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Development of a strain rate dependent material model of human cortical bone for computer-aided reconstruction of injury mechanisms

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ABSTRACT

Computer-aided methods such as finite-element simulation offer a great potential in the forensic reconstruction of injury mechanisms. Numerous studies have been performed on understanding and analysing the mechanical properties of bone and the mechanism of its fracture. Determination of the mechanical properties of bones is made on the same basis used for other structural materials. The mechanical behaviour of bones is affected by the mechanical properties of the bone material, the geometry, the loading direction and mode and of course the loading rate. Strain rate dependency of mechanical properties of cortical bone has been well demonstrated in literature studies, but as many of these were performed on animal bones and at non-physiological strain rates it is questionable how these will apply in the human situations. High strain-rates dominate in a lot of forensic applications in automotive crashes and assault scenarios. There is an overwhelming need to a model which can describe the complex behaviour of bone at lower strain rates as well as higher ones. Some attempts have been made to model the viscoelastic and viscoplastic properties of the bone at high strain rates using constitutive mathematical models with little demonstrated success. The main objective of the present study is to model the rate dependent behaviour of the bones based on experimental data. An isotropic material model of human cortical bone with strain rate dependency effects is implemented using the LS-DYNA material library.

We employed a human finite element model called THUMS (Total Human Model for Safety), developed by Toyota R&D Labs and the Wayne State University, USA. The finite element model of the human femur is extracted from the THUMS model. Different methods have been employed to develop a strain rate dependent material model for the femur bone. Results of one the recent experimental studies on human femur have been employed to obtain the numerical model for cortical femur. A forensic application of the model is explained in which impacts to the arm have been reconstructed using the finite element model of THUMS. The advantage of the numerical method is that a wide range of impact conditions can be easily reconstructed. Impact velocity has been changed as a parameter to find the tolerance levels of injuries to the lower arm. The method can be further developed to study the assaults and the injury mechanism which can lead to severe traumatic injuries in forensic cases.

1. Introduction

In order to study and predict injury mechanisms in various loading scenarios, mathematical and numerical models of the human body have been developed and used in the past 60 years in automotive industry. Finite element models of a whole human body provide a better insight into the mechanical consequences of impact loading, an assessment of the severity of impacts; and a detailed analysis of impact response. The finite element models are derived based on the CT data images of the human body part which is modelled. Among the finite element methods developed for forensic applications, the human head models are to be mentioned. The models vary from simple spherical shells with linear elastic material properties to models with complex geometry, viscoelastic and nonlinear properties. The first finite element model of human head was presented by Hardy and Marcal [1]. In 1975, Ward and Thompson developed a three dimensional finite element model of the brain for frontal impact [2].

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In 1993, Ruan presented a 3D finite element head model. The model contained the main anatomical features of an average adult head. It included the scalp, a three-layered skull, cerebral spinal fluid (CSF), dura materm falx cerebri and brain [3].

In 1997, Kang et al. developed the Universite Louis Pasteur (ULP) head model [4]. The model was digitized from a human adult male skull. The main anatomical features were the skull, falx, tentorium, subarachnoid space, scalp cerebrum, cerebellum and brain stem. The model has been developed and improved since then and is currently known as Strasbourg University Finite Element Head Model (SUFEHM). The application of the (SUFEHM) head model in forensic biomechanics is described by Raul et al. [5].

These models can be further used for forensic investigations to effectively establish the injury mechanism caused by an accident or an assault. With the recent advances in computer technology, complex finite element models employing hundreds of thousands of elements can be solved within a short period of time. However, the choice of parameters to describe the material behaviour of human hard and soft tissues is rather difficult and affects the verity of the resulting finite element (FE) models.

On the other hand, there have been also some physical models developed to study injuries resulting in forensic cases. Thali et al. (2002) have developed an artificial skin–skull–brain model to study the ballistic injury on the head by gunshot [6]. The model is composed of a silicon cap, a polyurethane sphere and ordnance gelatin to represent the artificial skin, scalp and brain.

In the current study, however, the main objective is to use numerical and mathematical model of human bone for injury analysis.

Strain rate dependency of the bone has been well demonstrated in literature [7–13]. One of the earliest studies on strain rate effects on bone and muscle tissue was performed by McElhaney [7].

McElhaney tested hydrated human compact bone in compression at rates ranging from 0.001 to 1500 s^{-1}. The human bone specimens were obtained from the femur of a 24 year old male. A Tinius Olsen electromatic testing machine was used for the static and low-rate tests, whereas an air-operated (air gun) testing machine was constructed for the high-rate tests. The compressive stress–strain curves were presented at various strain rates. The results indicated the existence of a critical velocity of bone at a strain rate of 1 s^{-1}. The elastic modulus and ultimate compressive stress both increased with increasing the strain rate.

