Finite Element Study on Strain Energy Release Rate and Von Mises Stress in Muscle Laceration

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***Abstract*—This study aims to present a finite element modelling and analysis of hyperelastic human muscle laceration by using a continuum mechanics approach under Mode I loading conditions. Two – dimensional model of the muscle was developed according to the dimensions that have been used in past research. The finite element analysis and construction of the model are done in Mechanical APDL (ANSYS) v14.0 software. The research was conducted mainly based on two conditions, which are according to various lacerations length and different loading force. To evaluate the fracture toughness of the human muscle thigh segment, this research has employed finite element method to predict the strain energy release rate by using three-point bending test. Various loading forces in the range of 500 N to 4000 N were applied in an attempt to study their effect on the strain energy release rate (J – integral) and von Mises stress. The results show that the strain energy release rate (*J*-integral) and von Mises stress increased as the laceration length been increased. It can be seen clearly that both trend of the graphs shown a nonlinear increment. By knowing the value of *J* – integral and von Mises stress, it will help the designer to create a more reliable and advanced prosthetic and orthotic devices. It can also provide a better view on the design of surgical intervention tools.**

***Index Terms*—*J*-Integral; Muscle Laceration; Strain Energy Release Rate; Von Misses Stress.**

I. Introduction

Muscles are known as biological soft tissues, and the characteristic is inhomogeneous, anisotropic and nearly incompressible. In another word, muscle also knows as a band or bundle of fibrous tissue in the human body that can contract, maintaining the position and producing movement for the body [1]. Skeletal muscle is anchored by tendons to bone and is used in the movement of skeletal especially in maintaining body posture. For smooth muscle is differ from skeletal because smooth muscle is not under conscious control. Smooth muscle can be found within the walls of organs and structures such as the oesophagus, intestines and stomach. The cardiac muscle (myocardium) is also muscles contraction without conscious and can be found in the heart. The three different muscles can be seen in Figure 1. In this study, all those muscles are combined to be one major muscle that presents the same properties and characteristic. Muscle building is similar for male and female, and it can speed up if they get a minimum of seven hours of sleep [2].

Muscle is soft tissue that can be defined as hyperelastic properties [3]. Muscle tissue behaviour can be depicted by assessing the scope of strain rates and scope of hyperelastic and viscoelastic constitutive models [4]. Both of viscoelastic and hyperelastic differs in muscle behaviour where viscoelastic cannot describe the tissues correctly at large strains while a hyperelastic could be more appropriate [5]. Besides that, to describe the muscle behaviour, the use of any hyperelastic materials can be used for the reason of the same properties [6]. Linear elastic models are usually not accurate to describe muscle behaviour. The most accurate example of the hyperelastic material is rubber because the stress-strain relationship can be defined as non – linear and generally independent of strain rate.

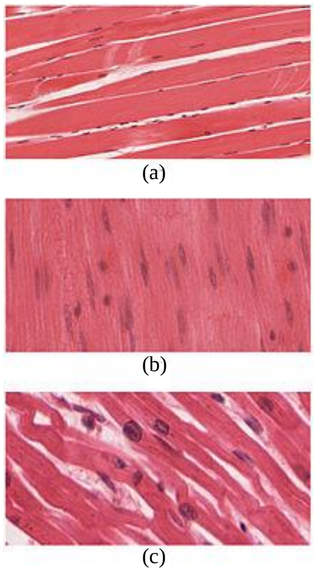


Figure 1: (a) Skeletal Muscle, (b) Smooth Muscle, and (c) Cardiac Muscle [2]

The strain energy release rate or in another word the energy release rate is known as the energy dissipated during fracture per unit of recently created fracture surface territory. This is imperative to fracture mechanics because the energy that must be supplied to a crack tip for it to grow must be balanced by the amount of energy dissipated. To calculate the strain energy release rate, the J – integral have already been introduced [18]. Therefore the theoretical concept of *J* – integral was developed in 1967 by Cherepanov [19] and Jim Rice in 1968 [20]. It shows that an energetic contour path integral (called *J*) was independent of the path around a crack [7][8]. The strain energy release rate also has been used to find the failure criterion for a variety of fracture phenomena in rubber [9].

