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FINITE ELEMENT MODEL DEVELOPMENT OF PROXIMAL FEMUR BONE UNDER STATIC AND DYNAMIC SIDEWAYS FALL

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ABSTRACT

A femoral fracture happens when the femur gains a very high stress concentration during fall and may result in femur fracture. In fact, most fall-related cases occur in sideways falls. Bone fracture leads to life quality impairment and may even be life-threatening. In this study, the effects of quasi-static and dynamic loading on the femur bone during a sideways fall are investigated by employing the finite element (FE) software ANSYS. The FE model is developed and simulated in different fall conditions; inclination angle of 10º and rotation angle from -20º to 30º for static and dynamic loading conditions. The capacity of the bone is evaluated in terms of von Mises stress, von Mises strain and the total deformation at three different positions: femoral neck, greater trochanter, and intertrochanteric, during sideways fall. For static loading, the femoral neck demonstrates the highest von Mises stress and strain at a 30º rotation angle and loading force of 4500 N. For dynamic results, the greater trochanter exhibits the highest von Mises stress and strain at 20º and -10º rotation angle, respectively subjected to 3 m/s impact velocity. On the other hand, the highest deformation occurs at a 30º rotation angle and impact velocity of 3 m/s. These findings show that the proximal femur bone is prone to fracture during sideways fall. The understanding of the femoral bone capacity under multiple loading conditions during a sideways fall is useful in assisting the medical practitioner to provide better treatment and support for patients and hence reduce repeated treatment cases.

Keywords: femur bone, fall, finite element, quasi-static, dynamic.

INTRODUCTION

In the human bone structure, the femur is the longest, largest, and strongest bone. The femoral bone is divided into proximal, shaft and distal. The proximal femur consists of the head, neck and trochanter (greater and lesser). The proximal femur and pelvis form a very important joint called the hip joint. The femur needs to support the maximum body weight when carrying out physical activities such as standing, walking, climbing, and running. These activities may involve a risk of a person falling, which can easily cause a human bone to crack or fracture.

More than 90% of hip fractures are reported to be due to falls [1] and most of the fall-related hip fractures occur at the proximal femur, as the femur is subjected to a high-level concentration force during the fall. In fact, 63-69% of fall-related fractures are due to falling in a sideways direction [2]. A bone fracture may result in life quality impairment for the patients, or even facing a life-threatening situation in severe cases if the crack is not recovered or repaired on time.

There are three types of hip fractures during falls: cervical fracture, intertrochanteric fracture, and subtrochanteric fracture [3, 4]. The magnitude and loading directions have been found to significantly affect the stress concentration and hence the structural capacity of the femur [5, 6]. The finite element method (FEM) has been widely employed and is considered as a handy tool for predicting the fracture behaviour of the femur bone. As such, prevention and better treatment can be provided to the patients. Fleps *et al*. [7] conducted a Finite Element (FE) study on the effect of reaction force on hip fracture during a sideways fall. The failure load, types of fracture, and failure criteria were investigated. Based on the results, the femoral neck and the greater trochanter showed high stress concentrations. Sarai *et al.* also employed a 3D FE model of the femur bone to investigate the influence of fall configurations on the impulsive stress waves propagation [8]. It was found that the stress is concentrated around the femoral neck.

In this study, a femoral bone FE model is developed to evaluate the effects of sideways fall configurations on the femur bone under static and dynamic loading conditions by employing the FE software, ANSYS. The inclination angle, θ and rotational angle, ϕ are chosen to represent the sideways fall configurations. Different femoral rotational angles, ϕ of -20º to 30º and a 10º inclination angle, θ are tested. The femoral bone is subjected to loading forces of 1500 N and 4500 N during static loading, whilst 1 m/s and 3 m/s impact velocities are applied under dynamic loading to analyse the impulse stress and strain as well as the total deformation developed during a sideways fall.

METHODOLOGY

Finite Element (FE) Model Development

Standard femur of a healthy male left femur from a 44-year-old, with weight 85 kg and height 185 cm was obtained from Grabcad website as proposed by Langford *et al.* [9]. The material properties of the femur cortical bone were considered as isotropic throughout the FE model. The elastic modulus, Poisson's ratio, and density of the cortical bone were 14 GPa, 0.3, and 1700 kg/m^3 [6, 10], respectively.

