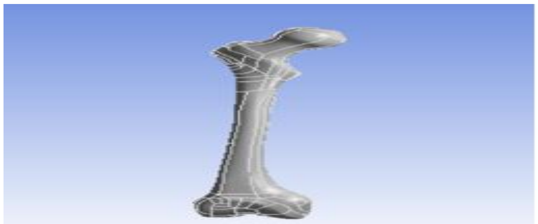


Figure 2 Geometrical model of femur bone

3.2Material properties

In Ansys, the femur bone model was assigned to the material properties. A linear elastic, isotropic and homogenous properties were set for the present simulation. A constant young's modulus and Poisson's ratio of 14 GPa and 0.3 were set respectively [4]. The density of femur bone was set as 1700 kg/m^3.

3.3Meshing

Figure 3 shows the graph of von-Mises elastic strain versus meshing size in the convergence test. Convergence test was performed in order to obtain the optimum size of elements. From the graph, the converged condition was found when the element size is 4 mm. It was selected because, if the size was reduced smaller than 4 mm, the von-Mises strain still constant. Hence, the solution number 3 was selected in this case. The finite element model was created and discretized into 55,969 elements with 4-node tetrahedral.

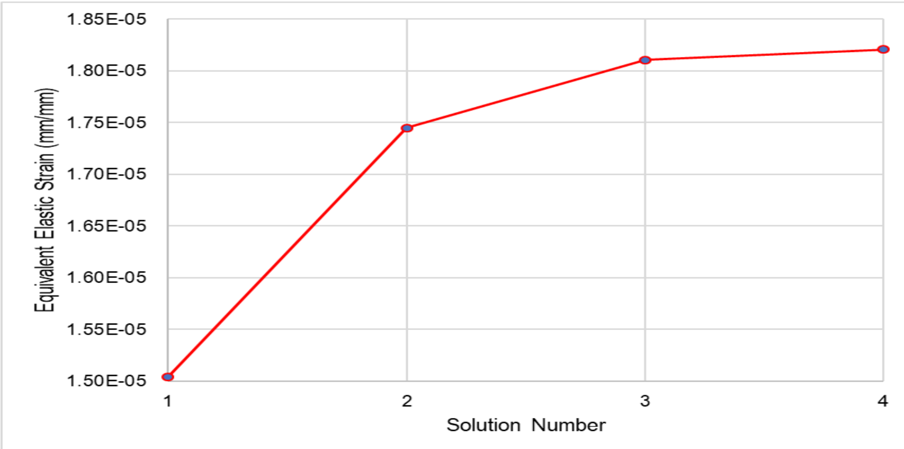
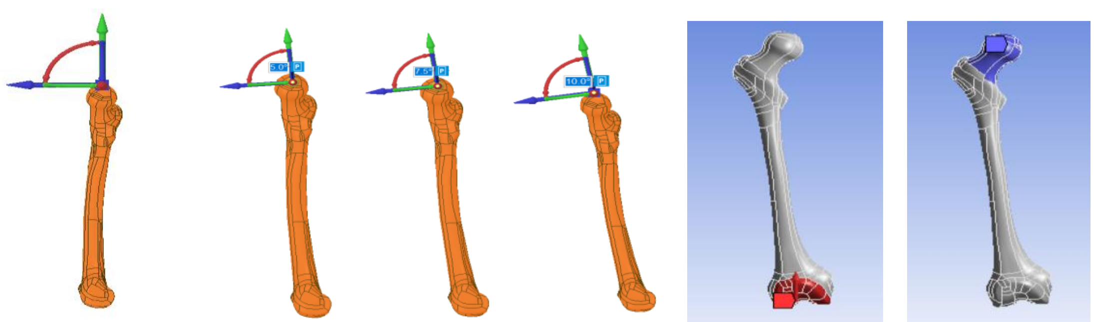


Figure 3 Convergence test based on equivalent elastic strain for each solution number

