

Dynamic Stress-strain Compressive Response of Soft Tissue using Polymeric split- Hopkinson Pressure Bar

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Abstract: *The characterization of soft tissues subjected to higher compressive strain rates is of increasing importance as the material properties of soft tissues were commonly used in impact applications such as automotive safety and crashworthiness for biofidable numerical modeling of the human body. Due to less availability of strain rate dependent data in the open literature and various challenges in the characterisation of soft tissues under impacts, need were felt for characterisation of soft tissues at higher strain rates. The purpose of this study is to investigate the dynamic mechanical behavior of soft tissues at varying compressive strain-rates. The viscoelastic split Hopkinson pressure bar (SHPB) is designed and developed to predict the high rate compressive behavior of soft tissues. The primary benefit in using viscoelastic bars is the reduced bar impedance allowing for high-quality measurements of the transmitted and reflected stress wave signals. The dynamic behavior of goat muscles has been measured at higher strain rates $\sim 500-1200\text{ s}^{-1}$ using a polymeric SHPB apparatus. The dynamic stress-strain response of muscle tissue exhibits non-linear behavior under compressive loadings and is strain-rate dependent.*

Index Terms: *Strain rate, Mechanical behavior, SHPB, Soft tissue*

I. INTRODUCTION

The characterization of soft materials and soft tissues having low impedance is becoming increasingly important. The material properties of soft tissues are used in automotive crashworthiness for human body modeling to predict the injury mechanisms. The investigation of injury mechanisms in high-speed automotive accident requires the integration of human body model and vehicle model. The detailed constitutive material models that accounts for non-linear material response and strain-rate effects are required to develop virtual human body models and study of occupant and pedestrian safety. Several studies were reported in the literature to understand the dynamic mechanical behavior of various soft tissues at varying strain-rates and it was observed that the stress-strain response is strain-rate dependent. Hence, the knowledge of the mechanical behavior of soft tissues at varying strain rates is crucial in impact biomechanics to improve the safety of pedestrian and occupant against crash, impact, and blast loads. Hence, it is necessary to study the influence of strain-rate on the characterisation of soft tissues in a dynamic loading condition.

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The SHPB method had been commonly employed for the investigation of rate dependent material properties of several engineering materials such as non-metals and metals [6-7]. But, SHPB method has various challenges in the characterisation of soft tissues and soft materials having low impedances. The lower mechanical impedance of material increases delay in achievement of dynamic stress equilibrium and thus, results in poor transmission pulses [8]. The conventional SHPB method with some modifications has been used in soft tissue characterization. These include use of most sensitive piezoelectric gauges, use of hollow transmission bars instead of solid bar, use of viscoelastic bars having less impedance, and application of pulse-shaping method [9-12]. An additional challenge is the selection of proper experimental method to characterize the soft materials from quasi-static to intermediate strain-rates in an automobile crash and higher strain-rates in impact loading. The several testing methods are depicted in Table 1 to achieve the desired strain-rates [1].

The most of the studies on biological soft tissues, tissue simulants and soft materials in available literature were done on quasi-static and intermediate rates of loadings due to the various challenges in impact characterisation. Therefore, few experimental results on biological soft tissues under high-speed impact loadings are available. The Hopkinson bar experimental technique was pioneered by J. Hopkinson [2] as a means to study the effect of impact loading on iron wires. B. Hopkinson [3] son of J. Hopkinson further carried out experiments and introduced a technique for determining the pressure-time relations due to an impact produced by a bullet or explosive. H. Kolsky [4] improved Hopkinson's bar technique by using two pressure bars connected in series (split bars). The cathode ray oscilloscope and electrical condenser were jointly incorporated in SHPB to record the propagation of stress waves through the pressure bars as pioneered by Davies [5, 7]. Later modifications had been made for tension, compression, shear and torsion testing.

The high strain rate dynamic experiments have been performed by using various modified versions of SHPB setups for testing human cadaveric body lower extremity muscles [21], bovine muscles [20], porcine muscles [19], porcine adipose tissue [16], bovine brain tissue [14], renal cortex [15], EPDM rubber [12], polyurea [10] and gelatin bio-material [11] under dynamic compressive loading conditions, while bovine tendon [17], pig skin [22], soft tissues [13], bovine ligament [18] under tensile

loading conditions. The biological soft tissues have been tested under dynamic torsional loading using modified SHPB to obtain a shear response. One of the most important requirements in the modeling of impact phenomena is the characterisation of soft materials under high deformation rates. The stress-strain response of goat muscle tissues

obtained from goat species is studied by using modified SHPB under dynamic load. After correlation between animal and human body, the high strain-rate properties of goat muscle tissues may be used in numerical modeling of muscles in the human body.

