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Effect of Load Direction on fracture type in tibia

An FEM Analysis

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Abstract—**The main purpose of this research was to predict the site and type of fracture in the tibial shaft under transversal and torsional impacts, using FEA**

In this research, tibia was supposed to act as an elastic-cortical shell with transversely isotropic symmetry. Effects of the spongy bone were ignored because of its much lower stiffness than the cortical shell.

Results of stress contours were in agreement with those previously obtained by experimental works, i.e. in cases of loading medially, laterally and dorsally mostly direct fracture mechanism was seen with transverse, oblique and wedge shaped fracture patterns while an indirect mechanism was created by ventrally loading with a pattern of oblique fracture lines >30°. Spiral fracture pattern was observed by loading a torsional moment.

Prediction of the fracture type and its propagation patterns in the tibial shaft were highly comparable to the radiography images taken from injured bones of pedestrians and experimental impact loadings of real bone by other researchers.

Keywords- bone mechanics; tibia; fracture pattern; finite element method; and load direction

I. INTRODUCTION

Injuries to the human lower extremities are mostly due to the collision of a vehicle and pedestrian, which results in fractures of long bones, injuries to the knee and ankle. This is because of the impact applied by the vehicle and high acceleration created in the lower extremities. Different injury mechanisms are seen in long bones which bending and torsional moments have been considered as major factors affected [1].

In the recent years many new models have been proposed to analyze the injury mechanisms in bone tissue caused by the collision of vehicle-pedestrian. Also, dynamic load tests were performed to obtain fundamental information on the fracture behavior and morphology of human bones, e.g. for tibia [2].

On the other hand, numerical methods, for instance finite element method are being widely employed to estimate mechanical stimuli in bones in order to get useful information on the mechanical properties and also the behavior of bone tissue.

Impact biomechanics in the collision of vehicle-pedestrian has been studied widely during the last three decades in order to recognize the injury mechanisms in human limbs, reaction of lower extremities to the impact and getting information on the strength of different human bone tissues [3]. Based on these researches, two main fracture mechanisms have been observed in long bones [2 and3]: Direct mechanism in which the fracture lines are produced at the impact site and mostly propagate transversally and indirect mechanism in which the fracture lines pass partly through the impact site and tend to propagate longitudinally.

The results of statistical surveys showed that nearly all tibia-fibula fractures were attributable to a direct fracture mechanism. Fracture patterns consistent with a direct mechanism included transverse or segmental fractures, the presence of a fragment or fracture obliquity less than 30°. Spiral fractures and oblique fracture lines >30° were attributed to an indirect force [4].

The study of main type and sub-type of shaft fractures according to the Orthopaedic Trauma Association (OTA) classification of long bone fractures revealed that the most common fracture type is bending wedge followed by transverse and oblique patterns [5]. For most of the tibial shafts, bending appeared to have been the primary local mechanism of fracture while torsion was responsible in some cases too [5].

In this research, a 3D finite element model of human tibia, based on the real geometry of tibia, was created to investigate the fracture mechanism under the impact loads. Also, by loading in four main directions, the effect of loading direction on the fracture pattern has been investigated. Using the real geometry of tibia is an advantage of this model in comparison with other similar studies; also the mechanical properties for material property adopted for the construction of the model were close to those of real bone tissue [6].

II. MATERIAL AND METHODS

In this research, a 3D model of tibia was created with the real geometry of one human male and mid-sized left leg using spiral scan images. It was materialized by MIMIX software (version 10.01). The model was then developed in ABAQUS software (version 6-7.1) for the purpose of modeling of some other *in-vivo* conditions (Fig. 1).

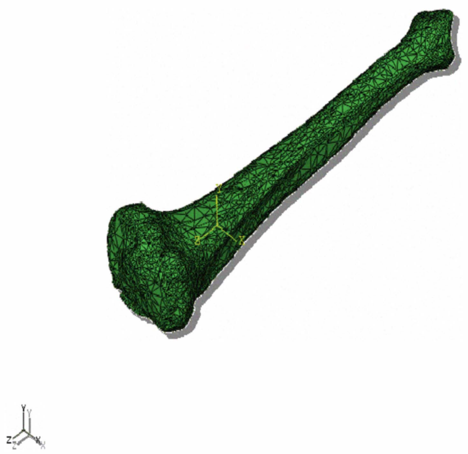

Figure 1. The 3D model of the human left tibia used in this research with the exact geometry of real bone using spiral scan images and MIMIX software.

As mentioned before, tibia was considered as a cortical shell with transversely isotropic material property. The stiffness matrix for cortical bone assumed as a transversely isotropic material, has 5 independent constants as follows [6].

$$C_{ij} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ \cdot & C_{22} & C_{23} & 0 & 0 & 0 \\ \cdot & \cdot & C_{33} & 0 & 0 & 0 \\ \cdot & \cdot & \cdot & C_{44} & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & C_{55} & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & C_{66} \end{bmatrix} \quad (1)$$

$$C_{11}=C_{22}\ , C_{13}=C_{23}\ , C_{44}=C_{55}, C_{66}=1/2(C_{11}-C_{12}) \quad (2)$$

In order to estimate these constants and to introduce them to the software, available data [7], were used (Table 1).