3.4 Boundary conditions

As for boundary conditions, the top surface of femur bone, which is femoral head was set as fixed support. Loading was applied as knee joint force, based on inclination and declination relative to the ground: 0° (horizontal surface), 5°, 7.5° and 10° anterior tilt, 5°, 7.5° and 10° posterior tilt. *Figure 4* shows the femur bone with 0° tilt (horizontal surface), 5° tilt, 7.5° and 10° tilt respectively. The force was applied at the bottom end of the femur bone as knee joint force. *Table 1* shows the magnitude of forces applied on femur bone for each of the slope angles that were obtained from the experiment.



(a) (b) (c)

Figure 4 Loading conditions and constraints on femur bone. (a) Angle rotation of femur at 0°, 5°, 7.5° and 10°. (b) The force applied on patellar surface. (c) Fixed support on femoral head

Table 1 Forces applied on different angle of slope

Walking level		**Force (N)**
Level	0°	696.22
Incline	5°	715.33
	7.5°	699.93
	10°	685.93
Decline	5°	725.62
	7.5°	691.29
	10°	656.95

3.5 Fracture risk analysis

In order to investigate the risk of fracture for each loading case under incline-decline walking, the maximum stress obtained was compared with the bone strength of the femur. In this study, the bone strength was taken as 115 MPa [38]. The fracture risk was calculated as the bone strength over the maximum von Mises stress obtained for each case.