Table 1 Rates of deformation and experimental strain rate testing methods [1]

Strain Rate (s ⁻¹)	Deformation Rate	Testing Technique
< 10 ⁻⁶ s ⁻¹	Creep domain	Constant load or stress machines
10 ⁻³ s ⁻¹ to 10 ⁻¹ s ⁻¹	Quasi-static	Servo-hydraulic and screw machines
10 ⁰ s ⁻¹ to 10 ² s ⁻¹	Intermediate strain-rate	Drop tower or special servo-hydraulic
10 ² s ⁻¹ to 10 ⁴ s ⁻¹	High strain-rate	Hopkinson techniques
10 ⁴ s ⁻¹ to 10 ⁶ s ⁻¹	Very high strain-rate	Impact techniques -Taylor anvil or flyer plate
> 10 ⁶ s ⁻¹	Ultra high strain-rate	Explosive techniques

II. SPLIT HOPKINSON PRESSURE BAR

A. Conventional SHPB

A conventional SHPB, as shown in Figure 1 consists of three pressure bars such as, incident, transmission and striker bar. The length of striker bar is limited to less than half of incident bar to avoid the superimposition of the stress waves at the gauge station, and the length determines the amount of deformation achieved in the specimen. The cylindrical specimen is sandwiched between the transmitter and incident

bar by using an adhesive. The conventional SHPB makes the use of metallic bars where stress wave attenuation and dispersion were neglected. The inertial and frictional effects were also not considered. The specimen is assumed to deform uniformly under compressive loading. The striker bar is accelerated by the pressurized air using gas gun launcher mechanism. It impacts on incident bar and produces the compressive stress pulse.

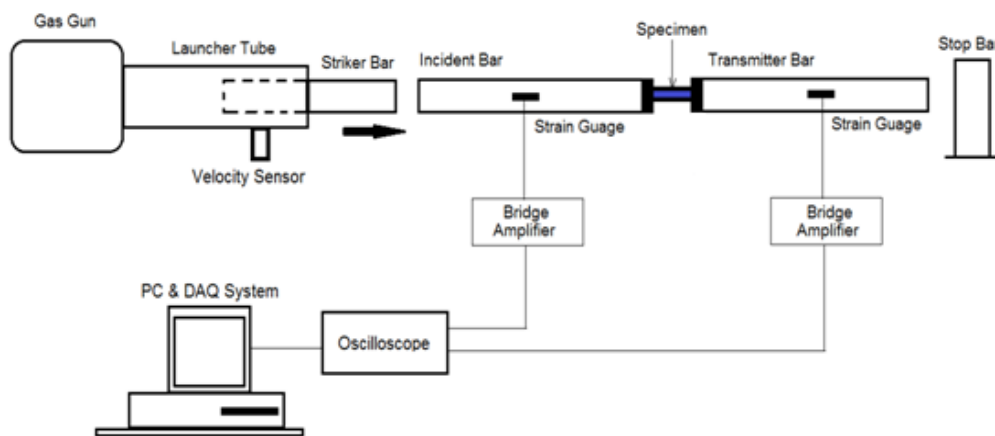


Figure 1 Conventional Split Hopkinson Pressure Bar

The stress waves in the incident bar were recorded by the strain gauges located at the middle of the incident bar. Stress wave pulse splits into two smaller waves at specimen-incident interface viz. reflected pulse and transmitted pulse. The transmitted pulse travels through the specimen and the transmitter bar. The stress waves in the transmitter bar were recorded by the strain gauges located at the middle of the transmitter bar. Some portion of stress pulses is reflected away from the test specimen, and travels back into the incident bar. A stop bar or momentum trap mechanism absorbs the impact of the transmitter bar.

