EFFECT OF IMPACTOR MASS IN FREE FALL IMPACT TESTS ON ISOLATED PASSIVE MUSCLE TISSUE

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Abstract: The effectiveness of the impactor mass in free fall impact tests on muscle tissues has not been reported in the literature. The present work investigates the influence of impactor mass on muscle tissue stress-strain characteristics, using finite element analysis. The impactor mass is varied from 0.25 Kg to 2.0 Kg. Initial velocity of impactor, geometry and material properties of the tissue specimen are kept constant throughout the analysis. Calculated contact forces and deformation of tissue specimen from the FE simulations, demonstrates the significant influence of impactor mass on duration of constant strain rate and percentage of strain. Results show that the strain rate remains constant for a longer duration when subjected to larger mass. This study concludes that, using an impactor mass of 1 kg or more for the free fall impact tests ensures that the experimental data analyzed up to 50% strain level with a minimum initial velocity of 1.2 m/s will always be suitable to characterize the muscle behavior for constant strain rate.

Introduction

Mechanical properties of muscle tissues under dynamic loadings are of special interest in the present scenario of biomechanics to simulate pedestrian – vehicle crashes [1, 2, and 3]. Studies [4 and 5] emphasize that the experiments for characterizing the mechanical behavior of soft tissues should be conducted at constant strain rates to identify the material properties for a particular strain rate. Two conventional testing methods for determination of strain rate sensitivity, namely controlled impact tests [6] and free fall tests [1 and 7] are reported in the literature. The first method uses the standard universal testing machines having a controller mechanism to regulate the velocity of impactor. Whereas the second method uses a free fall impactor and the required impact velocity is achieved by varying the drop height. Studies [8, 9, and 10] have reported the influence of impactor mass on the response characteristics of rate dependent materials such as padded surfaces and foams. As the rate dependency of muscle is well known [1, 3, 11 and 12], it is important to investigate the effect of impactor mass for characterizing the mechanical behavior of muscle tissue in free fall impact loading. However, no such study has been reported to the authors' knowledge thus motivated to conduct the present study.

To understand the significance of impactor mass on muscle tissue response, numerical analysis is carried out using finite element simulations for impact loading conditions. Influence of impactor mass on constant strain rate duration and on percentage of strain is studied by subjecting two null hypothesis stating, "The impactor mass influences the duration of constant strain rate" and "The impactor mass influences the percentage of strain".

Materials and Methods

Finite element modelling: Three dimensional solid models representing the specimen (length 14mm, width 14mm and height 9mm), lower platen (30x30x24mm) and impactor (30x30x24mm) are modeled using I-DEAS™ software and the schematic diagram of the model is shown in Figure 1. All the parts are meshed using eight-node solid brick elements. Dynamic finite element (FE) analysis is performed using PAM CRASH™, explicit finite element software. Element quality checks were performed to identify the existence of any distorted elements and to satisfy the minimum time step criteria.

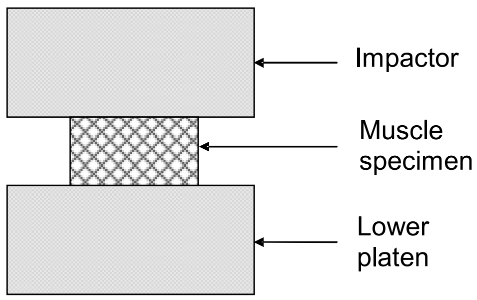

Figure 1: Schematic representation of finite element model for unconfined compression loading

A convergence study was performed to decide upon the mesh size and no of elements. Two different mesh sizes, course (2x2x2) and fine (1x1x1) representing length breadth and height of the specimen were studied. From the convergence study, it has been observed that the coarse mesh reduces the analysis time duration by 4 times approximately than the fine mesh with less than 5% deviation in force-displacement response and hence the coarse mesh is used for further analysis. Both lower platen and impactor were represented as rigid body and assigned with steel material characteristics. Muscle tissue is represented as linear visco elastic material and the properties were extracted from literature [13]. All the material properties are indicated in Table 1. Muscle tissue is placed above the lower platen with contact thickness of 0.1mm defined.

