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Research paper

Finite Element Analysis on Knee Joint with Leg Length Inequality

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Abstract

This study aims to investigate the effect of leg length discrepancy (LLD) on the joint reaction stress and strain of femur particularly in the knee joint. The knee joint model was developed using CATIA and imported into ANSYS to simulate the LLD case based on the value of the joint reaction force from the previous experimental study. The analysis was done under a linear static condition. The knee components were divided on three; bone (femur and tibia), cartilage (femoral cartilage and tibial plateau cartilage) and menisci. The effect of LLD on the knee joint was determined by observing the contour of equivalent stress and strain distribution on the knee joint components and the maximum equivalent von-Mises stress and strain. The result shows a higher value of stress and strain was found on the short leg compared to the long leg due to the LLD. The pattern of overall results shows that the magnitude of stress-strain is proportional to the level of increments in LLD. Since the short leg demonstrate the greater in stress and strain value, it is prone to experience failure in the future such as wear in cartilage.

Keywords: *Finite element; stress-strain analysis; leg length inequality; knee response.*

1. Introduction

Leg length discrepancy (LLD) namely as leg length inequality, is a condition of the inequality between the length of the legs[1]. With a significance difference, LLD can cause obvious distortion in a body figure and give difficulty to a person to walk or run [2]. In most cases, the bones that are affected by LLD are the femur (thighbone) and tibia (shinbone)[3], [4]. Unlike the other bones, the femur and tibia growth around the growth plate. If the growth plate is damaged, either from illness or injury, the bone growth rate may be slower or faster than the other side. This is categorised as a functional LLD.

Similarly, a person suffers from LLD case are classified into two, those who are suffering from childhood known as congenital, while those who are create LLD condition throughout of lifestyle or accident known as acquire LLD[5], [6]. Nonetheless, between these two categories, both are prone to develop an abnormal loads condition and stress distribution on one of the limbs as the weight-bearing are shifted to the contralateral leg. For the long-term of period, this condition would damage the soft tissue around the long bone. In term of gait alteration, yet an acquired LLD are more debilitated if compared to congenital LLD even they experience the same level of LLD. This is due to the mechanical composition they able to adopt such as flex the long leg during gait[7], [8]. The augmentation of ground reaction forces induced might lead towards a soft tissue damage and joint degenerative likely osteoarthritis. This event occurs as the repetitive cyclic of joint contact forces concentrated on specific joint especially on LLD's condition[9].

Previous study by Harvey et al, found that a 0.5cm of LLD magnitude increase the prevalence of symptomatic and progressive of the knee osteoarthritis[10]. Another study by Golightly et al., they pointed out that a LLD of 2.0 cm and above had a positive association on knee arthritis[11]. Development of knee osteoarthritis initiated by two pathogenesis; abnormal loading transfer on normal cartilage; cartilage become defected as it hits up the breaking phase[12]. However, the cause-effect relationships in the association of LLD level remain unclear. To the knowledge, there is less evidence quantified the amount of stresses across the knee joint as result from LLD. The stress analysis for bones is one of the ways to investigate the bone failure ether due to bone morphology[13], [14], tissue properties[15], [16] or loading types. In this study, the focus will be on analysing the relation between the joint reaction stress and the mechanical behaviour of the knee joint segment due to LLD, different force configuration according to the LLD level will be assigned to the FEM. It is expected for the joint reaction stresses to be linearly proportional to the level of LLD.

2. Computational Modelling

In this study, Ansys 18.1 was used to build a computational model. In order to obtain a correct and effective solution, it is essential to build a partial models likely geometrical model, material model, finite element model and loading model[17].

The geometry model of the lower limb was retrieved from online source in IGS format. Through CATIA, the model was converted into solid parts by healing, closing and joining the surfaces of the model. A further step was by altering the model leaving only some parts of the femur and tibia from the original model. Segments of the knee joint were created using CATIA to complete the 3D model of the knee joint segment including articular cartilage and menisci. The geometrical models were constructed based on previous literature[18].