The von Mises stress is usually used to predict yielding of materials under any loading condition from results of simple tests. It can be considered to be a safe haven for design engineers. By using this information, they can predict the failure of the design if the maximum value of von Mises stress induced in the material is more than the strength of the material. In another study, S. Ishihara et al., also done a test related to von Mises stress on pressure distribution inside the trunk on a mattress [10].

Nowadays, besides doing an experimental study in a laboratory, a researcher can also use a simulation analysis such as finite element analysis (FEA). The advantages of using it especially to avoid any unethical thing happen to a human. FEA is important to engineering for performing engineering analysis, and it includes the mesh generation techniques for dividing a complex problem into smaller elements. Finite element analysis (FEA) techniques can be done by using ANSYS, ABAQUS and other application.

II. METHODS

The procedure for finding J – Integral and von Misses stress under Mode I loading is shown in Figure 2 below.

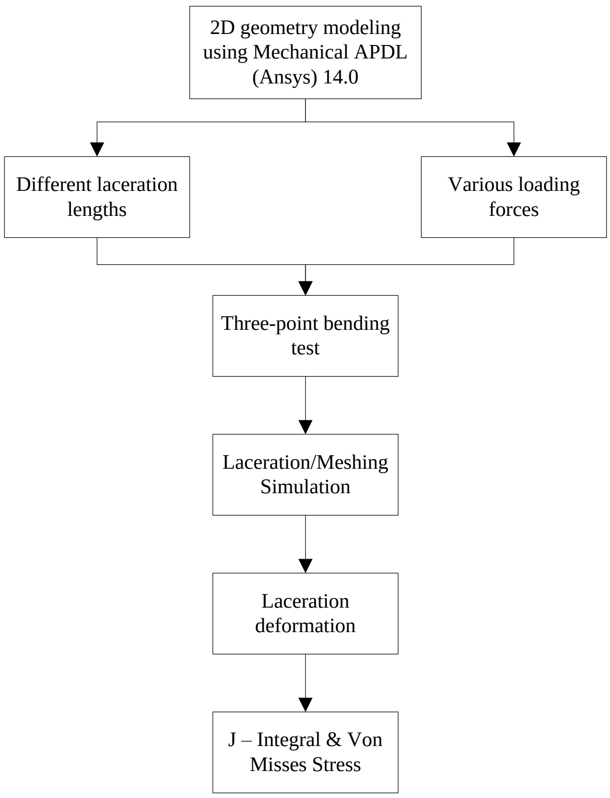


Figure 2: Block diagram that been used to obtain strain energy release rate and von Mises stress

A. Finite Element Analysis (FEA)

Over the previous decade, the Finite component technique has turned into a built up other option to do a vivo surgical assessment. The main advantage of finite element technique lies in its capacity to decide the anatomical reaction of life structures (muscle behaviour), without being subject to ethical restrictions [11]. Solid 8 node 183 has been chosen as an element type of the model as muscle can be considered as solid material. Element shape and behaviour of the model are clarified as quadrilateral and plane strain. By considering Mode I fracture, the J – integral value can be obtained after the simulation has been done.

B. Model Generation

Non – linear hyperelastic material model was used to describe the human muscle. In this study, Ogden's formulation was used for the hyperelastic material model. The coefficients and properties of human muscle are presented in Table 1 [12].

Table 1
Single term Ogden Model Coefficients for Human Muscle

	μ	α	ρ
Muscle	3.63 x 10^4	45	920

Eight different forces were applied to the model to identify the changes in muscle laceration. The muscle dimension was determined from human anthropometric parameters derived from measurement of axial CT scans [4]. The height of the model is defined as W = 46.5 mm, and the length between two support reactions are 4W = 186 mm as presented by Bower [13]. The test on the model was done by using three-point bending test as shown in Figure 3.

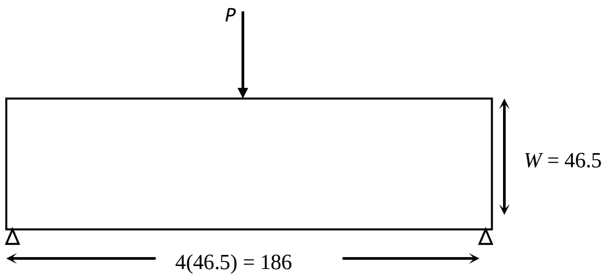


Figure 3: Configuration of three-point bending test on a human muscle

Free mapped areas meshed as in Figure 4 are used on the model. The displacement constraints were applied by picking two nodes on the x-axis, which their distances were set based on 4W that act as the support reaction. The centre of the model was loaded with P =500 N of force as in Figure 3. The range of force from 500 N to 4000 N was applied to the model as to study the effect of load variations from lower to higher load while the laceration length is also varied. The value of 0.0042 m is set for each increment in laceration lengths until it nearly reached the top surface of the model. The model solutions are run for the properties defined by the structural, nonlinear, and hyperelastic material.

