Mechanical Behavior of Bovine Tendon with Stress-Softening and Loading-Rate Effects

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Abstract

The development of predicting capabilities for impact-induced injuries for accurate medical intervention requires a thorough understanding of rate and damage effects on the mechanical behavior of biological tissues. Tissue response to such high-rate loading has been less studied. In this research, we examined the rate and damage effects on the tensile stress-stretch behavior of a bovine tendon. Low-rate (0.05/s) experiments were performed with a conventional material test machine and high-rate (2500/s) experiments were conducted with a Kolsky tension bar modified with pulse shaping, hollow transmission bar, and laser deformation measurement for soft tissue testing. The quasi-static experimental results show that, during
cyclic loading, the stress-stretch behavior of the bovine tendon exhibits hysteresis, permanent strain set, permanent stress set, and stress softening (Mullins effect). The dynamic experimental results reveal a significant dependence of the stress-stretch behavior on stretching rate. Quasi-static experimental results were successfully modeled with Dorfmann and Ogden’s model for the Mullins effects with permanent strain set.

Keywords: Tendon; Mullins effect; Loading-rate effects

1 Introduction

Mechanical impact encountered in accidental collisions and falls can cause serious injuries to human body. Accurate and timely medical intervention requires a prediction of the injury level and injury location. If mechanisms between the mechanical impact and the resultant injury can be revealed, it is possible that optimized protection gears can be designed to minimize injury. In order to develop such predictive capabilities for impact-induced injury, a thorough understanding of the responses of body tissues to such high-rate loading is required. In experimental investigations of the responses of body tissues, mannequin such as hybrid III is usually used to measure forces applied on the body. The forces are then applied to finite element analysis (FEA) model of human body to calculate quantitative changes in stress or strain in every tissue. In order for the FEA model to accurately represent the human body, mechanical properties of many biological tissues are required. While the mechanical behavior of biological tissues has been extensively studied under either quasi-static loading conditions ($\dot{\varepsilon} < 0.1/s$) or at moderate rates ($\dot{\varepsilon} \sim 5/s$)[1], high-rate response of such materials to impact loading has been much less studied, especially for soft tissues. High-rate experiments on soft tissues have been recently conducted under compressive loading conditions. For example, Song et al. [2] overcome the difficulties with radial inertia and determined the compressive response of a porcine muscle over a wide range of strain rates. Pervin and Chen [3] further extended the experimental methods to investigate the mechanical response of much softer brain tissues at high rates. However, many eventual failures are tensile in nature, but high rate tensile experiments are rarely performed due to many difficulties associated with the experiments. In this study, we take bovine tendon, which is a soft tissue, as the subject for the investigation of rate and damage effects. Tensile experiments are conducted under both quasi-static and dynamic loading conditions to examine rate-effects, and under monotonic and cyclic loadings to reveal damage effects. The dynamic experiments are challenging due to the low mechanical impedance of the tendon specimens. A series of modifications to a conventional Kolsky tension bar, also known as a split Hopkinson tension bar (SHTB) are needed to conduct such experiments.
Significant rate-effects on the stress-stretch behavior are identified, which indicates that material response obtained at low or moderate rates may not represent its mechanical behavior when the loading rate is much higher. Damage to the tissue under cyclic loading conditions are determined and modeled.

Tendons, as do most biological tissues, have a nonlinear, anisotropic, inhomogeneous, viscoelastic and hyperelastic stress-stretch behavior, whose primary role is to transmit contractile forces to the skeleton to generate joint movement. This tissue is composed of a network of collagen fibrils in a hydrated matrix of elastin and proteoglycans, similar to the structure of rubbers, which consist of polymer chains to produce a cross-linked monolithic three-dimensional network. The mechanical properties of tendon constituents are dramatically different. Collagen has a Young’s modulus of 400 ~ 1,000 MPa, tensile strength of 50 ~ 100 MPa, and failure strain of 4 ~ 20% while elastin has a Young’s modulus of only 0.3 ~ 3 MPa, tensile strength of ~ 1.4 MPa, but failure strain of 100 ~ 200%. Therefore, collagen fibrils provide strength to the tendon while elastin provides flexibility as matrix of a composite material. This composite tendon thus has a Young’s modulus of 50 ~ 600 MPa, tensile strength of ~ 60 MPa, and failure strain of 4 ~ 20% at quasi-static loading conditions. At high strain-rate loading, the strength, stiffness, and energy absorption can be increased by a fact of 3.

