Characterization of human passive muscles for impact loads using genetic algorithm and inverse finite element methods

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Abstract The objective of this study is to identify the dynamic material properties of human passive muscle tissues for the strain rates relevant to automobile crashes. A novel methodology involving genetic algorithm (GA) and finite element method is implemented to estimate the material parameters by inverse mapping the impact test data. Isolated unconfined impact tests for average strain rates ranging from 136 s\(^{-1}\) to 262 s\(^{-1}\) are performed on muscle tissues. Passive muscle tissues are modelled as isotropic, linear and viscoelastic material using three-element Zener model available in PAMCRASH\textsuperscript{TM} explicit finite element software. In the GA based identification process, fitness values are calculated by comparing the estimated finite element forces with the measured experimental forces. Linear viscoelastic material parameters (bulk modulus, short term shear modulus and long term shear modulus) are thus identified at strain rates 136 s\(^{-1}\), 183 s\(^{-1}\) and 262 s\(^{-1}\) for modelling muscles. Extracted optimal parameters from this study are comparable with reported parameters in literature. Bulk modulus and short term shear modulus are found to be more influential in predicting the stress-strain response than long term shear modulus for the considered strain rates. Variations within the set of parameters identified at different strain rates indicate the need for new or improved material model, which is capable of capturing the strain rate dependency of passive muscle response with single set of material parameters for wide range of strain rates.

Keywords Passive muscle · Viscoelastic material properties · Genetic algorithm · Inverse characterization method · Impact load

1 Introduction

Human body finite element models are being developed to simulate automobile crashes in order to understand the injury patterns and injury mechanism pertaining to pedestrians and occupants (Maeno and Hasewaga 2001). The closeness of capturing the injury mechanisms and patterns are directly influenced by the accuracy of tissue properties available. Hence development of the human body finite element models are limited by the knowledge of material behaviour of hard and soft tissues at strain rates experienced during automobile crashes.

Soft tissues exhibit large deformation, viscoelasticity, strain rate dependency and many more unresolved issues due to its complex nature. To characterize the tissue behaviour, several testing methods or procedures have been established by developing problem-specific material models and parameters, which work only for specific domains typically involving lower strain rates. These procedures need further development before these properties can be used for a wide range of conditions as those in vehicle impacts at different speeds.

McElhaney (1966) conducted in vitro test on bovine muscle for dynamic loadings for strain rates up to 1000/s. Viscoelastic response of live skeletal muscles have been investigated by Best et al. (1994) and Myers et al. (1998) for tensile loading at lower strain rates (less than 100/s). Bosboom et al. (2001) measured the mechanical properties of rat skeletal muscle under in vivo compression applied transverse to the muscle fiber direction. Dhaliwal et al. (2002) conducted low energy impact tests on volunteers and human cadavers. Slijtenhorst et al. (2006) determined the bovine muscle properties for strain rates ranging from 1,000 to 2,500 s\(^{-1}\).

However, properties of different human muscles under transverse impact loading are not yet fully known. The
available properties thus cannot be used to represent the human muscle in pedestrian impacts. Existing Finite Element Human body models use a three-element linear viscoelastic material model to model the muscle tissues (Bandak et al. 2001; Lizee et al. 1998; Chawla et al. 2004). The suitability of other material models like Prony series based models and QLV theory model to impact loads is not yet established in the literature. In the current study we, therefore, use the three element linear visco-elastic model for representing the soft tissue and try and estimate the parameters for the same.

We use an inverse characterization based method to estimate the parameters of the linear visco-elastic model at different strain rates. Controlled tests have been conducted and an iterative procedure is then used for parameter estimation by comparing the experimental and theoretical response. An iterative procedure is then used for parameter estimation by comparing the experimental and theoretical response for different material inputs (Karthikeyan et al. 2006). Such inverse characterization methods using quasi-static compression experiments (Miller and Chinzei 1997; Miller-Young et al. 2000), ramp tests (Bosboom et al. 2001), aspiration experiments (Kauer et al. 2002) and indentation tests (Durand-Reville et al. 2004; Delalleau et al. 2006; Erdemir et al. 2006) have been reported to characterize the soft tissues at lower strain rates, less than 100/s using optimization techniques. Most of these studies use the conventional search techniques such as direct search methods or gradient-based optimization algorithms (Erdemir et al. 2006; Kauer et al. 2002; Moulton et al. 1995) and couple with finite element methods to obtain the optimal properties for modelling the soft tissue behaviour. Direct search methods use objective function(s) and constraint(s) for searching the optimal parameter(s), and consume more time to converge. Gradient-based methods involve the derivatives along with the objective function(s) and or constrain(s) for faster convergence but they are not efficient in discontinuous and non-differentiable problems (Deb 1999). Both these methods are influenced by the initial solution chosen and can lead to local optima and are not efficient in solving multi-optima problems. Recent trends in the literature have shown that the application of evolutionary algorithms like Genetic algorithms (GA) can overcome the above mentioned problems in inverse characterization studies (Muc and Gurba 2001; Liu et al. 2002a,b; Rahul et al. 2006; Chwastek and Szczegowski 2006) for extracting the optimal parameters.

Studies for identifying the impact properties of passive muscle using GA have not been reported so far to the authors’ knowledge. Hence the applicability of this global optimization method, for characterizing the passive muscle tissue, is explored in this study.

In this paper, a feasible Genetic algorithm (GA) based procedure to map the experimental force data to a form that is directly useful for finite element simulations have been formulated. Passive muscle tissues are modelled using linear viscoelastic material model and the values of bulk modulus, short term shear modulus and long term shear modulus are iterated. Optimal material parameters extracted for the strain rates at 136, 183 and 262 s\(^{-1}\) are presented in this paper.

### 2 Genetic algorithms

Genetic algorithms (GAs) are global search and optimization methods based on Darwin’s natural evolution theory with underlying principle, “survival of fittest”.

#### 2.1 Summary of the GA process

Genetic algorithms evaluate the fitness of individual designs in a population. The size of the population is the number of (feasible) alternatives (called chromosomes, and represented as strings) involved in a particular generation. The population for the first generation is created randomly within the predefined variable range. Based on the fitness values of the strings, GAs then use three basic operators namely the selection, crossover and mutation operators to generate new populations from generation to generation. In the process they produce populations with better chromosomes. The algorithm stops when a predefined convergence criterion is reached (no significant change in the best fitness value in successive iterations). In the absence of convergence the process can be terminated after a predefined number of generations and the best fitness value reported. The present study is conducted using the termination criterion of 50 generations. More details on GAs can be found in Goldberg (1989) and Deb (1995, 2001).

#### 2.1.1 The selection operator

Selection operator reproduces the stronger (better) strings in a population and eliminates the weaker ones. Eliminated strings are replaced by additional copies of the better string thereby improving the average quality of the population. The strings generated after reproduction are called parent solutions and are sent to a mating pool for cross over and mutation. The selection operator only creates copies of the existing good strings and does not create new strings. New chromosomes (called children solutions) are generated using crossover and mutation operators.

#### 2.1.2 The crossover operator

In crossover operations, two parent strings are first selected based on a crossover probability. A part of the first parent string is then interchanged with the other parent’s string to produce a child solution. A number of types of crossover operators, based on how the crossover of the bits is done, are used in practice. For instance, in the fixed point crossover