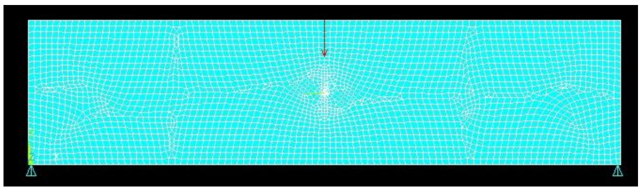


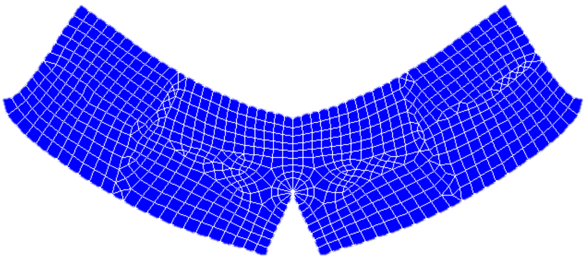
Figure 4: Meshing sizes after free mapped areas had been used

III. RESULT AND DISCUSSIONS

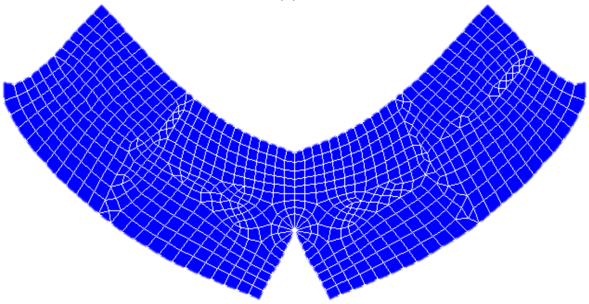
As mentioned before, this study will focus on finding strain energy release rate and von Misses stress. The analysis was done by applying the different forces range from 500 N to 4000 N on different laceration lengths within 0.0085 m to 0.038 m.

A. Strain Energy Release Rate in Different Applied Loads and Laceration Lengths

As we can see in Figure 5, the muscle model was deformed after a load of *P* has been placed on the model. The laceration length for the model in the figure was 0.0296 m. When the load increased, the deformed shape is also changed as in hyperelastic materials. From the simulation also, it can be concluded that muscle shows a nonlinear behaviour.



(a)



(b)

Figure 5: Different applied loads with a laceration length of 0.0296 m (a) P = 1500 N, (b) P = 3000 N

The different forces with a different crack length that has been used to find *J* – integral is 500 N, 1000 N, 1500 N, 2000 N, 2500 N, 3000 N, 3500 and 4000 N. For laceration length, 0.0085 m, 0.0127 m, 0.0169 m, 0.0211 m, 0.0254 m, 0.0296 m, 0.0338 m and 0.038 m are used. From Figure 5 also, we can see that the model bend more from (a) *P* = 1500 N to (b) *P* = 3000 N, when there is an increment in applied load.

From the graph that has been plotted in Figure 6, it was found that the values of strain energy release rate (*J* – integral) were well correlated with the value of laceration lengths. It can be seen that the energy that must be supplied to a laceration to grow was increased due to the formation of new surfaces. Also, the strain energy release rate shows clearly a nonlinear increment when the applied loads were increased. It was determined that the strain energy release rate (*J* – integral) increase as the laceration's length increase.