The bony structure was assumed to be in a rigid body, which only represents the outer surface (cortical bone). The FEM model was created using 'tetrahedron' shaped elements by varying the size of the elements. On the contact area of the knee joint model, the size of elements was narrowed down to 2mm as shown in Figure. 1.

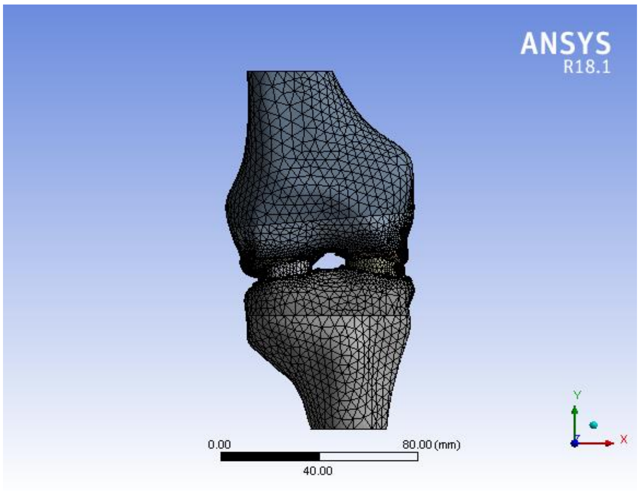


Fig 1: FEM model of knee joint segment

Each individual component was set to be homogenous, isotropic with linear behaviour for the material properties which can be described by Young's modulus and Poisson's ratio as in Table 1.

Table 1: Assigned material properties [11], [12]

Material	Young's Modulus, MPa	Poisson's ratio
Bone	17400	0.30
Cartilage	12	0.45
Menisci	59	0.49

Menisci and cartilage are categorized as the soft tissue with hydrate structure. In this study, the loading applied to these soft tissue was approximate 1500s corresponding to the single-leg of stance phase (toe off), then these soft tissue react as a single-phase linear elastic and isotropic. Based on study by Donzeli et al., who demonstrated there was no significant changes in the cartilage during short interval loading condition[19]. For these reason, cartilage and menisci were assumed to be linearly elastic and isotropic.
The force will be distributed from the bottom of the FEM model with upward direction simulating the reaction force from the foot to the knee during standing position while restraining on the top of the FEM model as fixed-end as shown in Figure 2. The value for the applied force was obtained from the previous study[5], [20] of the LLD's cases. The joint contact force was accessed from the male subject of healthy Body Mass Index range 21 with the Body Mass of 62.8kg.
Connection for each individual model is defined as in Table 2. 'Bonded' connection means that there is no gap and sliding is not allowed between the individual models. While 'no separation' connection means, there is no gap but sliding is allowed between the individual models. After defining the connection type, the mesh was controlled by adding 'patch independent' method at the cartilage and meniscus, and 'contact sizing' at the femur and tibia contact area.

Table 2: Connection type at the contact area

Contact area	Connection type
Femur + femoral cartilage	Bonded
Tibia + tibial cartilage	Bonded
Femoral cartilage + menisci	No separation
Tibia plateau cartilage + menisci	No separation