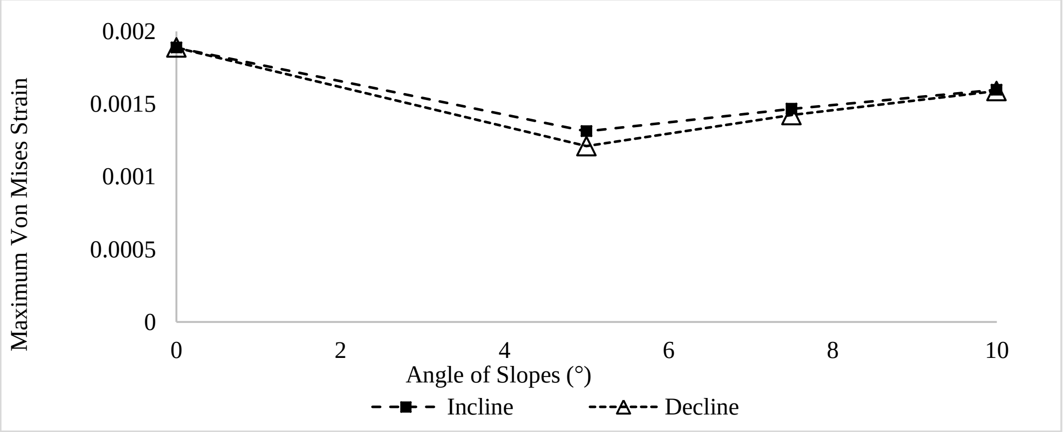
4.Results

4.1Effect on Von Mises strain and stress of femur

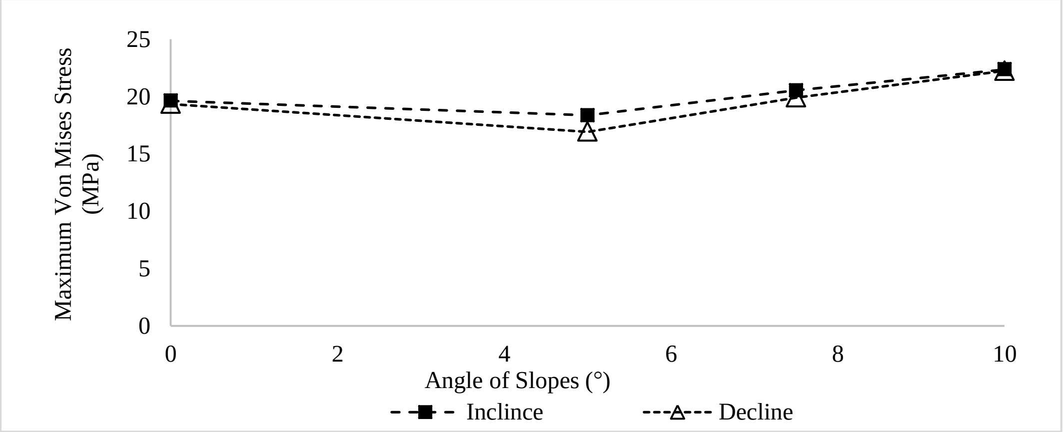
Figure 5 shows the effect of incline-decline walking on von Mises elastic strain and stress of the femur bone. The peak of the maximum von Mises strain was found during walking on the horizontal slope surface (level) with 0.001888 as shown in *Figure 5(a)*. Whereas von Mises elastic strain of femur at incline-decline slope of 5° were the lowest which is between 0.001312 and 0.00121, respectively. The elastic strain was increased with respect to the increase of slope angles for both incline-decline walking. The trend for both incline-decline walking are same, however, incline walking always generated higher elastic strain than decline walking.

On the other hand, the highest von Mises stress of femur bone was found at incline slope of 10° which is 22.37 MPa. The lowest von Mises stress of femur bone was at a decline slope of 5° which is 16.934 MPa. For both strain and stress responses, the values were increased gradually from 5° to 10°. Surprisingly, at an angle of 10°, the values of von Mises strain and stress were almost similar on both incline-decline walking cases. The magnitude of von Mises strain and stress during incline walking are much higher than decline walking.

As shown in *Table 2*, the maximum von mises elastic stress and strain for all loading cases was found concentrated on the body of the femoral bone which is known as femur shaft. The region size of the high stress and strain as indicated by the red contour, was observed to increase with respect to the increase of slope angles. This result is consistent with the trend of the maximum von mises strain and stress versus slope angles.