The reflected stress waves are used to calculate strain and the portion of compressive stress waves that continues through the specimen is used to calculate stress. The theory of one dimensional stress-wave propagation in elastic pressure

bas along axial direction yields the calculation of strain ϵ_s , strain rate $\dot{\epsilon}_s$, and maximum stress σ_s induced in a specimen using the following equations.

$$\epsilon_s = \frac{-2c_0}{L_s} \int_0^t \epsilon_r dt \tag{1}$$

$$\dot{\epsilon}_s = \frac{-2c_0}{L_s} \epsilon_r \tag{2}$$

$$\sigma_s = \frac{A_0}{A_s} E \epsilon_t \tag{3}$$

The metallic bar has a short rise time and this can be increased by using pulse shaper, and using shorter test specimens.



Table 2 Acoustical impedance of different materials [20]

Material	Modulus of Elasticity (GPa)	Density (Kg/m ³)	Acoustical Impedance (MPa sec/m)	Wave Speed (m/s)	Poisson's Ratio
Steel	207	7840	40.28	5138	0.3
Aluminum	68.9	2700	13.64	5052	0.33
Magnesium	45	1738	8.84	5088	0.35
PMMA	3.5	1178	2.02	1716	0.35
Muscle	--	1070	1.66	1540	--

The use of viscoelastic polymeric bar addresses the need for moderate rise time. The uniformity of deformation can also be implied through the measurement of the forces at the incident and transmitter bar interfaces with the specimen. If the forces are similar in magnitude over the loading history, the specimen should undergo uniform deformation. The measurement of useful results from a high rate test relies on a good signal-to-noise ratio, particularly in the transmitter bar. The weak signals are propagated through the transmitter bar due to the mismatch of acoustical and geometrical impedance between the test specimen and pressure bars. Acoustical impedance matching could be achieved by reducing the impedance of the bars through material selection. The impedance of different materials is shown in Table 2, where the impedance of PMMA is similar to that of soft tissues and other low impedance materials. The specimen aspect ratio of diameter to length was limited by the need to reduce the frictional effects and specimen inertia effects. The frictional effects can be minimized by using appropriate lubrication at the interfaces of test specimen and pressure bars. The self-lubricated bushings made from Derlin® material are used to support the pressure bars. The specimen inertia effects increases with increase in length to diameter ratio, and could be minimized as suggested by Davies and Hunter [7].

B. Viscoelastic SHPB

The use of metallic bars for soft tissue testing results in impedance mismatch and low-level signals passing through the transmitter bar were difficult to differentiate from the intrinsic noise in the test setup. Thus, polymeric bars having impedance closer to the soft tissue and elastic modulus lower than the metallic bars was used in the SHPB analysis of soft tissue. The polymeric SHPB setup enables the measurement of low-stress signals and allows the inspection of stress-equilibrium in the test specimen. The specimen is subjected to longer test time due to the lower sound velocities as compared to the metals, and thus enables large strains applied before the effects of reflected stress-waves. This gives the uniform deformation of the specimen. Poly Metha Methyl Acrylate (PMMA) bars have been used in the present investigations as the PMMA has very closer impedance match with the human body muscles than other soft materials and engineering materials

The analysis for the metallic SHPB is not directly applicable for polymeric SHPB bar. These bars are viscoelastic. The stress wave attenuates and disperses in the medium due to the use of polymeric bars in SHPB. Hence, the strain measured at the middle location of the pressure bar is different from the strain measured at the interface of

bar-specimen. The attenuation and dispersion correction has to be applied to account the strain mismatch. The theory of one-dimensional stress-wave propagation along axial direction and experimental procedure developed by Bacon (1998) is used to find the attenuation and the propagation coefficient in viscoelastic pressure bars. The reflected pulses were reconstructed using the attenuation and dispersion coefficients. The stress-wave equation of viscoelastic pressure bar is represented in the Fourier domain by

$$\frac{\partial \tilde{\sigma}(x, \omega)}{\partial x^2} = -\rho \omega^2 \tilde{\varepsilon}(x, \omega) \tag{4}$$

Where, $\tilde{\varepsilon}(x, \omega)$ and $\tilde{\sigma}(x, \omega)$ denote Fourier transformations of the longitudinal strain and normal stress, respectively. The frequency f is determined by $\omega = 2\pi f$. The angular frequency, ω and frequency, f is represented in radians and Hz, respectively.