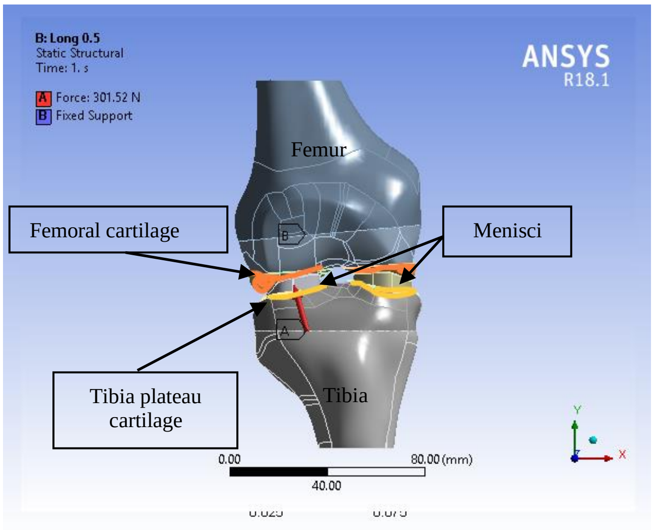


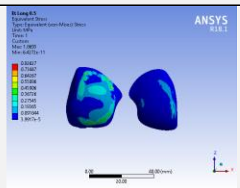
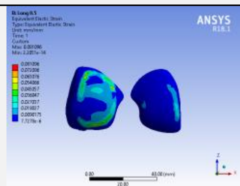
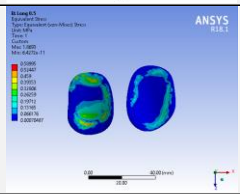
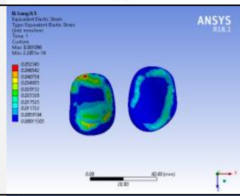
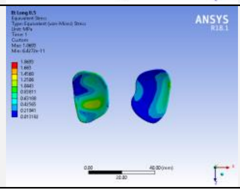
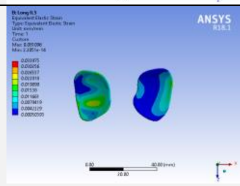
Fig 2: Boundary conditions on the FEM model

3. Results and Discussion

3.1. Stress and strain distribution

Table 3 depicted the contour band on stress-strain distribution as the contact forces were applied. Based on the Table 3, it is shows that the maximum stress-strain contour of all knee joint components were concentrated on the lateral part instead of medial. The most affected seem on the menisci components as it received greatest magnitude of strain-stress response. It can be concluded that during standing position, the lateral side of knee joint tolerate more stress than the medial side [18].

Table 3: Contour band of stress-strain distribution

Knee joint component	Stress	Strain
Femoral Cartilage		
Tibial Cartilage		
Menisci		

3.2. Effect of LLD increments on knee joint

Figure 3 shows the maximum equivalent von-Mises stress due to the force based on the LLD level. From this result the stress on the short leg can be seen is higher in magnitude value, than the long leg in all of the knee joint components. The highest stress magnitude was obtained at level 3.5cm for the short leg, while long leg at the level of 2.5cm. It can be said that the increasing LLD level cause the stress on the short and long leg to be increased. However, on the overall increments, it was showed irregular pattern, where it rises and drops drastically within the

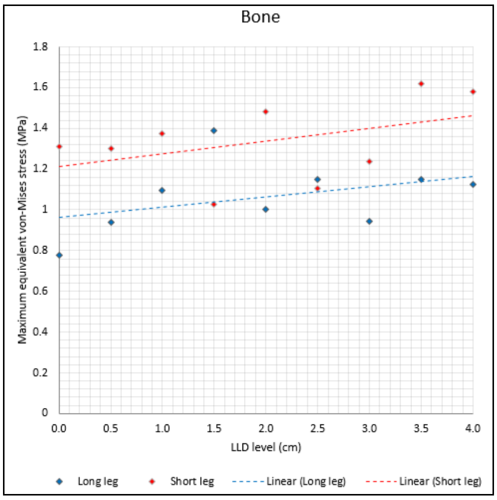
LLD level. There were drastically drops on level of 1.5cm, 2.5cm, 3.0cm and 4.0cm for the short leg. Whereas, for long leg, the drops in magnitude were detected on level 2.0cm, 3.0cm and 4.0cm.

The pattern of the result also same for the strain response as shown in Figure 4. The highest magnitude were at the level of 3.5cm for the short leg and 2.5cm for the long leg of all the components. Anyhow, there were drastically drops on level of 1.5cm, 2.5cm, 3.0cm and 4.0cm for short leg. Contradict results were obtained for the long leg which the magnitude of strain responses had drops along level 2.0cm, 3.0cm and 4.0cm for the bone and menisci. Yet, for the cartilage, the results showed the drops in magnitude on level 0.5cm, 2.0cm, 3.0cm and 4.0cm. For the case of long leg, the drops in pattern were presented along the level of 2.0cm, 3.0cm and 4.0cm.