Boundary Condition for Static Simulation

In this study, the femoral head was subjected to the loading force, F of 1500 N and 4500 N. The distal end of the femur was fixed, and the greater trochanter was

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prohibited in the vertical direction for the falling configuration. The diaphyseal axis was positioned at a θ = 10º incline from the horizontal axis to the bone axis as shown in Figure-1. To further study the effect of the loading force in different directions, the rotation angle of the femur from the vertical axis, ϕ was varied from -20º (posterior) to 30º at every θ = 10º as shown in Figure-2. It was assumed that the femur is separated from the pelvis by the articular cartilage.

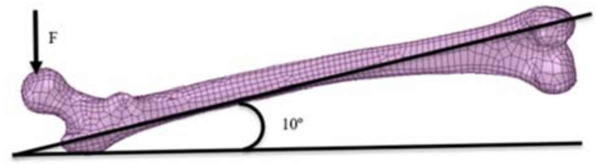

Figure-1. The femur inclined at θ=10º with the diaphyseal axis from the ground.

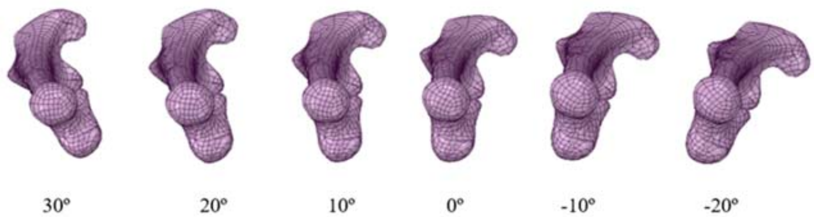

Figure-2. The position of the femur after rotated at the angle of ϕ = -20º to 30º.

Boundary Condition for Dynamic Simulation

In the dynamic nonlinear simulation, the femoral bone was set at 10° inclined from the ground and the impact velocity for the femoral bone was tested under the speeds of 1 m/s and 3 m/s [11, 12]. Besides, the effective mass acting on the femoral head was 32 kg with the gravitational acceleration of 9.81 m/s^2 [11, 12]. The loading force was applied in the vertical direction to the femoral head as the greater trochanter was hitting the ground. To further investigate the effect of the angle of rotation on the femur bone, the femur rotation angle was varied from -20° to 30° (increasing every 10° from the posterior).

Mesh Generation

The femur model mesh size was determined using a convergence test to find the most suitable mesh size for the calculation. The mesh size of 2 mm was used in this study as the total deformation of the femur bone was starting to converge. 4-node tetrahedral elements were employed to mesh the FE model, resulting in 97,604 nodes.

RESULT AND DISCUSSIONS

The model was evaluated under a sideways fall configuration under static and dynamic loading conditions. The results were obtained in terms of von Mises stress, von Mises strain, and total deformation. According to the previous studies, three different types of fracture occurred on the hip: cervical fracture, intertrochanteric fracture, and subtrochanteric fracture [3, 4, 9]. Therefore, this study is focused on obtaining the result on the femoral neck, intertrochanteric area, and the greater trochanter.

Static Simulation

Figures 3 and 4 show the maximum von Mises stress and strain at the femoral neck, greater trochanter, and intertrochanteric at 1500 N and 4500 N for the inclination angle, θ = 10º and the angle of rotation angle, ϕ = -20º, -10º, 0º, 10º, 20º, and 30º.

The highest von Mises stress occurs at the femoral neck, followed by the greater trochanter and intertrochanteric for the 1500 N and 4500 N loadings. At 1500 N, the von Mises stress of the femoral neck gradually increases from 58.1 MPa to 70.2 MPa from -20º to 30º. In a similar trend, the von Mises stress increases from 174.4 MPa to 210.7 MPa at 4500 N. At 1500 N, the stress of the greater trochanter starts to increase from 17.2 MPa up to 47.7 MPa. However, there is a dramatic increase at ϕ=10º and a similar pattern can be seen at 4500 N loading. On the other hand, the von Mises stress of the intertrochanteric demonstrates a gradual decrease and becomes constant at ϕ =10º for 1500 N and 4500 N loadings. Similar patterns are observed for von Mises strain at the femoral neck, greater trochanter, and intertrochanteric area of the femur.