Tendons may be damaged, temporarily or permanently, when subjected to excessive high-rate loading, either from athletic actions or from impact. It is important for surgery decision purposes to be able to predict the severity of the injury to the tendons involved. A key component of such predictive capability is the determination and understanding of the mechanical response and the damage/failure modes of tendons as a function of loading rates. However, the effects of such high loading rates on the mechanical behavior of tendons have been rarely addressed.

Quasi-static tensile properties of tendons have been the subject of many hundreds of investigations, most of which were conducted on excised animal tendons undergoing stretching after preconditioning cycles with a conventional material-testing machine [4, 5, 6]. When a tendon is subjected to high-rate loading, it experiences large stretch ratios at high stretching rates. The mechanical response at such high rates may not be rate independent, as has been commonly concluded [7]. Furthermore, the tendons are not necessary in “exercised” condition (preconditioned) when subjected to dynamic loading. The mechanical properties obtained from fully exercised tendons may not be applicable to describing the behavior of less or not exercised tendons. It is therefore necessary to characterize the stress-stretch behavior of tendons accounting for their loading history. However, rarely has the literature reported how the tendons were preconditioned (e.g., maximum stretch, stretch rate, or the number of repeated exercising cycles) before stable stress-stretching data were recorded.
Although loading-history effects on many tissue responses are not well-documented, rubbers have been extensively investigated for the loading-history dependence of mechanical properties. Stress softening, hysteresis, and permanent strain set are all loading-history-related rubber characteristics [8]. For example, during stress softening, a phenomenon also known as the Mullins effect [9], a rubber specimen undergoes significant softening during the first few loading cycles before the material response approaches stability. The stable stress-stretch response of a rubber depends significantly on the maximum stretch it experienced previously. It is expected the micro-structurally similar tendons will also exhibit loading history effects. In this study, the influence of the Mullins effect and the loading rate effects on a bovine tendon are investigated using quasi-static and dynamic tensile experiments.

2 Experiments

In order to facilitate a comparison of the data from the quasi-static and dynamic experiments, the geometry of the specimens and the specimen grips for both sets of experiments were identical. Since tendons associated with different species or different anatomical sites are similar to each other in their mechanical behavior [6], no attention was paid to the anatomical location of the tendons because this study was focused on the Mullins effect and the loading rate effects. Before specimen preparation, the tendons were screened for degenerative changes visually and no evidence of degeneration was observed. Four specimens were excised from one tendon segment, as shown in figure-1, to avoid the potential ambiguity of experimental data resulting from different specimen resources. The specimens were then kept hydrated for tests. Two specimens from one tendon were used for quasi-static tests and the remaining two for dynamic tests. The length of specimen selected for this study was restricted by the requirement that dynamic force equilibrium must be maintained during dynamic loading for the purpose of measuring the point-wise valid material properties from the finite-volume specimen under valid dynamic testing conditions. The gauge section of the specimens was $3 \times 2 \text{ mm}^2$ in cross-sectional area and 8 mm in length.
Due to the large stretch ratios achieved in the experiments and the high Poisson’s ratio values (about 0.3) for the tendon materials, careful attention was paid to how the specimen was clamped and details were noted in order to obtain valid data. Grips similar to the ‘cryo-jaw’ device designed by Cheng and Chen [10] were used, which also introduced minimum disturbances to the stress wave propagations in a SHTB when employed in dynamic tests. Miller’s [11] equation was employed to evaluate the actual stretch ratio with its gain calibrated for this specimen configuration of rectangular cross section [10].

2.1 Quasi-static experiments

All quasi-static tensile experiments were carried out using an MTS 810 servo-hydraulic material testing machine. At first, a virgin specimen was stretched to a stretch ratio of 1.077 with a constant stretching rate of 0.05/s. Then, the specimen was unloaded with the same stretching rate until the actuator returned to its original place, which meant that the length between the two grips was the original length of the specimen. Once the first cycle was finished, another two identical cycles were performed. The stress-stretch history recorded during these three cycles is shown in figure-2.
The stress-stretch curves possess a typical stress-softening characteristic, similar to that of rubber materials [10]. After the first loading path reaches its maximum stretch ratio, the first unloading curve is well below the first loading curve. The subsequent loading paths are then slightly higher and the subsequent unloading paths are slightly lower than the first unloading path. The hysteresis is significant over the first loading cycle, but decays quickly after this cycle. Although the actuator returned to its original place, the specimen could not recover its original state. A permanent strain set existed immediately after the first loading cycle, causing the specimen to be in a compressive state when the grips returned to their original positions. Permanent strain set, which means the residual strain, is a term commonly used in the rubber industry. As marked in figure-2, the stress could not return to the previous loading cycle level at the same maximum stretch ratio either. This drop in stress between the different loading cycles when the stretch ratio reaches the maximum value has been named the permanent stress set [10]. Similar to the permanent strain set, the permanent stress set is an indication of material damage (in the sense of damage mechanics instead of physiology) over a loading cycle with a specific maximum stretch. Once the specimen experiences the first loading cycle, the subsequent loading cycles cannot reach the highest stress level of the first loading cycle if they keep the same maximum stretch ratio. The highest stress level of the subsequent loading cycles decreases gradually. It takes more than five cycles at the same maximum stretch ratio to approach a relatively stable value.