Neglecting lateral motion of the bars, the linear behavior of the polymeric bar can be given by the complex Young's modulus, $E^*(\omega)$ as follows

$$\tilde{\sigma}(x, \omega) = E^*(\omega) \tilde{\varepsilon}(x, \omega) \tag{5}$$

The wave propagation coefficient $\gamma(\omega)$, dependent on frequency in the polymeric bar is specified by

$$\gamma^2 = -\frac{\rho \omega^2}{E^*} \tag{6}$$

A general solution of one-dimensional wave equation along axial direction in the Fourier domain can be expressed by

$$\tilde{\varepsilon}(x, \omega) = \tilde{P}(\omega)e^{-\gamma x} + \tilde{N}(\omega)e^{\gamma x} \tag{7}$$

Where, $\tilde{N}(\omega)$ and $\tilde{P}(\omega)$ defines the Fourier transformations of the strains at $x = 0$ due to stress-wave propagation along decreasing and increasing x, respectively.

The wave propagation coefficient $\gamma(\omega)$, is the divided into two parts, viz real part $\alpha(\omega)$, and imaginary part $k(\omega)$.

$$\gamma(\omega) = \alpha(\omega) + ik(\omega) \tag{8}$$

The real part is the attenuation coefficient, and the imaginary part is the wave number. The wave number can be, the, used to determine the phase velocity.

The equations (9) and (10) represent the general solution and can be, further used to determine the Fourier transformations of force $\tilde{F}(x, \omega)$ as a function of frequency and velocity $\tilde{v}(x, \omega)$ as a function of position.



$$\tilde{v}(x, \omega) = -\frac{i\omega}{\gamma} \left[\tilde{P}(\omega)e^{-\gamma x} - \tilde{N}(\omega)e^{\gamma x} \right] \quad (9)$$

$$\tilde{F}(x, \omega) = -\frac{\rho A_0 \omega^2}{\gamma^2} \left[\tilde{P}(\omega)e^{-\gamma x} + \tilde{N}(\omega)e^{\gamma x} \right] \quad (10)$$

Lastly, the equations (9) and (10) are solved using inverse Fourier transforms, and used together with equations (2) and (3) to determine the stress-strain histories induced in the test specimen due the impact loading.