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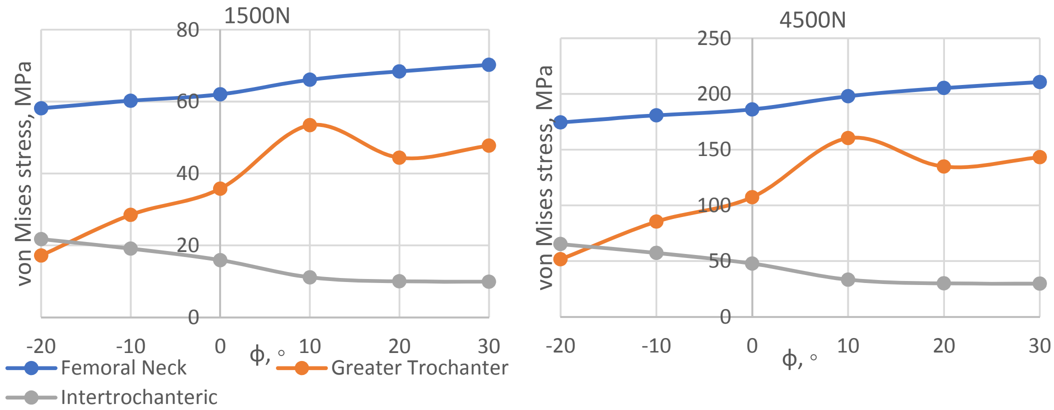

Figure-3. The maximum von Mises stress at the femoral neck, greater trochanter, and intertrochanter for the force applied at the femoral head of 1500 N and 4500 N.

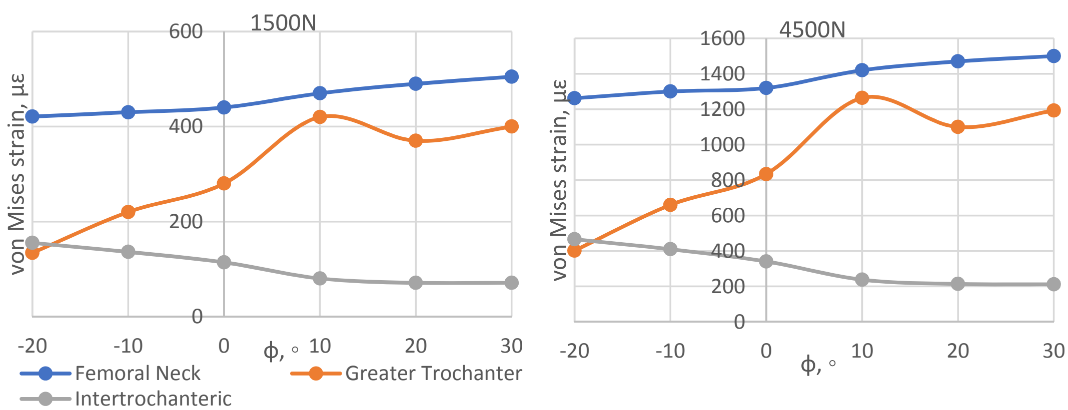

Figure-4. The maximum von Mises strain at the femoral neck, greater trochanter, and intertrochanter for the force applied at the femoral head of 1500 N and 4500 N.

Dynamic Simulation

The distribution of von Mises stress and strain of the femur are presented in Figures 5 and 6 for the inclination angle, $\theta = 10^o$, the angle of rotation, $\phi = -20^o, -10^o, 0^o, 10^o, 20^o$, and 30^o and the impact speed of 1 m/s and 3 m/s. The stress and strain differ according to the different angles of rotation.