Table 1. Material properties of muscle and impactor

a) Muscle (Lizee et al. 1998)

Element type	K MPa	G_0 MPa	G_1 MPa	β s^{-1}	ρ kg/m^3
Brick 8 node	0.25	0.115	0.086	100	1000

b) Impactor

Element type	E GPa	ν	ρ kg/m^3
Brick 8 node	210	0.3	7800

Muscle specimen placed on the lower platen, is allowed to deform laterally. The lower platen is constrained for all translations and the impactor is allowed only to move freely in vertical direction. During compression, specimen squeezes in between the lower platen and impactor. Contacts between the specimen-lower platen and specimen-impactor interfaces are defined using surface-node contact type definition 34 in PAM CRASH^{TM}. Specimen is always represented as “slave” interface while both impactor and lower platen are represented as “master” interface. Internal solid anti-collapse contact is defined for the muscle tissue specimen to prevent negative volume problem due to large deformation of elements. Friction coefficient (μ = 0.3) at the contact interfaces of specimen-lower platen and specimen-impactor are defined as reported in literature [14 and 15]. To avoid contact nonlinearity at all stages in finite element simulations, cross section of the impactor is kept larger than the cross section of the muscle specimen. An acceleration of 9.81 m/s2 is defined to represent the gravity field.

Simulation protocol: Eight finite element simulations were performed by varying the impactor mass from 0.25 kg to 2 kg with an increment of 0.25 kg. An initial velocity of impact of 1.2 m/s is used. The geometrical and material properties of the specimen are kept constant in all simulations. The geometry of the impactor is unaltered and the masses are varied by adding lumped mass.

Data analysis: Contact force between specimen-impactor interface and the displacement of the impactor has been measured along the impact load direction for varying impactor mass. Engineering stress and engineering strain are calculated from the force–displacement response and initial specimen dimensions. The constant strain rate duration is calculated as total time taken from the first contact between specimen and impactor (when the displacement is in the order of 0.1 mm) to 5% deviation in the initial strain rate. The percentage of strain for any constant strain rate is calculated from the product of initial strain rate and the duration of constant strain rate.

Results

It is observed that the larger impactor mass has produced greater contact forces and larger deformations in the muscle tissue. However, the change in duration of constant strain rate is not linearly proportional to change in impactor mass. It can be calculated from the following polynomial equation (R^2 = 0.9983) for any impactor mass from 0.25 Kg to 2 Kg.

$$\mathbf{Y1 = -0.6631x^2 + 3.1576x + 1.0273} \quad \mathbf{(1)}$$

Y1 is duration of constant strain rate in seconds and x is the mass of the impactor in Kg.

Peak forces produced by the larger mass are consistently greater than those produced by the smaller mass throughout one complete loading and unloading cycle (Figure 2).

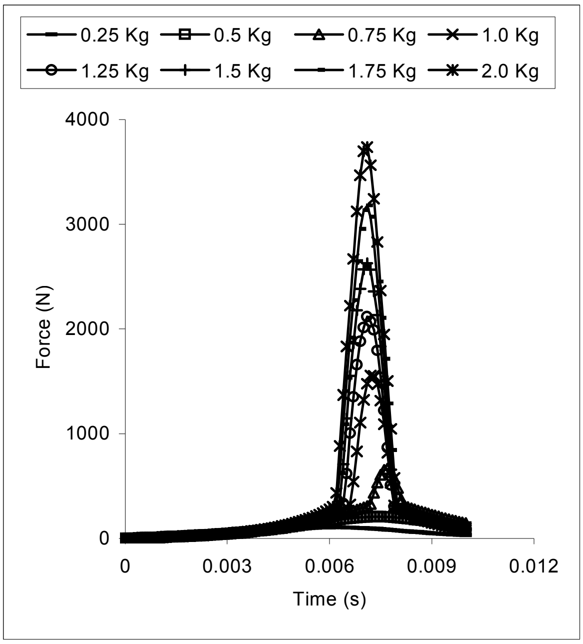

Figure 2 Effect of mass of the impactor on Force-time history

Percentage of strain shows a nonlinear relationship with change in impactor mass. It can be calculated from the following polynomial equation (R^2 = 0.9983)

$$\mathbf{Y2 = -9.9349x^2 + 47.331x + 15.326} \quad \mathbf{(2)}$$

Y2 is the percentage of strain.

