Examination of brain injury under impact with the ground of various stiffness

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Abstract

In this study, the finite element (FE) method is implemented in order to examine the reaction of the brain under a fall and impact loading. The head and its constituent parts are designed by three-dimensional (3-D) FEs. Soft tissues and the brain are modeled as viscoelastic material and assembled by various types of elements. In the analysis, the ground is regarded as the impactor and is also simulated by 3-D FEs. The fall, or accident, is assumed to happen under different heights, or velocities. Such scenarios are considered to represent the realistic falls, or accidents, which might occur in sports, or in other situations. The impacting ground might be of different material, rigidity and stiffness. In this study, the sensitivity of the injury in the brain is studied using different materials, different heights of the fall and different velocities. The materials used for the ground are wood, polymer carpet, soil and concrete slabs. The intracranial coup pressure, contrecoup pressure and shear stresses in the brain and skull are monitored during the impact and are recorded for the analysis. Under each impact, the coup pressure and shear stress peaks in the brain are observed. Such results are proportional functions to the stiffness of the ground and the velocity of the head. The computational results of this FE head model are consistent with the cadaveric experiments of previous studies.

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Keywords: Brain injury; viscoelastic; intracranial coup pressure; contrecoup pressure; shear stress

1. Introduction

In the field of biomechanics, traumatic brain injury (TBI) has become a major area of research. Damage to the brain is caused due to the brain motion inside the skull when the head is accelerated, or hit by an external body. This results in to and from motion of the brain relative to the skull. The motion of

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the brain inside the skull creates high positive pressure (coup pressure) when the brain initially comes in contact with the skull. At the same time a negative pressure is developed at the opposite side of the brain (contrecoup pressure) which may lead to the cavitations (Lindgreen and Rinder [1]; Nahum et al. [2]). Cavitations usually produce small bubbles with eventual collapse. Due to collapse of the bubbles there is brain tissue damage (Lubock and Goldsmith [3]; Hardy et al. [4]).

In this paper, a parametric study has been conducted on the brain response under impact loading by varying the stiffness and speed of the different impacting materials. A finite element (FE) head model is employed by considering viscoelastic material properties for the brain, as implemented by Chafi et al. [7], and the results are validated by comparing them with the results of the experimental studies of Hardy et al. [5]. Studies have also been conducted on the sensitivity of the stiffness of the hitting material (ground) and on the brain response under impact loading with varied velocities. The different velocities considered are based on the realistic scenarios of a person falling from different heights due to gravitational force, and comparing the coup and contrecoup pressures inside the brain while the head makes impact with different materials, namely wood, rubber and soil. The analysis is done using the LS-Dyna FE code. The study is conducted with the focus on coup and contrecoup pressures and shear stresses in the brain. The analysis is run for a time history of 10 ms after the incident.

2. FE Modeling of the Human Head and the Ground

Considering the ground as a complete flat plane, a three-dimensional (3-D) rectangular block has been modelled using 8 nodded solid elements. The total numbers of elements and nodes are 1600 and 2583, respectively. Different material properties are used for the parametric study in order to understand the response of the brain under impact of the head with different ground materials.

The FE head and neck model simulate all parts of a human head and neck. The geometrical data from Horgan and Gilchrist [8] has been employed. Shell elements are used for the modeling of the pia mater, dura mater, tentorium and falx. The brain, cerebral spinal fluid (CSF) and skull are modeled with brick elements, with the skull having four layers of eight nodded brick elements. The neck is also modeled with eight nodded brick elements. The total head neck model consists of 5344 shell elements and 34635 solid node elements.

2.1. Material properties of the head model

In FE modeling literature on the human head, a wide variety of material properties for the brain and other parts of the human head has been used. Linear elastic properties are considered for the scalp and membranes like tentorium, falx and dura mater [9] [10]. In much of the published research, the brain is considered to be primarily linear elastic. Subsequently, linear viscoelastic, hyperelastic and hyper-viscoelastic models have been also introduced [9] - [12]. In this study, the brain tissue is assumed to have linear viscoelastic behaviour. Fluid-like properties have been assumed for CSF and this coincides more with the Hardy et al. [5] experimental data.

The ground modelled with soil and wood is considered to have elastic-plastic behaviour. Rubber ground is considered to have viscoelastic behaviour.

2.2. Elements interfacial modelling

In the head model, the interface between the brain and other components are defined by using various contact types. Tied contact conditions are suitable for brain membrane interface as they can transfer loads of compression and tension. The interface between the falx, dura, pia and tentorium is defined as tied
node-to-surface contact type. The surface to surface contact type is used for the interface between the ground and the head as the ground is considered to be the plane.