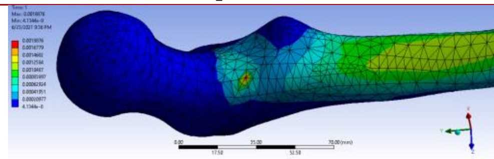
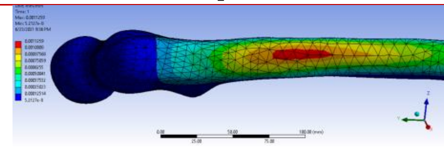
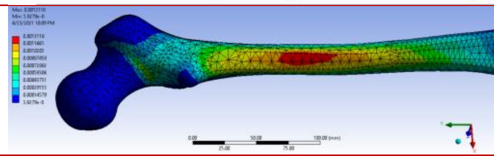
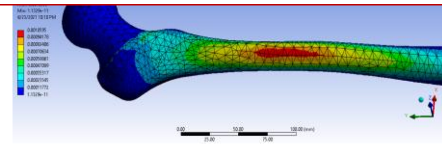
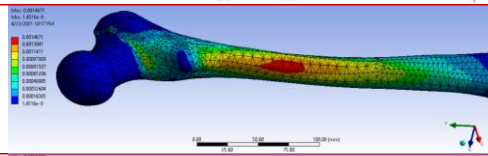
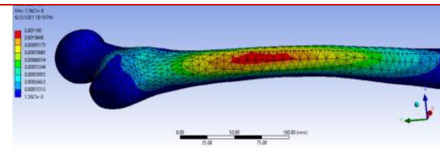
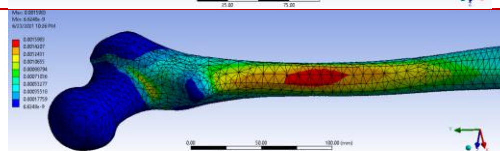
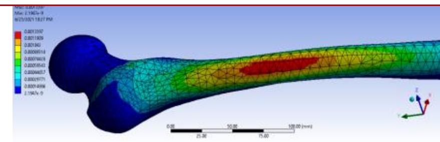
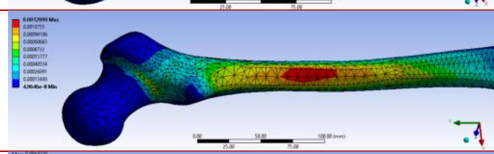
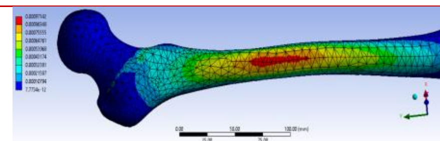
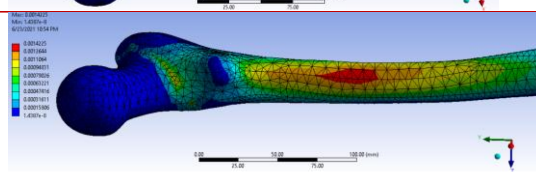
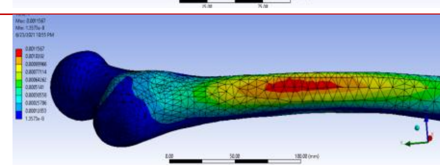
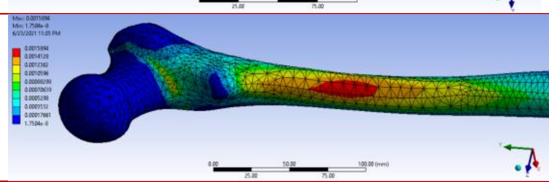
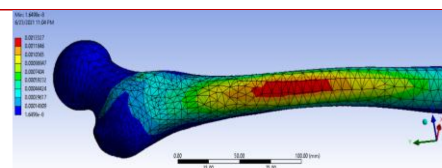
(a)



(b)

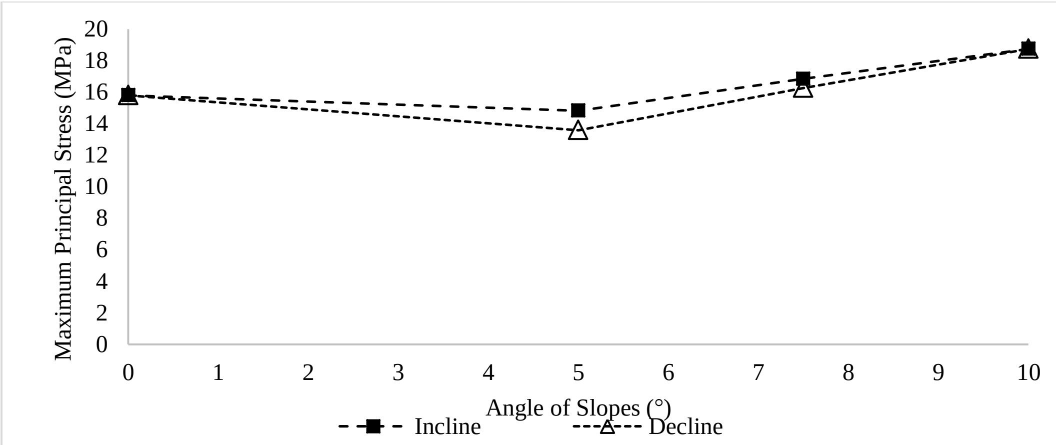
Figure 5 Effect of incline/decline walking on the maximum (a) von Mises strain response; (b) von Mises stress response