TABLE 1. Material properties used for modeling of tibia [7]

Young Modulus (GPa)	Poisson Ratio	Shear Modulus (MPa)
E_1= 12 E_2= 12 E_3= 18	$\upsilon_{12}=0.300$ $\upsilon_{23}=0.253$ $\upsilon_{13}=0.253$ $\upsilon_{21}=0.300$ $\upsilon_{32}=0.390$ $\upsilon_{31}=0.390$	G_{12}= 4850 G_{23}= 5700 G_{13}= 5700

Bending and torsional moment Impacts were applied to investigate the fracture mechanism of tibia and its propagation pattern. The effect of loading direction on the fracture pattern was also studied by loading a transversal impact in four main directions, i.e. medially, laterally, ventrally and dorsally. The transversal impact function was extracted by the forces inserted to tibia in simulation of the collision of a vehicle-pedestrian (Fig. 2) [8].

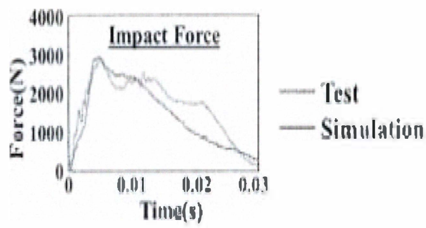

Figure 2. The transversal impact function of the collision of a vehicle-pedestrian [8]

To investigate the effects of torsion on the fracture mechanism and its pattern, a torsional moment function for the tibia (Fig. 3), was applied to the proximal part of tibia [9].

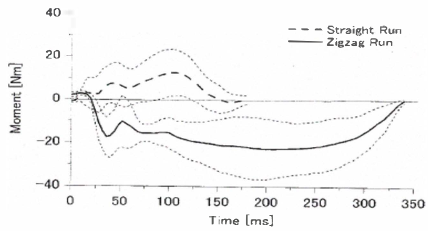

Figure 3. The torsional moment function applied [9]

In agreement with some of the previous studies [8 and 9], the boundary conditions in the case of transverse loading, both ends of tibia were considered to be clamped, while in torsional loading just the distal end was constrained.

An optimized free mesh was used in this model to keep the bone shape in the best form with totally 12150 linear 3-node triangular elements (S3R).

Von-Mises stress contours were used to predict the fracture mechanism in tibial shaft under the impact loadings. It must be noted that Von-Mises stress is a numerical parameter and is valid just for an isotropic material, nonetheless was used as a comparing scale.

III. RESULTS

Figure 4 shows the stress contour of a medial transversal impact load on tibia. The maximum stress of 150 MPa compared with the bending ultimate stress of the cortical bone of 140 MPa [10], shows that fracture occurs in the mid-shaft of tibia but near the dorsal edge. Also, a direct fracture mechanism with transversal fracture pattern was observed from this stress contour during the impact cycle.

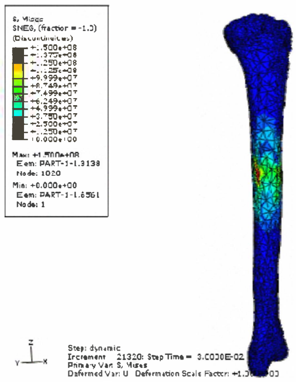

Figure 4. The stress contour in tibia under a transversal medial impact load

When a lateral impact load is applied on the tibia, results showed that fracture will possibly occur with initial fissures near the edges of tibia and propagate transversally but sometimes oblique (Fig.5). Also a wedge shaped fracture pattern was observed occasionally while loading in these two directions (Fig.6).

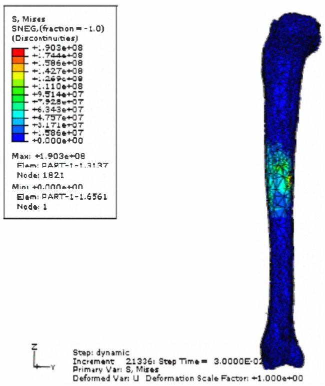

Figure 5. The stress contour in tibia under lateral impact loading

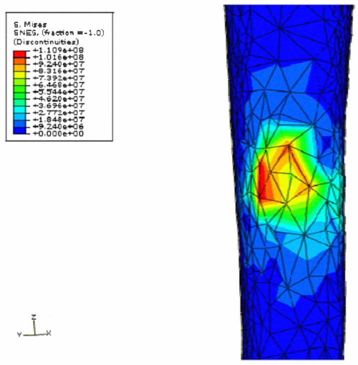

Figure 6. Wedge shaped fracture pattern in medial loading

Dorsal loading resulted in a direct and transverse fracture mechanism with longitudinal hairline cracks at the impact site (Fig.7).