III. EXPERIMENTAL METHODS

A. Polymeric SHPB

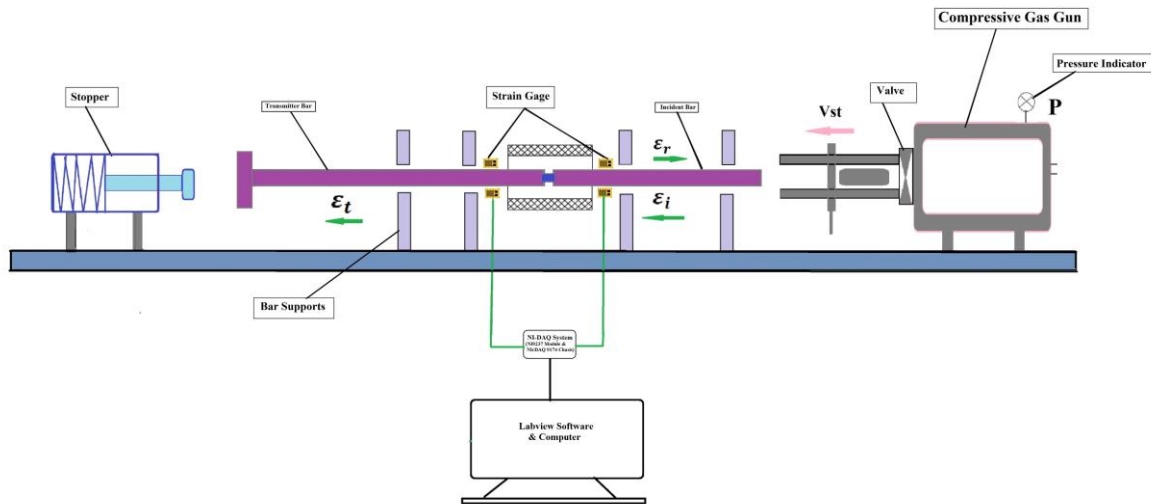


Figure 2 A Schematic of a polymeric SHPB Setup

A polymeric SHPB setup has been designed and developed using PMMA to test soft tissues at high strain rates under compressive loading. Figure 2 shows a schematic of a polymeric SHPB setup. A polymeric SHPB setup consists of two polymeric bars of 16 mm diameter and 1220 mm length. All the pressure bars were supported by axially aligned self-lubricating Delrin® bushings on custom made bar supports. Two strain gauges were mounted on each pressure bar at 610 mm apart from the bar-specimen interface. These are mounted diametrically opposite to form half-Wheatstone Bridge. Due to this configuration of strain gauges, bending effect is neglected. A data acquisition system composed of NI 9237 module and NIcDAQ 9174 chassis with LabVIEW software is used to acquire the voltage-time history. A signal conditioning and amplification were done in programming by setting the gain of 1000 to amplify the signal before capturing with a 50 MS/s capacity.

The solid striker bar of length 300 mm and diameter 16 mm was used as a projectile to obtain the compressive stress pulse after impacting it onto the incident bar. The striker bar in gas operated launcher mechanism was accelerated forward against the incident bar by using quick acting solenoid valve. The striker bar end velocities in the range of 3 to 15 m/s were achieved through this mechanism. The striker bar length can be varied between 300 mm to 700 mm without superposition of the stress waves within the bars. The primary challenge in the development of polymeric SHPB is the viscoelastic nature of the bars resulting in attenuation and dispersion pressure waves and must be accounted in the processing of signals.

The primary benefit of this setup is impedance matching between the pressure bars and soft materials or soft tissues so that high quality signals may be measured on the pressure

bars. Second, longer stress wave rise time for the PMMA material allows the more flexibility in specimen geometry. Hence, the specimen with longer length and reasonable diameter can be used to ensure a high quality signal. A key requirement of any test setup is validation and testing to ensure the basic assumptions and criteria are met. The operation and data analysis procedures for the polymeric SHPB have been validated through several independent measurements including bar end velocity measurement using IR sensor system, through comparable material testing using polymeric SHPB and metallic SHPB setup and calibration of pressure and velocity curves.

B. Specimen Preparation and Experimental protocol

The muscle specimens from the lower extremity of adult goats were collected from a slaughterhouse and tested to establish the experimental procedures for the calibration of dynamic compressive polymeric SHPB setup. All the specimens were stored in saline solution at room temperature about 20°C for two hours before testing. All the specimens were thawed at room temperature for less than three hours before testing. The fascia layer was removed from the muscles. The dehydration of the muscle tissue is prevented during experimentation. The ten samples were cut into cuboids having size of 12×12×10 mm measuring length, breadth and height respectively. The height of the specimen, which represents the direction of loading, was kept perpendicular to the fiber orientation of muscle tissue. The physical loading of muscle tissue was avoided till performing the tests.





Figure 3 Photograph of a Polymeric SHPB Setup

The only one test was conducted on each sample under unconfined condition. Total 18 tests were conducted in 2 hours time duration. Each specimen is tested under compressive loading for the pressure range from 1 bar to 5 bars. Each specimen was loaded at an average impact velocity of about 1 to 4 m/s which achieves the range of strain rate $\sim 500-2000 \text{ s}^{-1}$. The muscle tissues were tested at 500, 750 and 1200 s^{-1} .

C. Data analysis

The wave attenuation and propagation coefficients of viscoelastic pressure bars were calculated after acquiring stress wave signals from free end tests using Bacon's experimental approach (1998). The calculated propagation coefficients are used during the processing of actual specimen test data to deduce specimen stress-strain response. Hence, the transmitted and reflected pulses were reconstructed by applying the attenuation and dispersion correction to the corresponding recorded pulses for the distance it has propagated. The calculation of specimen strain, stress, and strain rate using viscoelastic analysis for polymeric bars in the frequency domain were done, where the phase velocity is a function of frequency. Using inverse Fourier transform, specimen strain, stress, and strain rate can then be calculated in the time domain. NI-LabVIEW assisted data acquisition system has been established to acquire the stress pulses using strain gauges. The Labview program has been developed to plot the stress-strain response at each strain rate. Infra-red sensor based velocity measurement system is incorporated in SHPB setup to record an experimental striker bar impact velocity for the calibration of theoretical striker bar impact velocity.