In order to fully investigate the Mullins effect, the specimen was then loaded to a maximum stretch ratio of 1.158 with the same constant stretching rate of 0.05/s,
followed by unloading. The loading and unloading paths are shown in figure-3, which depicts the overall loading and unloading cycles applied on this specimen, including the first three cycles shown in figure-2. At the fourth loading before the stretch ratio reached 1.077, the loading path is almost the same as the third loading path—the last loading cycle with a maximum stretch ratio of 1.077. As the stretch ratio during the fourth loading path extended across the previous maximum value of 1.077, a transition on the loading path led the loading curve on a path as if a virgin specimen were loaded. The following unloading path was much below the loading path, similar to the first unloading path except for an even larger permanent strain set when completely unloaded. After unloading, another two identical cycles were repeated at the maximum stretch ratio of 1.158. The loading and unloading cycles then go around the fourth unloading path instead of the first one, similar to the loading and unloading paths of the second and third loading cycles. Finally, the specimen was stretched until the maximum strength was observed.

![Figure-3: Stress-stretch behavior at 0.05/s stretching rate](image)

### 2.2 Dynamic experiments

In order to investigate loading rate effects over a wide range, the SHTB experimental technique [12, 13] was employed to determine the tensile stress-stretch behavior of the bovine tendon under dynamic (high-rate) loading. When a soft specimen is tested with a SHTB, there is a dramatic mechanical impedance mismatch between the specimen and the bars. Such an impedance mismatch causes two significant problems associated with the accurate determination of the stress and strain histories in the specimen under dynamic deformation. When the impedance of the specimen is much lower than that of the incident bar, nearly all of the incident pulse is reflected back to the incident bar,
making the profile of the reflected signal nearly irrelevant to the specimen. However, according to the Kolsky bar data-reduction scheme, the reflected signal is proportional to the strain rate in the specimen, which should depend on the specimen material and its response to mechanical loading. On the other side of the specimen, only a very small stress pulse is transmitted into the transmission bar due to the very small strength and mechanical impedance of the soft specimen compared to those of the metal bars. This makes it very difficult to accurately determine the transmitted signal, which is proportional to the stress history in the specimen according to the Kolsky bar theory based on one-dimensional wave propagation, using conventional strain gauges mounted on the bar surface.

To overcome the difficulties associated with accurate data acquisition, a laser displacement measurement device was used to measure the actual strain history in the specimen. The device includes a laser diode, a line head, and a photo detector. The details and working principles of the laser device are given by Ramesh and Narasimhan [15]. The only differences are that the setup was turned 90° from Ramesh and Narasimhan’s design and an opening gap was measured instead of an expanding rod cross section. A hollow bar technique [15] was used to accurately measure the transmitted force signal for stress assessment. To shorten the force disequilibrium period at the very beginning stage of the loading cycle and obtain a constant loading rate, a pulse-shaping technique [16] was employed. Furthermore, since it is important for the sample to be loaded only once during one loading cycle due to the loading-history dependence, a momentum trapping technique [17] was adopted to prevent undesired repeated pulses from loading the specimen. A schematic illustration of the dynamic experimental setup is provided in figure-4.

Figure-4: Modified Kolsky tension bar technique
During a dynamic experiment, the gas gun speeds a striker tube toward the flange. Once the striker tube impacts the flange through a pulse shaper, a well-controlled tensile stress pulse is created within the incident bar and the end face of the flange moves toward the momentum trap bar. The momentum trap bar is initially placed at a distance, $\delta$, away from the flange, as shown in figure-4. The gap distance ($\delta$) is set according to the particle velocity at the flange face during the tensile pulse period, such that the incident bar and the momentum trap bar are in full contact through the flange at the end of the loading pulse. Then, the tensile pulse travels toward the specimen, where it is partly transmitted into the transmission bar through the specimen and the rest of the pulse reflected as compression back into the incident bar. Since biological soft tissues are small in mechanical impedance compared with metal incident bars, the reflected compression is often nearly the same as the incident pulse. The reflected compressive pulse is then transmitted into the momentum trap bar through the now-in-contact interface between the flange and momentum trap bar. The compressive pulse crossing through the interface will be trapped in the momentum trap bar since the contact interface cannot support tension. The gap setting is critical in the experimental procedure. Without this momentum trap bar technique, the repeated tensile loading would overlap an extra specimen stretch on previous stretches, making it impossible to determine the maximum stretch the specimen experiences during one experiment, which is critical for examining the Mullins effect at high loading rates.