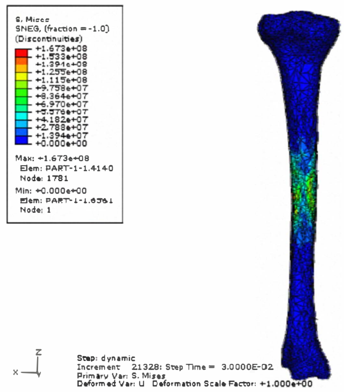

Figure 7. The stress contour in tibia under dorsal impact loading

In case of ventral loading, the amounts of stress were higher than the strength, and so it will likely experience fracture but with longitudinal fracture lines along the tibial edges to the distal third. Characteristically, fracture lines of this type predominantly showed a longitudinal pattern which stands for an indirect fracture mechanism (Fig.8).

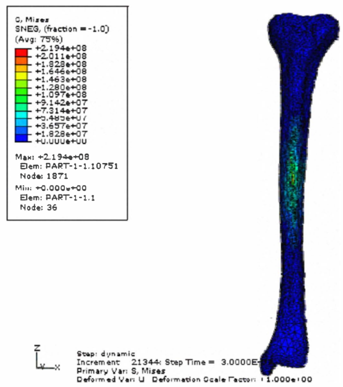

Figure 8. The stress contour in tibia under ventral impact loading

The second major factor which causes fractures in tibial shaft is torsion [3]. In this case, a torsional moment is created because of a sudden change in body position, e.g. while running in a zigzag way which affects the lower extremities [9]. In order to study this type of fracture, a torsional moment was applied to the proximal tibia.

The maximum stress of 71 MPa, in comparison with the ultimate torsional strength of tibia which is 55 MPa [10], was found here that fracture occurs along the edges of tibia (Fig. 9).

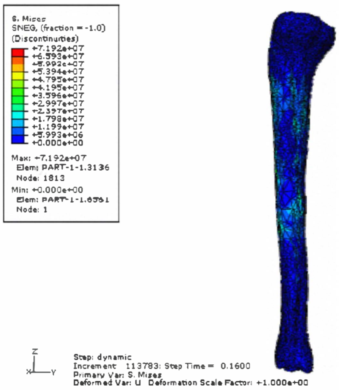

Figure 9. The stress contour in tibial torsional loading

As can be seen in Figure-9, the discontinuities propagate from the proximal third to the distal end. The major pass was seen along the tibial edges and passed through the adjacent surfaces. This type of fracture lines propagation made a spiral fracture pattern which is an indirect fracture mechanism which is in agreement with experimental observations [10].

IV. Discussion and Conclusion

The literature concerning the fundamental mechanical properties of compact fresh bone is sadly poor. The majority of studies are based on animal material because of the different dimensions of human bones make the standardized testing of their material difficult. Also, these fundamental material characteristics are not automatically applicable to whole bones, because bone geometry has a decisive influence on post impact mechanical changes [2].

It is known that bone is a semi-brittle material and will experience fracture with forces greater than its ultimate strength. Three factors must be considered while a long bone is going through a fracture process: the force intensity; the duration of force application; and finally the direction of applied force.

Results of previous studies, in regard to the effect of parameters like the force direction and its intensity, showed that all fracture patterns -except spiral- , can be seen in case of transversal loading of long bones [11].

The differentiation between direct and indirect long-bone fractures was, in some cases in the literature, only based on radiographs. Transverse, wedge shaped and oblique fractures with fracture-line obliquity less than 30° were commonly classified as direct, while spiral fractures and oblique fracture lines >30° were classified as indirect [12].

In this research, by using a real geometric model of tibia, according to its complex and unique geometry, the fracture mechanism and also the effect of loading direction on the fracture pattern under transversal and torsional impacts, has been investigated and the results can be summarized as follows :

1- In agreement with experimental evidence [2], two main types of fractures were seen in tibia under an impact load which classified as direct and indirect fractures. When the fracture lines originate directly at the impact site and propagate in a transverse direction, a direct mechanism and if the fissures propagate at a different site of the impact, is called indirect. These results are the same as the classification of long bone fractures in previous studies and radiography images [12].
2- All of the observed fracture patterns (except spiral), can be produced by transverse loading of the shafts of long bones. In this case, mostly a direct fracture mechanism with transverse, oblique and wedge shaped patterns was observed; while in torsional loading an indirect mechanism with a spiral pattern was created which are in agreement with experimental tests on long bones [11].
3- The site of maximum stress and strain was seen near the tibial edges under the impact loadings. So, we came to the conclusion that primary and main fissures were created near the edges. This was proved by the images taken from the crack creation and its propagation during the impact loading of tibia [2].
4- According to the results of loading in different directions, in cases of loading medially, laterally and dorsally, a direct mechanism with a transverse pattern was observed, while in ventral loading, an indirect mechanism with a pattern of oblique was created, which are in accordance with experimental results [2].

It is clear that the geometry of loaded sides have a decisive influence on the fracture pattern. With attention to the results of loading in different directions, it was concluded that the flatter the loaded surface, the higher the incidence of direct fracture patterns; and more edged side, will result in an indirect mechanism with a longitudinal course of fracture lines. In agreement with this finding, the previous studies performed by other researchers, confirmed the effect of loaded side geometry on the fracture pattern as well [2].

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