Table 1. Material properties of ground surfaces

| Material | Properties |
|----------|------------|
| Soil     | $\rho = 6.747 \times 10^8$ Kg/m$^3$, $G = 57.6$ GPa, $K = 17.94$ GPa, $\nu = 0.12$ |
| Wood     | $\rho = 0.499 \times 10^6$, $E = 7$ GPa, $\nu = 0.32$ |
| Rubber   | $\rho = 1.254 \times 10^6$ Kg/m$^3$, $K = 2.19$ GPa, $G = 5.28 \times 10^4$ GPa, $G_1 = 1.68 \times 10^4$ GPa, $\beta = 0.7$ m/s |

Where $\rho$ is density, $E$ is Young’s modulus, $K$ is bulk modulus, $G$ is shear modulus, $G_1$ is dynamic shear modulus, $\beta$ is decay constant and $\nu$ is Poisson’s ratio.

3. Results

In this study, a realistic scenario of a human head falling from different heights onto different ground materials, due to gravity, is considered. The head model is loaded with gravity and is allowed to hit the ground, from different heights, onto different types of ground materials. The intracranial coup pressures and shear stresses are compared for different heights of impact with the ground being the same type of material and also compared by changing the ground material types but using the same height of impact. Intracranial coup-pressures, contrecoup pressures and brain shear stresses are monitored for the comparison between different simulations of the scenarios presented.

At the time of impact, according to the pressure contours in Figure 1, the maximum pressure is at the point of contact on the head. This is not unusual because load, due to impact, is concentrated at the point of contact (compressive load). The pressure contour on the head and brain are compared in Figure 1 showing the effects of the impact on the brain and head (scalp) at two different time intervals.

As the CSF is considered to be fluid-type, the brain inside the skull oscillates making a relative movement with respect to the skull. Due to the impact of the head with the ground, the brain moves with respect to the skull and hits the skull. When the brain oscillates inside the skull, compression and tension loads are created on the brain tissues creating a high pressure at the compression side and low pressure at the tension side. After the time of impact, oscillation begins with compression at the point of contact and with tension on the opposite side. The relative motion of the brain inside the skull induces high pressures and shear stresses in the brain. Negative pressure is created all over the head other than on the area of contact with the ground. This is not unusual because the brain, inside the skull, hits the walls of the skull. At the point of impact, compression is created and this leads to high pressure and tension on other areas of the brain resulting in a negative pressure.

3.1. Head impact under different velocities and constant stiffness of the ground

In this study, the realistic scenario of a head falling from different heights due to gravity is taken into consideration for the parametric study. Five different heights (10, 5, 3, 2, and 1 ft) are considered, which will cause impact velocities of 7.729, 5.465, 4.232, 3.456 and 2.444 m/s, at the time of impact, respectively.
Fig. 1. Effects of impact on brain and head (scalp) at two different time intervals (T=3.2ms, T=4.2ms).

Fig. 2. Intracranial coup pressures for different heights in impact with wooden ground.

Fig. 3. Contrecoup pressures for different heights in impact with wooden ground.
3.2. Ground as wood, soil and rubber

The stiffness of the ground is kept constant (E=7GPa). The wood constitutive law is considered and the velocity of the impact is varied. Figure 2 compares the intracranial coup pressures of five different velocities (heights) with the ground as wood. From this figure, it can be observed that the pressure graphs of simulations with different velocities are following in the same manner. Figure 3 shows the contrecoup pressures of the five different velocities.

The soil constitutive law is considered for the ground and, again, the velocity is varied with the five impact scenarios. The intracranial pressures on the head over an area can also be examined for the five simulations now with the ground modeled as soil. Figures 4 and 5 show the comparison of shear stresses at different heights with the ground considered as wood and soil, respectively.

The rubber constitutive law is considered for the ground and the velocity is varied. Figure 5 shows the comparison of shear stresses in the brain.

4. Discussion and Conclusion

In this paper, the intracranial coup, contrecoup pressure and shear stresses on the brain are compared by varying two parameters: 1) stiffness of the ground, and 2) the velocity of impact. The study is
conducted in two ways: 1) by varying the stiffness of the ground which is nearby to the rubber, soil and wood; and 2) by varying the impact velocities based on realistic scenarios and considering the constant stiffness to the ground. Modest impact to the skull can coincide with high stresses in the brain tissue. Primarily, by comparing the pressure contours on the skull and brain, shown in Figure 1, it can be inferred that the effect of impact on the skull is less when compared to the brain. This finding is of clinical relevance during a patient’s evaluation in the emergency room (ER).

When the velocities of the impacts are varied from 10 to 1ft, the intracranial coup pressure peaks, contrecoup pressure peaks and shear stress peaks are decreasing as the velocity of impact decreases, as shown in Figures 2-5. This is not unusual because as the velocity of impact increases, it is obvious that the energy of system increases which leads to increase in the severity of impact injury.

In comparing the coup pressure peaks, contrecoup pressure peaks and shear stress peaks for the three ground materials, for the impact velocity of $v=7.729m/s$ (i.e. head falling the height of 10ft) from Figures 2-5, it can be observed that the peaks of coup pressures, contrecoup pressures and shear stresses decrease from wood to rubber.

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