Similar observations are made on displacement history with larger mass exhibiting the maximum displacement than the smaller one (Figure 3). Constant strain rate duration is measured up to 4.7 ms for 2 Kg impactor mass which is 2.75 times more than that of response at 0.25 Kg (Figure 4).

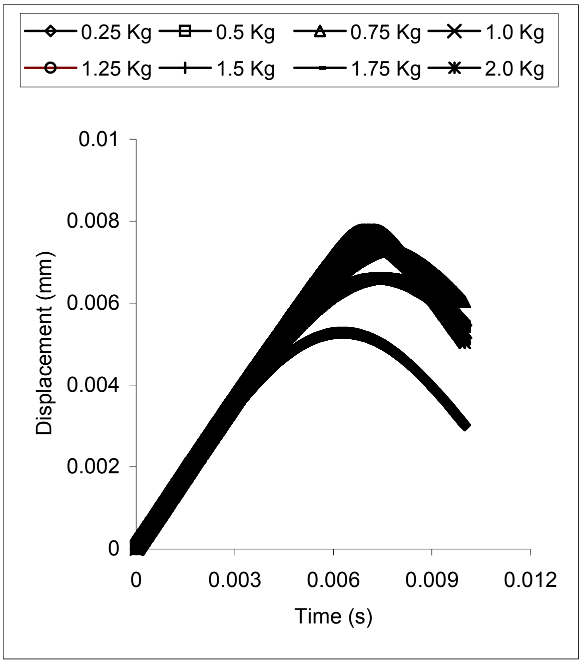

Figure 3 Effect of mass of the impactor on displacement-time history

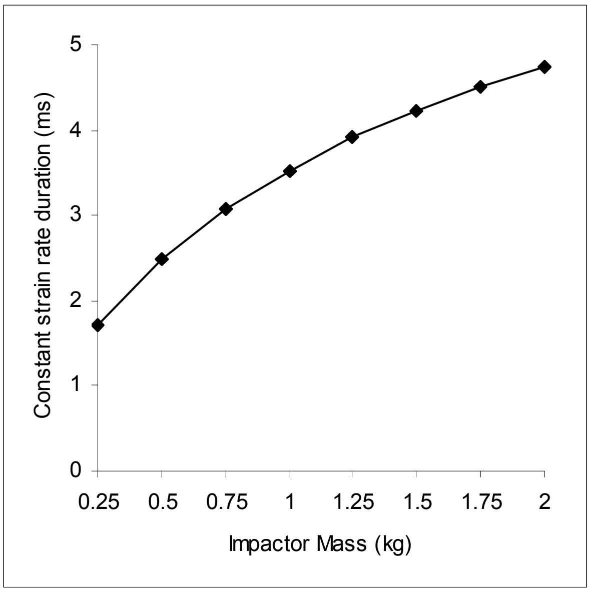

Figure 4 Effect of mass of the impactor on constant strain rate duration

Strain level up to 25 % is achieved at constant strain rate by using a minimum impactor mass of 0.25 Kg (Figure 5). A maximum strain of 70 % with constant strain rate can be achieved by using 2 Kg impactor.

However there is no significant effect of impactor mass on the force-displacement and stress-strain response is observed for the simulated conditions from 0.25Kg to 2 Kg impactor mass (Figure 6).