The dynamic stress-stretch behavior of the tendon specimen is presented in figure-5. Since it is difficult to fully eliminate the repeated loading, the actual maximum stretch ratio of the first impact experiment is about 1.20. The unloading data are not shown in figure-5 because it is impossible to control the dynamic unloading path on the tendon. The subsequent loading paths are well below the first one and gradually approach a stable path, similar to the quasi-static counterpart except the dynamic loading paths have higher slopes than their quasi-static counterparts.
3 Discussions

The experimental results shown in figure-1 and figure-5 illustrate that the Mullins effect significantly affects the stress-stretch behavior of tendons, both quasi-statically and dynamically. The subsequent loading paths on the stress-stretch curves depend on the maximum stretch the specimen experienced previously (see figure-3). Therefore, any material model describing the stress-stretch behavior without considering the Mullins effect provides only a partial description of the behavior. It has been common practice to ignore this phenomenon and perform data acquisition after several preconditioning cycles [18]. Most published stress-stretch properties were obtained at subsequent loading cycles and no details on the preconditioning were provided, including the maximum stretch ratio the specimens experienced [1, 6, 19, 20]. In our study, we explored the loading rate and history dependence of a tendon material because the tendon may not be in an exercised condition when it experiences sudden high-rate loading. Rate-dependent material data and models are thus necessary for tendons that are not fully exercised in order to make realistic injury predictions through simulations.

No unanimously accepted explanation of the mechanism of the Mullins effect is available so far, even for rubbers. The first modeling effort on the Mullins effects incorporating the permanent strain set was published by Holzapfel et al. [8].
Meanwhile, Ogden and Roxburgh [21] developed a phenomenological theory of pseudo-elasticity to model an idealized Mullins effect under quasi-static loading that considers the stress-stretch behavior without hysteresis and permanent set and they also modified this theory to provide a modeling frame that can accommodate the permanent strain set [22]. Recently, an explicit formulation for this case was proposed [23]. This latest model successfully describes the Mullins effect with permanent strain set in particle-reinforced rubber.

There is no model available that can accommodate all of the properties associated with tendons, i.e., the Mullins effect, permanent strain set, permanent stress set, hysteresis, and loading rate effects. In the following, Dorfmann and Ogden’s [23] Mullins effect modeling theory with permanent set will be employed to heuristically describe the behavior of the bovine tendon at a quasi-static loading rate. Although this model does not cover hysteresis, permanent stress set, or loading rate effects, after taking permanent set into account, it does provide enough flexibility to produce a more accurate description of the stress-stretch behavior of the tendon studied in this research.

Following Dorfmann and Ogden’s theory [23], we can obtain the following model for engineering stress under simple tension loading,

\[
\sigma_{e} = \eta \sum_{i=1}^{3} \mu_{i} \left( \lambda^{\alpha_{i} - 1} - \lambda^{\alpha_{i} - 1} \right) + \left( 1 - \eta \right) \left( 1 - v \lambda - \nu_{2} \lambda^{-2} \right)
\]  \hspace{1cm} (1)

where \( \lambda \) is stretch ratio, \( \alpha_{i} \) and \( \mu_{i} (i = 1, 2, \text{ and } 3) \) are material constants associated with Ogden’s strain energy function [24], which is in the following form in the case of unaxial tension loading,

\[
W_{0}(\lambda) = \sum_{i=1}^{3} \frac{\mu_{i}}{\alpha_{i}} \left( \lambda^{\alpha_{i}} + 2 \lambda^{\frac{\alpha_{i}}{2}} - 3 \right)
\]  \hspace{1cm} (2)

\( \eta \) is a damage or softening variable and depends on the maximum stretch ratio \( \lambda_{\text{max}} \) attained on the original loading path.

\[
\eta = 1 - \frac{1}{r} \tanh \left[ \frac{W_{m} - W_{0}(\lambda)}{\mu m} \right]
\]  \hspace{1cm} (3)

where \( m \) and \( r \) are two positive empirical material parameters, \( \mu \) is the shear modulus,
\[ \mu = \frac{1}{2} \sum_{i=1}^{3} \mu_i \alpha_i \quad (4) \]

\( W_m \) is the strain energy at the maximum stretch ratio the specimen experienced, and \( \tanh(\cdot) \) is the hyperbolic tangent function.