IV. RESULTS AND DISCUSSIONS

The high rate compression response of muscle tissues has been measured using a polymeric SHPB apparatus. The typical waveform record of the incident and transmitted stress

signals measured during impact using LabVIEW was shown in Figure 4. As suggested by Bacon (1998), the propagation coefficient in pressure bar does not vary notably in the range of 1 to 5 m/s. The propagation coefficients obtained from free end tests conducted on the incident bar at 2m m/s were used in testing of muscle tissues.

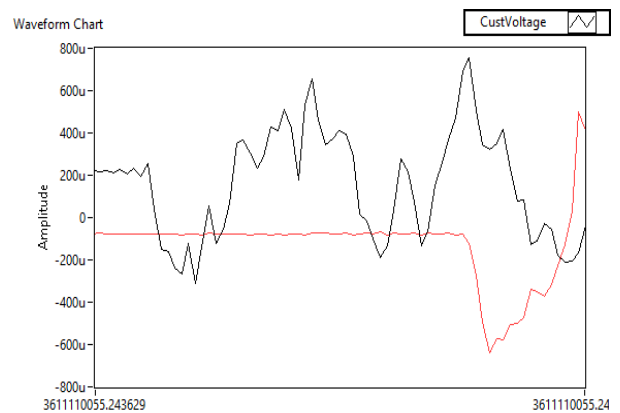


Figure 4 Waveform history in polymeric pressure bars

The wave number and attenuation coefficient are determined through spectral analysis of the incident bar waveform by conducting free end test. The phase velocities at various frequencies were determined using the wave number. For frequency upto 15 KHz, the mean phase velocity is 1950 m/s. The standard deviation is found to be 30 m/s, which indicates that the effect of geometry is small, and hence negligible. The dynamic stress-strain compressive response of goat muscles exhibits a concave-up curve and shows nonlinear behavior, as depicted in Figure 5. The nonlinear stress-strain relationship is observed in goat muscles. The compressive stress induced in the goat muscle increases with strain-rate.

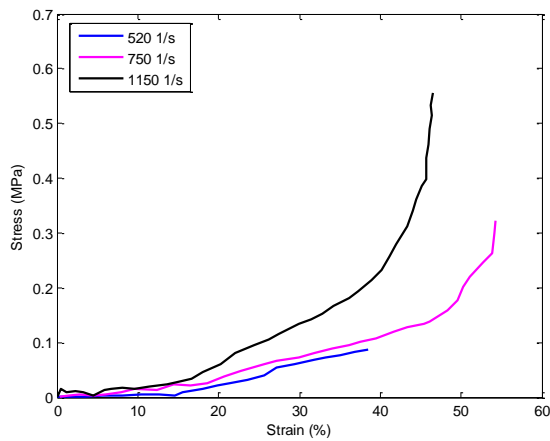


Figure 5 Stress ¹ strain response of goat muscle at varying strain rates under dynamic compressive loading

The maximum stress of 0.5 MPa is observed at 50% strain at a strain rate of 1150 /s in the goat muscles.

Table 3 Maximum stresses induced in muscle specimens

Impact velocity (m/s)	Strain rate (1/s)	Maximum stress (MPa)
30 m/s	1150	0.5
25 m/s	750	0.3
20 m/s	520	0.1

V. CONCLUSIONS

A polymeric SHPB setup has been designed and developed to establish an experimental procedure for the characterization of impact response of muscle tissues at varying strain rates under dynamic compressive loading. The use of polymeric pressure bars to conduct impact tests on goat muscles was illustrated. The attenuation and dispersion correction has been incorporated in experimental testing using wave propagation theory. The validation and calibration of polymeric SHPB setup were done through independent measurements of sound velocity, impact velocity of pressure bars and pressure-velocity regression analysis. The stress-strain behavior of goat muscles was investigated under dynamic compressive loading conditions at ~500 – 1200 s⁻¹ and the stress-strain curve exhibits non-linear behavior under compressive dynamic loadings. The stress-strain response exhibits non-linear behavior under compressive dynamic loading and is strain-rate dependent. The muscle specimens are failed in a brittle manner.

The strain-rate dependent data will be used to formulate the constitutive material model to be used for muscle tissue modeling. The strain – rate dependent numerical model of muscle tissue requires a suitable constitutive material model. The muscle response obtained though the present study could further be used in finite element analysis.

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