Table 2 Von Mises strain and stress distribution

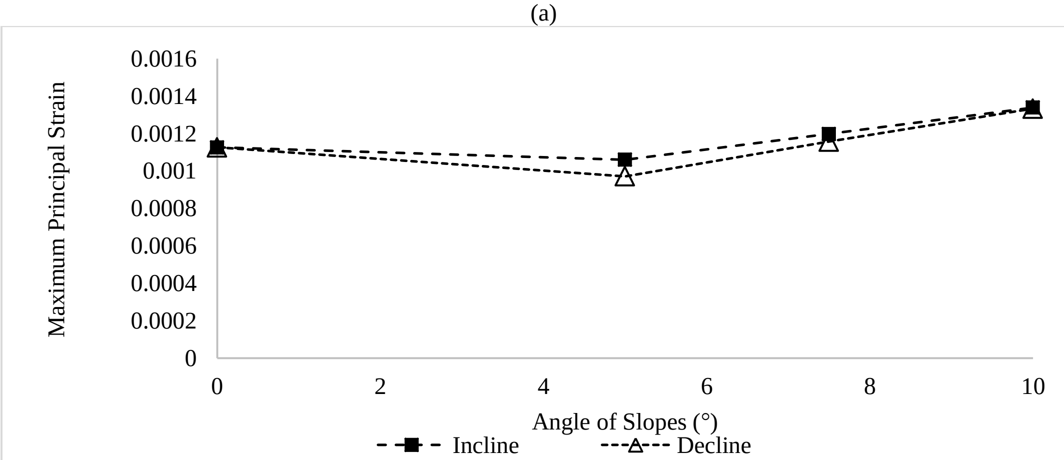
Walking angle		**Von mises strain response**	**Von mises stress response**
Level	0°		
Incline	5°		
	7.5°		
	10°		
Decline	5°		
	7.5°		
	10°		

4.2Effect on maximum principal stress and strain of femur

Figure 6 shows the effect of incline-decline walking on maximum principal stress and strain of the femur. The results show the highest maximum principal elastic strain of femur bone was inclined slope of 10° which is 0.001339. Whereas the lowest maximum principal elastic strain of femur bone was at a decline slope of 5° which is 0.000971. The highest maximum principal stress of the femur bone is a decline slope of 10° which is 18.743 MPa. While the lowest maximum principal stress of the femur bone is decline slope of 5° which is 13.592 MPa. The trend is similar to the results found on von Mises stress and strain.



(a)

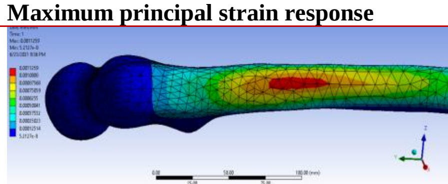
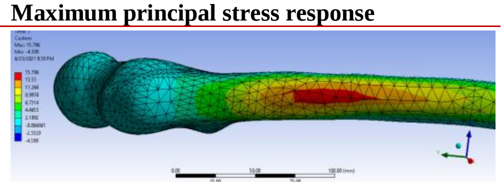
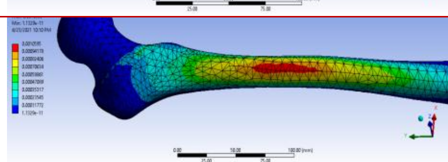
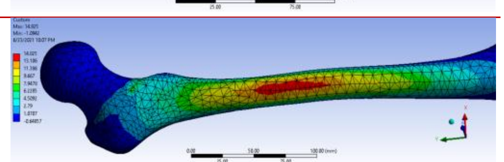