Tennyson et al. (1972) studied the response of bovine femur using the split-Hopkinson pressure bar (SHPB) in compression at strain rates in the range of 10–45 s^{-1} [8].

Panjabi et al. (1973) investigated the effects of loading velocity on tubular bones in torsion. The study revealed that the strength and energy absorption to failure of bone increases with a corresponding increase in torsional loading rate [9].

Crowninshield and Pope (1974) performed an experiment similar to that of McElhaney [10]. They examined the behaviour of compact bone at a range of strain rates from 0.001 to 1000 s^{-1} in tension. The tensile specimens were obtained from mid-diaphysis of the tibia of bovine. An Instron TT-CM1 testing machine was applied for lower strain rates whereas a drop hammer device was employed for velocities up to 8 m/s. The results were presented as ultimate stress–strain, modulus of elasticity and energy absorption with respect to strain rate. The results were compared to those from McElhaney for compact bone in compression. The breaking stress for bone was significantly rate sensitive both in tension and compression. The modulus of elasticity of bone in compression has been significantly affected by strain rate while in tension the modulus of elasticity is not greatly affected by rate of loading. In both modes of loading (tension and compression), the energy absorption decreased at higher strain rates. Maximum energy absorption was observed at lower strain rates.

Lewis and Goldsmith et al. (1975) conducted dynamic tests to measure mechanical properties of bovine femoral cortical bone in compression, tension, torsion and combined compression and torsion [11]. They utilized the split Hopkinson bar technique to measure dynamic material properties of bone. The results demonstrated the evidence of viscoelastic behaviour of bone in compression. A relaxation function was introduced to describe the viscoleastic property of the bone.

Saha and Hayes (1976) performed quasi-static and dynamic tensile test on human compact bone at a strain rate of 133 s^{-1}. The tensile strength in dynamic test was higher than the static one which indicated the strain-rate sensitivity of the bone [12].

In a more recent study in 2008, Hansen et al. (2008), tested the human femoral cortical bone longitudinally at strain rates ranging between 0.14 and 29.1 s^{-1} in compression and 0.08–17 s^{-1} in tension [13]. The tests were carried out by a servohydraulic material testing machine Dartec series HC25. It was found that Young's modulus increases with the rate for both tension and compression. Strength and strain increased slightly in compression and decreased in tension for strain rates beyond 1 s^{-1}.

The results showed a simple relationship between yield properties and strain rate and a more complicated one between the corresponding strain rate and post-yield properties.

In forensic applications, it is of importance to have a sophisticated material model of hard and soft tissues, in order to achieve a higher level of fracture prediction and injury risk assessments. The main objective in this study is to develop a strain rate dependent material model for the human femur based on recent experimental results and to discuss the possible use of this model for a forensic case of impact to the lower arm. The stress–strain curves for human femoral compact bone at tension and compression at various strain rates are obtained from the study performed by Hansen et al. [13]. These results are utilized for implementing the material model of human cortical bone. The model is primarily developed for the femur and consequently it is extended for the ulna. These two long bones feature in many fracture scenarios which may result from criminal actions, an accident, or negligence. In all cases the verity, validity and sophistications of the FEA model is the crucial factor which determines if true justice is delivered.

2. Materials and methods

Biofidelic finite element (FE) models of the human body include both realistic geometry of the various body segments and of their material properties. Several numerical human models, including finite element (FE), models have been developed to predict kinematics and kinetics of a whole human body. THUMS (Total Human Model for Safety) is a whole human body model which has been developed by Toyota Central Research Lab in collaboration with Wayne State University [14,15]. The THUMS model represents a 50 percentile American male (height 175 cm, weight 77 kg) in standing position. The model contains about 108,000 nodes and 145,000 elements. The purpose of the THUMS is to simulate gross motions and stress or strain distributions of the human whole body for impacts, using the finite element method and utilizes anatomical geometry data and human biomechanical properties. Various studies have been performed by the Toyota Group for validation of different parts of the THUMS model [15–17]. The THUMS model is shown in Fig. 1.

For development of a strain rate dependent material model of compact bone, a FE model of human femur is extracted from the THUMS lower extremity. Lower extremity in THUMS includes the foot bone, tibia, fibula, patella, femur, ligaments, muscles, tendons, skin and soft tissue. The FE model of femur is taken from the lower limb for further development of the material model.