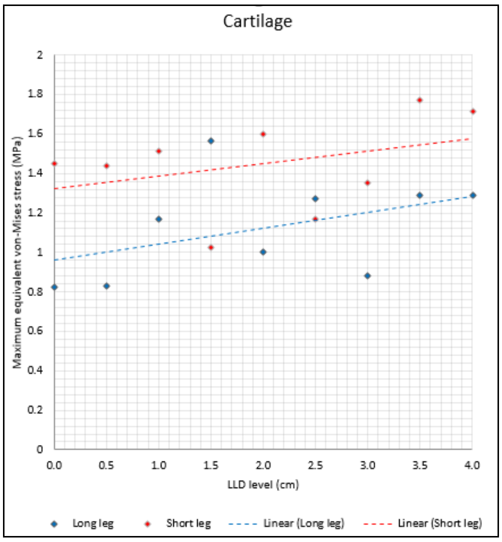
Based on the results in Figure 3 and 4, short leg will suffer a higher stress and strain on the knee joint components compared to the long leg. This is because of short leg having a greater force distribution than the long leg described by the resultant force data taken from the experiment of LLD case and previous study [4]. Meanwhile, the highest maximum equivalent von-Mises stress and strain happened on the menisci compared to the other components of the knee joint for both short and long leg.

As can be seen on the Figure 3 and 4, the pattern of the long leg stress-strain distribution shows an increasing trend while the overall trends of short leg seem fluctuate. However, when comparing to the long leg, the short leg induced more stress if compared along the increment level of LLD. This statements are in agreements of study by Pereira et al.[11]. They found that short leg would induced more stresses when compared to long leg. Another study of finite elements by Kiapour et al.[4], they supported the statement that even a greater loads was applied, the stress-strain distribution on the knee components does not lead to a greater stress response. This is because the stress response is depending on the contact area not the load itself. For this reason, the stress-strain distribution on the Figure 3 and 4 depicted fluctuate in pattern.

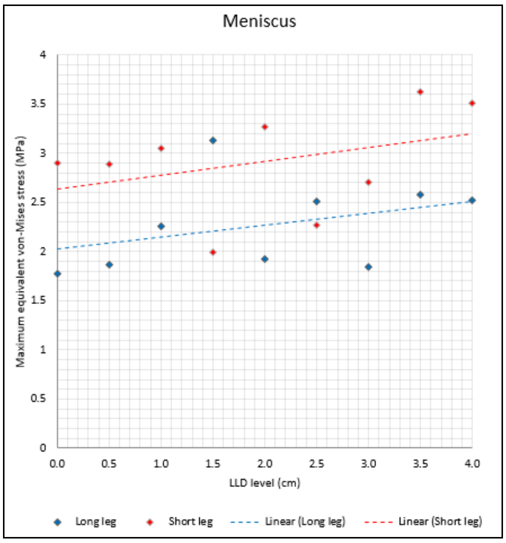
The current study had ignored the several impact of others things. First of all, the result were analysed based on static model of full extension by neglects the different joint angles contribution which would modify the contact area and the distribution of stress response in menisci and cartilage. Next, the contribution of muscle and ligament were excluded. Lastly, we limit our study to only load corresponds to the maximal forces obtained during stance phase of the gait cycle obtained on the previous study. Definitely, the dynamic load should be analysed at the future study so that the real picture of gait response could be explained.