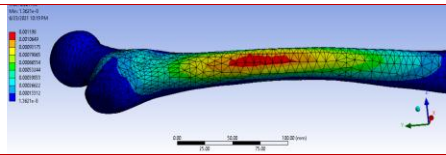
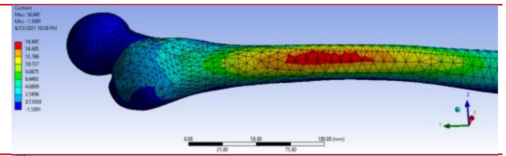
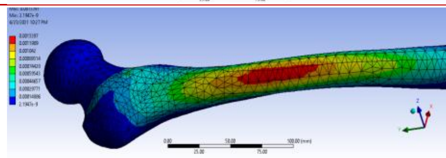
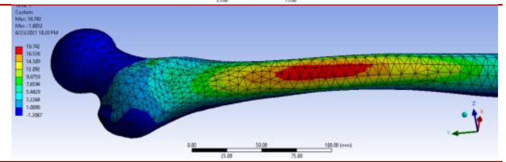
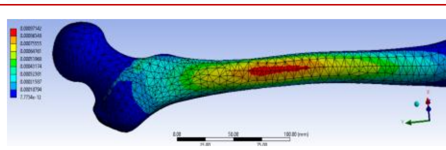
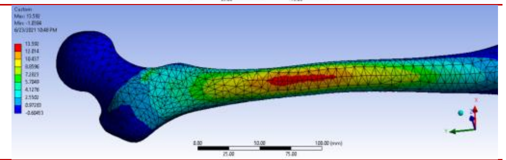
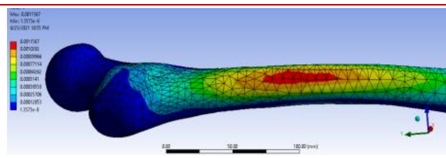
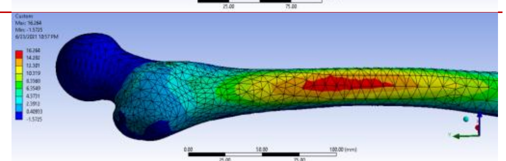
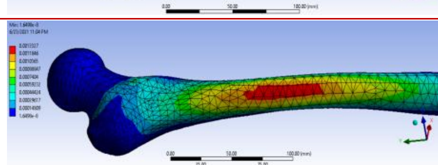
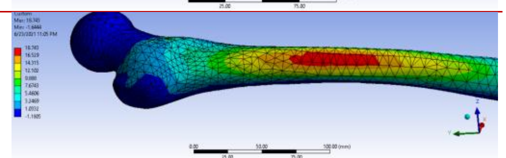
(b)

Figure 6 Effect of incline-decline walking on (A) maximum principle stress response. (B) maximum principle strain response

Moreover, the maximum principal strain and stress distribution were found similar to the findings for von Mises strain and stress as depicted in *Table 3.* The critical part (as shown in red contour) was concentrated at the femoral shaft and the size of the region was observed to be increased when the slope angles increased.

Table 3 Maximum principal strain and stress distribution

Walking angle		**Maximum principal strain response**	**Maximum principal stress response**
Horizontal	0°		
Incline	5°		

	7.5°		
	10°		
Decline	5°		
	7.5°		
	10°		

4.3Fracture risk analysis

As shown in *Figure 7*, none of the fracture risks are smaller than 1, therefore the femur was not subject to fracture under all loading cases. Incline slopes produced a higher risk of fracture than decline slopes as all fracture risk is lower than decline slopes. Slope with 5° shows the highest fracture risk, as the maximum principal stress on the femur bone was the highest. The smaller the maximum principal stress of the femur bone, the larger the fracture risk. It decreases gradually from 5° to 10°. Surprisingly, at an angle of 10°, the value of fracture risk is almost similar on both incline-decline walking. The magnitude of fracture risk during incline walking is much lower than decline walking. It should be noticed that the lower of fracture risk is, the higher tendency of femur to get a fracture.