In the case of an impact velocity of 1 m/s, the von Mises stress and strain at the femoral neck fluctuate twice, with the maximum at t = 250 and t = 350 µs, followed by abrupt decrease at t = 280 µs and t = 420 µs as shown in Figures 5 and 6. At the impact velocity of 3 m/s, the equivalent stress and strain at the femoral neck increase and decrease four times until 500 µs. The stress and strain drop at t = 280 µs, 320 µs, 420 µs, and 500 µs. For femoral neck, the highest von Mises stress is 46.4 MPa ($\phi = -10°$) and 76.4 MPa ($\phi = 10°$) for an impact velocity of 1 m/s and 3 m/s, respectively. The highest strain is 3346 µε ($\phi = -10°$) and 5440 µε ($\phi = 10°$) for an impact velocity of 1 m/s and 3 m/s, respectively.

On the other hand, the von Mises stress and strain at the intertrochanteric show several rise and fall with the highest peak at t = 290 µs. The von Mises stress at the highest peak are 27.0 MPa ($\phi = -20°$) and 60.9 MPa ($\phi = -10°$) whilst the von Mises strain reaches the maximum at 1929.2 µε ($\phi = -20°$) and 4355.7 µε ($\phi = -10°$) for 1 m/s and 3 m/s, respectively. The stress and strain start to drop steeply at this point until t = 450 µs. The stress and strain are then slowly regained up to t = 500 µs.

However, only one peak can be seen for the von Mises stress and strain at the greater trochanter for the impact velocity of 1 m/s and 3 m/s. The von Mises stress increases gradually and reaches a maximum of 166.0 MPa at $\phi = 10°$ and 282.4 MPa at $\phi = 20°$ for the impact velocity of 1 m/s and 3 m/s, respectively. As expected, the maximum von Mises strain is observed at $\phi = 10°$ for the impact velocity of 1 m/s. On the other hand, the highest von Mises strain at 3 m/s is 33802 µε, found at $\phi = -10°$.

Figure-7 compares the deformation of the femur bone at the impact velocities of 1 m/s and 3 m/s. The highest deformation of 1.6 mm and 2.4 mm are both found at $\phi = 30°$ for 1 m/s and 3 m/s, respectively.

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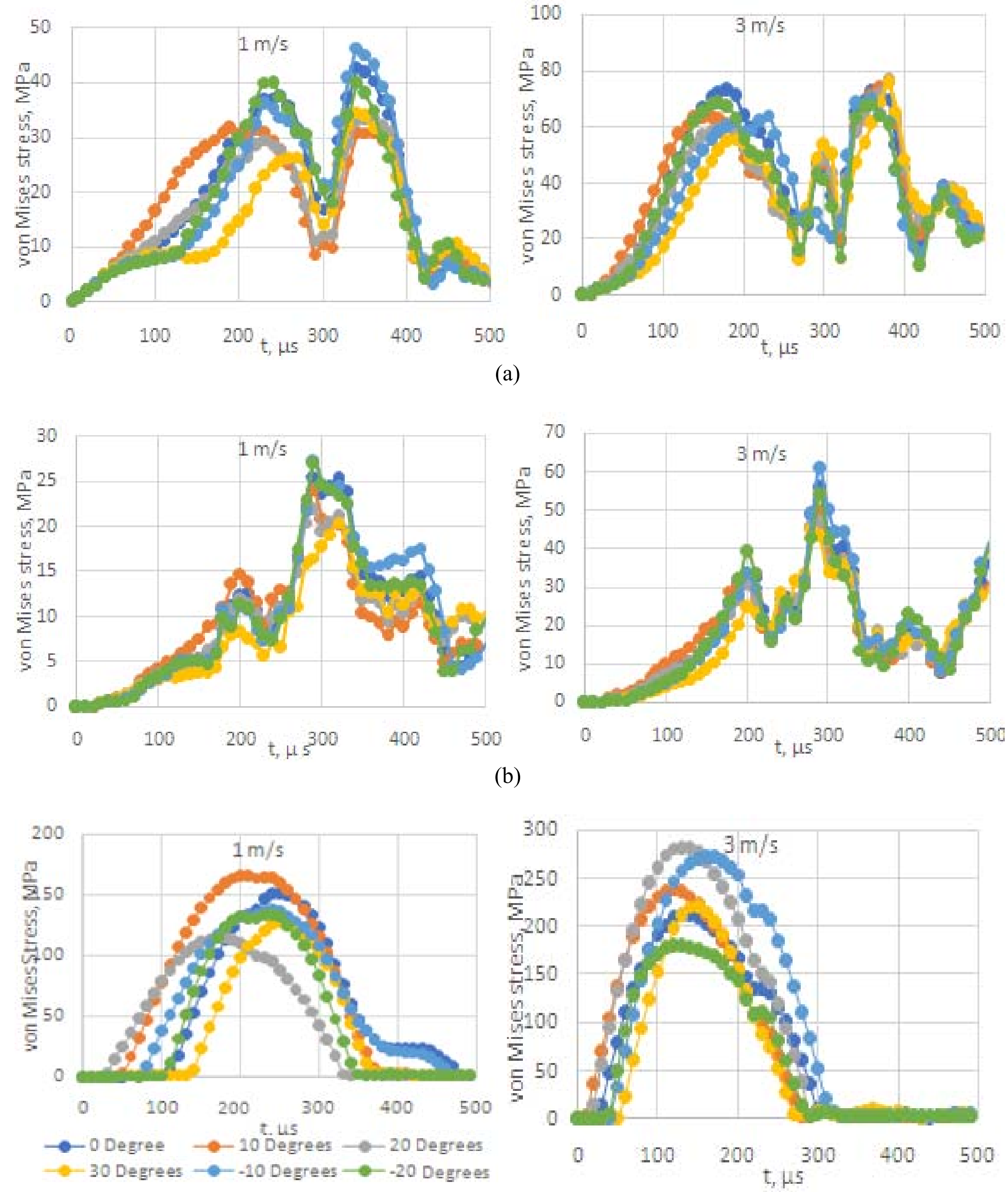