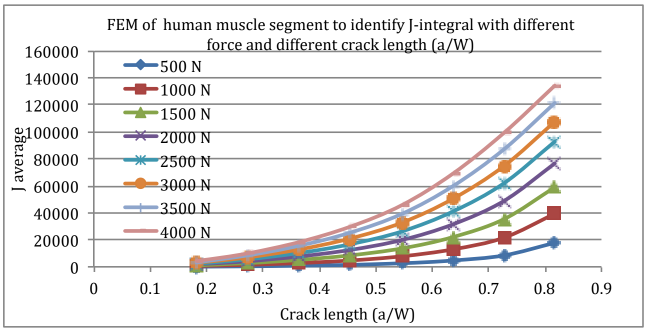
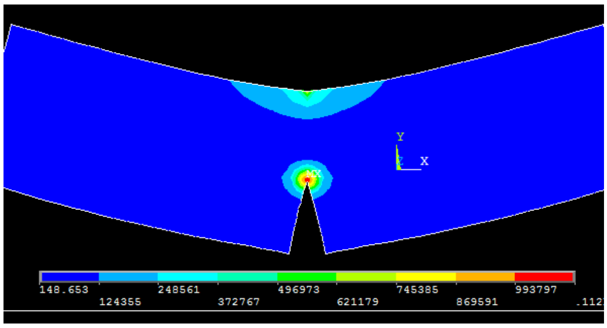


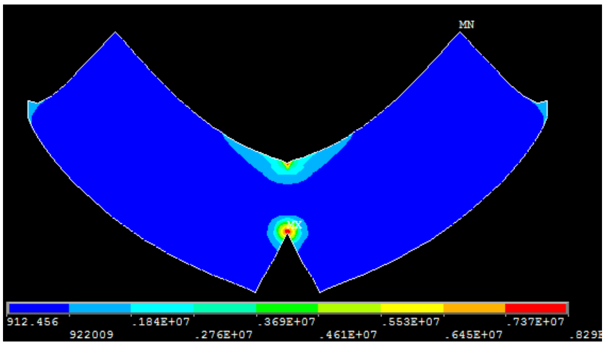
Figure 6: Different applied loads with different laceration lengths

B. Von Mises Stress In Different Applied Loads And Laceration Lengths

The same parameter and setup have also been used to find von Mises stress. The red colour in the contour represents the highest stress after the load being applied while the blue colour represents the least stress in the model as in Figure 7. It was found that the value of Von Mises stress was well correlated with the value of crack length. It can be seen that Von Mises stress values also shows clearly a nonlinear increment. We can conclude that von Mises stress is proportional to laceration lengths as in Figure 8.



(a)



(b)

Figure 7: Different applied loads with a laceration length of 0.0296 m (a) *P* = 500 N, (b) *P* = 3000 N

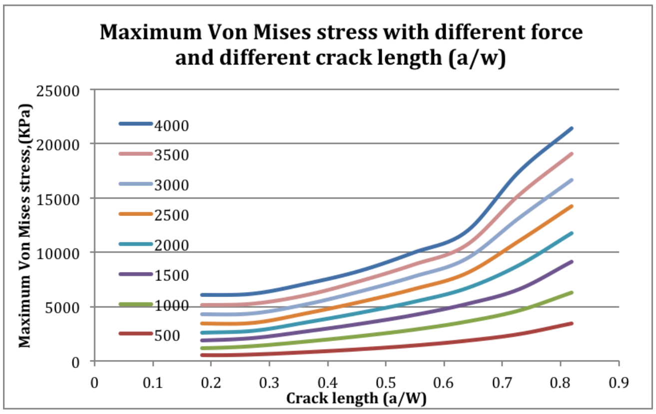


Figure 8: Von Mises stress with different applied load and different crack length

IV. CONCLUSION

The different force with a different laceration lengths that have been used to find the strain energy release rate (*J* – integral) and von Misses stress is 500 N, 1000 N, 1500 N, 2000 N, 2500 N, 3000 N, 3500 N and 4000 N while 0.0085 m, 0.0127 m, 0.0169 m, 0.0211 m, 0.0254 m, 0.0296 m, 0.0338 m and 0.038 m for laceration lengths. It was determined that the strain energy release rate increase as the laceration's length increase and the longer the laceration length, the higher the values of von Mises stress. It was determined that both trends show clearly a nonlinear increment. Also, there are many other tests existed which are tensile test and compression test that could be used as one of the approaches to analyse and investigate the strain energy release rate based on Mode I. Besides that; there were no related previous studies been done on finding laceration behaviour of a human muscle segment. More researchers only focused on fracture toughness and mechanical stress distribution of the bone segment especially. Strain energy release rate and von Mises stress should be considered as another field since the laceration on muscle can lead to injury in our life.

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