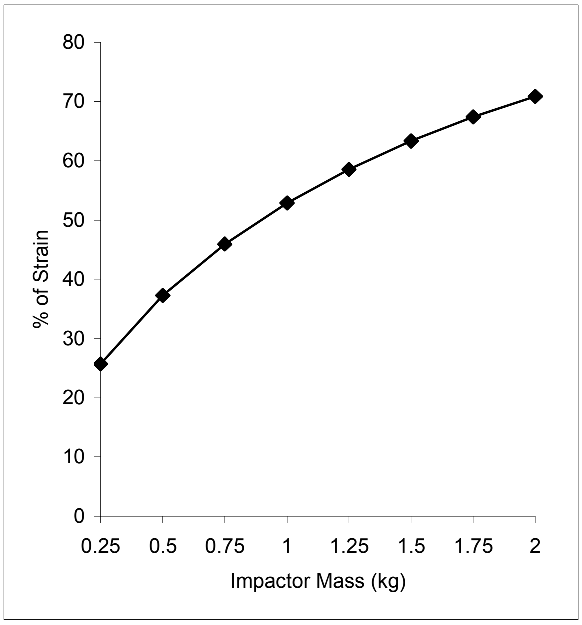

Figure 5 Effect of mass of the impactor on percentage of strain

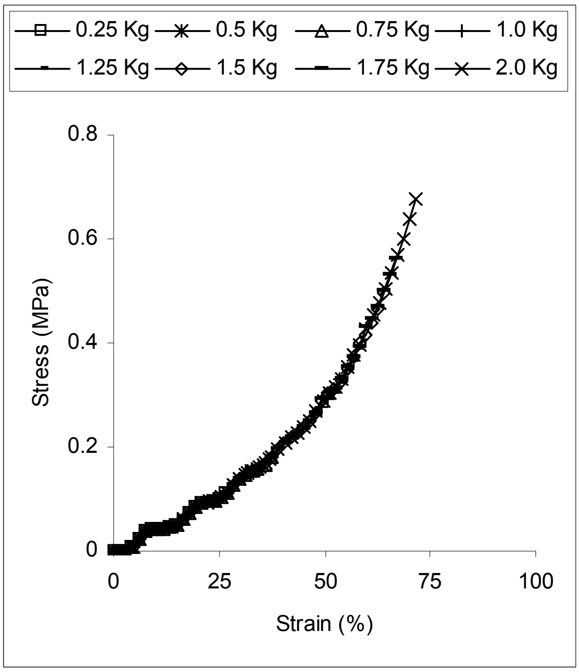

Figure 6 Effect of mass of the impactor on stress-strain characteristics of muscle tissue

Discussion

The effect of impactor mass on the soft tissue behavior under impact loads is studied through finite element analysis. This study provides information on variation of both constant strain rate duration and strain levels for a specific constant strain rate for the variation in impactor mass. It is observed from the results that with the increase in impactor mass from 0.25 to 1 kg, the duration for constant strain rate increases from 25 to 30% (Figure) and percentage of strain increases from 24% to 52% (Figure). Therefore it can be concluded that if an impactor mass of 1 kg or more is used in free fall impact tests, the strain rate will always remain constant up to 50% strain level. Thus it ensures that the experimental data analyzed till 50% strain level will always be suitable to characterize the muscle behavior for constant strain rate.

This study will be helpful for deciding upon the mass of an impactor for the development of miniature free fall impact testing machines to be placed inside an operation theater for testing the isolated muscle specimens available from the surgery.

Though the impactor mass shows significant influence in strain rate duration and percentage of strain, there is no significant change observed in the loading path of stress-strain characteristics. In other words, the magnitude of stress at any strain is similar for different impactor mass implementation.

Conclusions

An increase in constant strain rate duration and strain level is observed during the increase in impactor mass from 0.25 Kg to 2 Kg. The increase of characteristics like constant strain rate duration and strain level is not proportional with increase in impactor mass. The stress-strain loading curve is unaltered by change in impactor mass. With usage of 1 Kg. impactor, 50% of compression can be achieved at constant strain rate on characterizing soft tissue properties.

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