Figure-5. Time history of the equivalent stress (MPa) at a) femoral neck, b) intertrochanteric, and c) greater trochanter at the impact speed of 1 m/s and 3 m/s.

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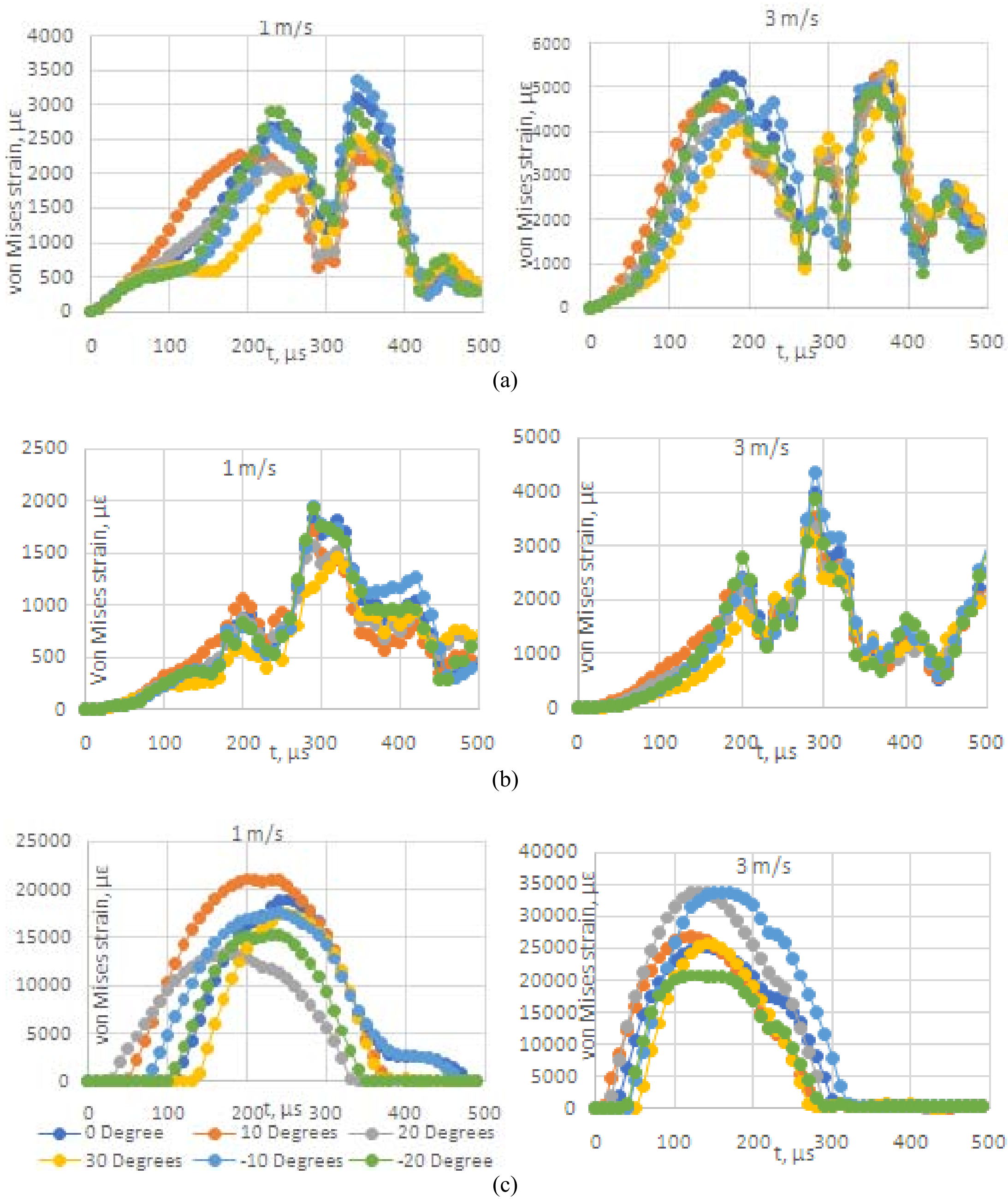