(a)

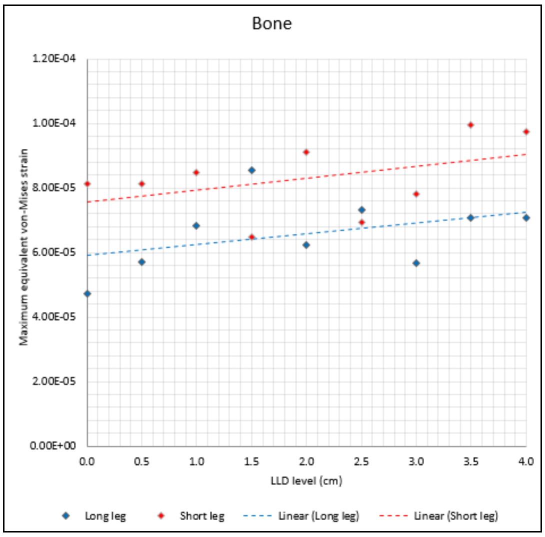


(b)

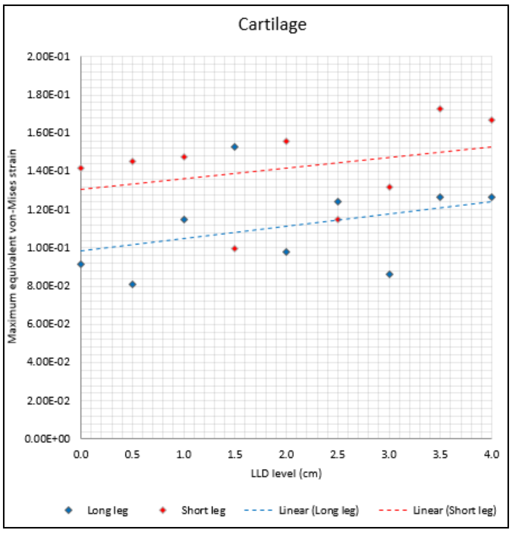


(c)

Fig 3: (a), (b), (c): Maximum von-Misses stress response on the short and long leg



(a)



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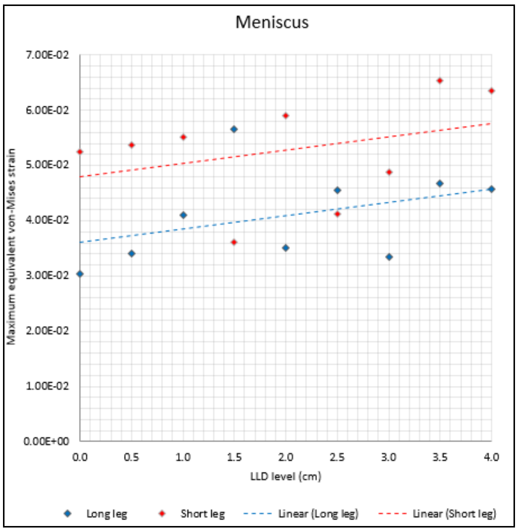

(c)

Fig 4: (a), (b), (c): Maximum equivalent von-Mises strain, on the short and long leg.

4. Conclusion

In this study, a FEM model of knee joint had been successfully developed through CATIA and ANSYS. Using the FEM model, a linear static structural analysis was conducted to simulate LLD case on human. Results showed the stress and strain distribution on both short and long leg concentrated on the lateral side of the joint. The stress and strain value was found higher on the short leg compared to the long leg. By looking through all the components of the knee joint for both short and long leg, maximum equivalent von-Mises stress and strain values found to be occurred on the menisci. Excluding the menisci, the structural deformation on the knee joint can be seen to happen on the cartilages described by the equivalent von-Mises strain value. It can be concluded that, due to the force distribution regarding LLD case, the knee joint of the short leg suffered a higher stress and strain distribution compared to the long leg.

For further extension of this study, the model of the knee joint can be optimized by including the ligaments between the femur and tibia. This would be very accurate attempt in getting stress and strain data. Using the FEM model of knee joint segment as reference, various mechanical responses on the knee joint due to LLD can be observed. This will help to improve the understanding of the effect of LLD. Moreover, the cause for the several diseases due to LLD can be found and explained in terms of mechanical responses. These findings can be used to give solutions for the treatment on a person who suffered LLD.

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