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QUASI-LINEAR VISCOELASTIC MODEL OF FOOT AND ANKLE LIGAMENTS FOR STRESS RELAXATION

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Introduction

Diabetics are at great risk of receiving below-knee amputations [1]. The causal pathway between having diabetes and receiving an amputation indicates ulcer formation as the primary relationship [2]. The mechanisms behind ulceration are not well understood; however, computational modeling combined with cadaver studies can help bring an increased understanding to these mechanisms. The goal of this research is to investigate a quasi-linear viscoelastic (QLV) model of ankle and foot ligaments for future implementation into a computational model of the lower extremity. Eventually, a comprehensive computational model will illustrate mechanisms that cause ulceration unique to diabetes.

Methodology

Experimental Procedure. Five foot-ankle cadavers were obtained, and the following bone-ligament-bone specimens were harvested from each cadaver: inferior calcaneonavicular (ICN), long plantar (LP), plantar first-cuneiform first-metatarsal (PFCFM), and posterior tibiotalar (PTT). LP was not harvested beyond its initial insertion into the cuboid. Ligaments were potted in polymethylmethacrylate and tested on an MTS Materials Testing System (MTS Systems Corporation, Eden Prairie, MN). Specimens were preconditioned to maximum passive physiologic strain, an average 10.5%; afterward, stress relaxation tests were performed. A ramp and hold was performed, where ligaments were deformed at 1 mm/s to the preconditioned strain, then held for 300 seconds.

Quasi-linear Viscoelastic Model. Several variations of QLV have been used to model ligaments [3-6]. The variant used for this study has been described in Ledoux [7]. Stress is modeled as a time-history and strain dependent function. Stress is defined by six parameters. A and B are elastic coefficients, C_1 is the amplitude of viscous effects, C_2 is the rate of change of amplitude, whereas τ_1 and τ_2 represent the low frequency and high frequency limits respectively.

Nonlinear Curve Fit. The parameters A, B, C_1, C_2, and τ_1 were fit using the nonlinear Levenberg-Marquardt least-squares optimization routine of Igor Pro (WaveMetrics, Inc., Lake Oswego, OR). The parameter τ_2 was set to the final time-point. Stress and strain data were averaged over the number of feet prior to parameter optimization.

Results

Figure 1 shows a relaxation fit of the PFCFM ligament, where confidence and prediction bands were calculated at 95% confidence. This fit is representative of the other ligaments. Table 1 lists the parameters from the curve fit of all the ligaments, as well as the reduced chi-square Goodness of Fit value.

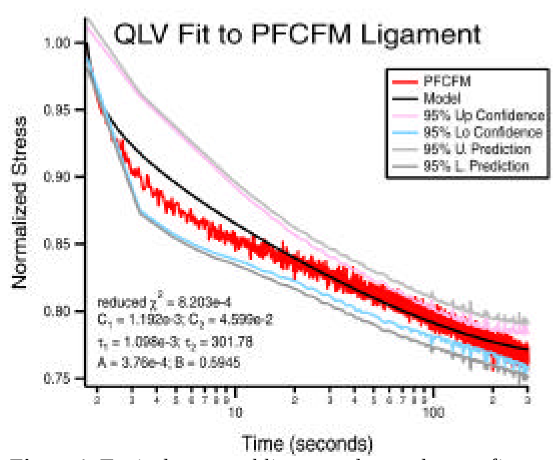

Figure 1: Typical averaged ligament data and curve fit.

Table 1: Relaxation curve fit data

	ICN	PTT	LP	PFCFM
C_1	4.06e-3	8.00e-2	3.50e-3	1.19e-3
C_2	3.26e-2	1.00e-3	2.86e-2	1.00e-3
τ_1	6.10e-4	1.00e-3	3.88e-2	1.10e-3
τ_2	301.86	303.3	301.84	301.78
A	1.87e-3	1.26	5.03e-2	3.76e-4
B	1.53	10.0	5.47	0.595
N	4	5	5	5
Red. χ^2	5.43e-3	1.14e-2	2.69e-3	8.20e-4

Discussion

The reduced chi-square values listed in Table 1 were all less than one, indicating successful fits with QLV. This work is an initial step to understanding foot biomechanics. Future work will involve accommodation of greater ligament diversity within the foot-ankle complex, and the classification of ligaments based on area-length ratios. Future work will also involve comparison with two other nonlinear constitutive models for ligament behavior, the Weibull-based stress-stretch relationship developed by Hurschler [8] and a nonlinear three-element model composed of a nonlinear spring in series with a nonlinear Voigt body.

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