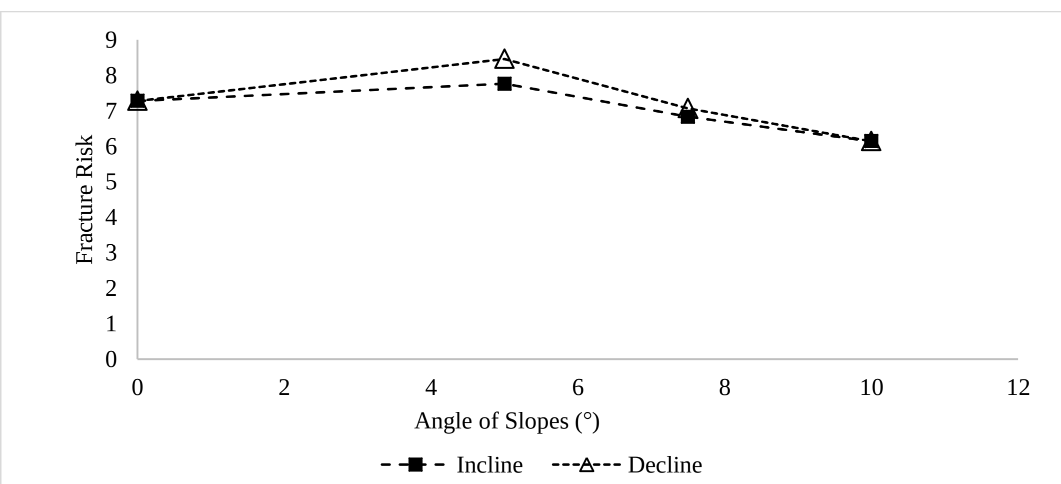


Figure 7 Effect of incline-decline walking on hip joints fracture risk

5.Discussion

In the present study, the effect of incline-decline walking on elastic strain and stress of femur bone was investigated using finite element method. The stress responses that lead to fracture risk of femur bone was then analysed based on the bone strength. The results show that the elastic strain and stress were sensitive to the slope angles during incline-decline walking. The maximum elastic strain and stress for incline walking was always higher than the decline walking for all slope angles. According to Zeng et al. [4], femur bone will break when the maximum equivalent von Mises elastic strain on the bone is equal or higher than 25,000 µstrain. All the von Mises elastic strain in this study was found not larger than 25,000 µstrain. Hence, the highest strain found in this study still hasn't reached the limit which is 1. 88×10-3.

On the other hand, the critical area of stress and strain was observed to be located in the femoral shaft for all cases. The region size was increased with respect to the increase of slope angles. The trend of the strain and stress concentration was consistent with the trend of maximum strain and stress obtained. The risk of femur bone to get fracture also was found to increase when the slope angle is increasing for both incline-decline walking. Therefore, the present study has successfully predicted the strain and stress responses on the femur bone due to incline-decline walking.

There are some limitations that associated with this study. The analyses were conducted in a linear elastic condition where the bone properties of the femur were modelled as a solid part (not considered the existence of cancellous bone). However, it has not influenced the findings of the current work since the assumptions are quite common for bone mechanics studies. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion

This study focuses on the effect of incline-decline waking on femur with respect to von Mises stress-strain, maximum principal stress-strain and fracture risk responses. The results found that the increase of slope angles contributes to the increase of stresses and strains, whereas the magnitude of stress and strain due to incline walking always higher than decline walking. Therefore, this study shows that there is a significant effect of incline-decline walking towards stress and strain response of the femur. The findings of this study could provide additional information on prediction of bone fracture and injury due to walking activity on incline-decline surfaces.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Yeap Chee Wei: Conceptualization, investigation, data collection, writing – original draft. **Khairul Salleh Basaruddin:** Conceptualization, writing – review and editing, supervision. **Fauziah Mat:** Study conception, investigation, review and funding. **Ruslizam Daud:** Analysis and interpretation of results. **Muhammad Juhairi Aziz Safar:** Writing – review and editing. **Tien-Dat Hoang:** Study conception, investigation, review.

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Appendix I

S. No.	Abbreviation	Description
1	3D	Three Dimensional
2	CAD	Computer-Aided Design
3	FEA	Finite Element Analysis
4	GPa	Giga-Pascal
5	MPa	Mega-Pascal