The variable \( \eta \) in Eq. (1) is a residual strain variable and determined by the following method proposed by Dorfmann and Ogden [23].

\[ \eta = \tanh \left( \left( \frac{W_m}{W_m(\lambda)} \right)^{\beta(W_m)}\tanh(1) \right) \quad (5) \]

The exponent \( \beta(W_m) \geq 1 \) describes residual strain after loading. Finally, the variables \( \nu_1 \) and \( \nu_2 \) are two other material variables depending on the maximum stretch ratio.

Experimental results were used to determine the material constants associated with the above model for the bovine tendon. First, a loading path was used to determine the material parameters with the Ogden’s elastic strain energy function (Eq. 2). These values are summarized in Table 1. Then, two unloading paths with maximum stretch ratios of 1.085 and 1.162 were used to determine the other parameters. The dimensionless parameters \( r \) and \( m \) were determined to be 0.15 and 0.06, respectively. The exponent in Eq. (5) were obtained to be a linear function of the maximum strain energy

\[ \beta(W_m) = 1.0914 + 9.7415 \frac{W_m}{\mu} \quad (6) \]

and the other variables were determined to be

\[ \nu_1 = 5.4 \mu \left[ 1 - 0.3219 \tanh(\lambda_m - 1) \right] \quad \text{and} \quad \nu_2 = 5.4 \mu \quad . \quad (7) \]
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Table 1
Model parameters $\mu_i$ and $\alpha_i$ (i = 1, 2, and 3) at a stretching rate of 0.004/s

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<th>$i$</th>
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<th>2</th>
<th>3</th>
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<td>9.066</td>
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<tr>
<td>$m$</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>0.15</td>
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</tbody>
</table>

The model prediction with the above material parameters and the experimental results at a stretching rate of 0.05/s are both shown in figure-6. This model can well describe the strain softening phenomenon as well as the original loading path of the bovine tendon.

Figure-6: Comparison between experimental data and model prediction

The dynamic stress-stretch behavior of the bovine tendon is different from its quasi-static counterpart. First, the original loading path is well above the one from the quasi-static test, which means the bovine tendon behaves in a much stiffer manner at a high stretching rate (2500/s) than at a quasi-static stretching rate (0.05/s). There are reports in the literature that the Young’s modulus of tendons in the linear phase is independent of stretching rate [1, 6, 25]. This statement originated in Ker’s [1] work on the tensile properties of the plantaris tendon of sheep, based on tensile experiments performed with frequency of oscillation in the range 0.22 to 11Hz. The stretching rate depends on the length of the specimen and the maximum displacement of the actuator, as well as the loading frequency. Since the ultimate strain of tendons is about 10% [26], the stretching rate
associated with Ker’s experiments [1] was estimated to be below 3.0/s. Within such a low stretching rate, the effects of stretching rate are not apparent. The stretching rate in the current study was three orders of magnitude higher, revealing the rate dependence of the mechanical behavior of tendons.

Another difference associated with the stretching rate is the ultimate stress the bovine tendon can sustain. The ultimate stress at the high stretching rate (2500/s) is at least twice as much as the one at the quasi-static stretching rate (0.05/s). The subsequent loading at the high stretching rate also shows the Mullins effect and permanent strain set, but the degrees are smaller than their counterparts at the quasi-static stretching rate. The reason is probably that the damage mechanism changed when the stretching rate was varied from quasi-static to dynamic.

4 Conclusions

The tensile behavior of a bovine tendon was investigated at both a quasi-static stretching rate (0.05/s) and a dynamic stretching rate (2500/s). During cyclic loading, the quasi-static experimental results revealed that the bovine tendon possesses characteristics such as the Mullins effect, hysteresis, permanent strain set, and permanent stress set. Both the permanent strain set and permanent stress set increase with increasing maximum stretch. Dynamic experimental results show that the stress-stretch behavior of the bovine tendon is significantly dependent on stretching rates. In addition, the Mullins effect also exists under high-rate loading.

Dorfmann and Ogden’s model [23] was employed to describe the loading cycles of the stress-stretch curves at various maximum stretch ratios at the quasi-static stretching rate, which provides a good description of the behavior of the quasi-static loading cycles with stress softening.

References

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