Figure-6. Time history of the equivalent strain (με) at a) femoral neck, b) intertrochanteric, and c) greater trochanter at the impact speed of 1 m/s and 3 m/s.

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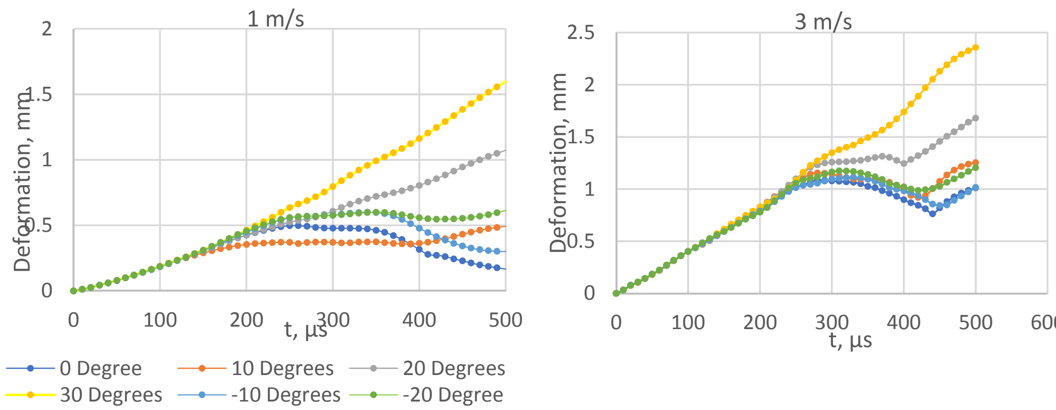

Figure-7. Time history of total deformation of the femur bone at the angle of rotation -20°,-10°, 0°, 10°, 20°, and 30° under 1m/s and 3m/s.

DISCUSSIONS

Static Simulation

The values of the von Mises stress and strain are higher at 4500 N compared to 1500 N loading for the femoral neck, greater trochanter, and intertrochanteric. Here, it implies that the von Mises stress and strain increase as the loading force increases from 1500 N to 4500 N at all angles of rotation for the femoral neck, greater trochanter and intertrochanteric. In fact, the von Mises stress and strain of the femoral neck, greater trochanter and intertrochanteric become double at 4500 N. Similar findings presented by Ikhwan *et al.* [6] have shown that the increase in applied loading increases the stress concentration on the femoral neck, hence reducing the structural capacity of the bone and increasing the risk factor for bone fracture.

At both loading conditions, the highest von Mises stress and strain occur at the femoral neck with a 30º rotation angle, which is consistent with previous findings [4, 5, 13]. According to Bisheh *et al*., the highest von Mises stress has been observed at the femoral neck for 10 clinical cases studied [4]. For the femoral neck, the highest von Mises stress is 210.7 MPa at 4500 N loading. The lowest von Mises stress is 9.9 MPa observed at the intertrochanter at 1500 N loading. Based on the results obtained, it is clearly shown that the femur bone's structural capacity is significantly influenced by the loading and femur position.

Similar results are found for the von Mises strain at 1500 N and 4500 N. As observed for the maximum von Mises stress, the femoral neck shows the highest maximum von Mises strain. The von Mises strain at 4500 N loading is higher than that at 1500 N loading. The maximum von Mises strain is 15000 $\mu\varepsilon$ observed at a 30º rotation angle for 4500 N loading. The lowest von Mises strain is 71 $\mu\varepsilon$ observed at the intertrochanter for 1500 N loading.

For the stress distribution of the femoral bone at 4500 N loading, high von Mises stress is observed at the femoral neck as the result of the high stress concentration. A similar finding is presented by Kheirollahi and Luo [14-16]. They found that the effect of von Mises strain in the hip fracture risk assessment is most dominant, followed by von Mises stress. This indicates that humans may have a high possibility of a hip fracture at the femoral neck during a sideways fall at the angle of -20º to 30º.

Dynamic Simulation

The values of the von Mises stress and strain are higher at 3 m/s than 1 m/s for the femoral neck, greater trochanter, and intertrochanteric. Thus, it can be deduced that the stress and strain increase with increasing impact velocity. Compared to the femoral neck and the intertrochanteric, the stress and strain at the greater trochanter is the highest. The highest stress and strain are 282.4 MPa and 33802 $\mu\varepsilon$ occurred at ϕ = 20° and ϕ = -10°, respectively. In the previous study, Majumder *et al*. [17] has found that the highest compressive principal strain distributed at the area of the greater trochanter. They simulated the FE model of a fall against a rigid floor under gravitational acceleration with the impact velocity of 3.17 m/s.

As depicted in Figure-7, the deformation is the highest at ϕ = 30° for both impact velocities of 1 m/s and 3 m/s. In the matter of fact, the deformation at 3 m/s is higher than that of 1 m/s. It can be inferred that the deformation increases with increasing rotation angle and velocity.

CONCLUSIONS

This work aims to evaluate the effects of sideways fall configurations on the femur bone under static and dynamic loading conditions by employing the finite element (FE) software ANSYS. Rotational angles, ϕ of -20º to 30º and a 10º inclination angle, θ are tested. The femoral bone is subjected to forces of 1500 N and 4500 N during static loading, whilst 1 m/s and 3 m/s impact velocities are applied under dynamic loading to analyse the impulse stress and strain as well as the deformation developed during a sideways fall. The capacity of the bone is evaluated in terms of von Mises stress, von Mises strain and the total deformation at three different positions: femoral neck, greater trochanter, and intertrochanteric during a sideways fall.

Based on the results obtained, the static simulation shows that the femoral neck has the highest risk of fracture, followed by the greater trochanter and intertrochanteric. The femoral neck demonstrates the highest von Mises stress and strain at $\phi = 30^{\circ}$ rotation angle and an impact loading of 4500 N. Under static loading, the increase in loading magnitude increases the von Mises stress and strain to almost double at all rotational angles.

However, the greater trochanter exhibits the highest von Mises stress and strain compared to the femoral neck and intertrochanteric under dynamic loading. The highest von Mises stress and strain occurred at $\phi = 20^{\circ}$ and $\phi = -10^{\circ}$ rotation angle, respectively and impact velocity of 3 m/s. Under dynamic loading condition, rotational angle and impact velocity appear to significantly influence the stress and strain observed at the femoral bone. On the other hand, the highest deformation is found at $\phi = 30^{\circ}$ rotation angle with the velocity of 3 m/s. The deformation increases with increasing rotation angle and velocity.

These findings denote that a fall sideways may lead to a higher risk of femur fracture.

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