# VISCOELASTIC MODELS FOR PREDICTING FORCE RESPONSE OF PROSTHETIC FOOT COMPONENTS

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## Introduction

A typical transtibial prosthesis system consists of a socket, pylon, connection hardware, and a prosthetic foot system. The latter is comprised of a keel (the underlying structural component) and a footshell (cover). Critical to design improvement in these devices is an ability to predict energy storage and loss during activity. Recent studies of energy management in non-actuated (passive) prosthetic feet have developed new approaches to the analysis and testing of these deformable systems [1,2]. However, the mechanical behaviour of polymeric prosthetic feet is time-dependent and often non-linear. While viscoelastic theory has been used to model non-linear elastic and viscous behaviour of materials used in these devices, such methods have had limited application to whole structures.

## Methods

The specific objective of this study was to compare empirical models for the force-displacement and time-dependent relaxation response of a foot prosthesis during maximum forefoot loading. Two material models were adapted for structural analysis: the standard linear solid (SLS) model proposed by Geil, *et al.* [3]; and the quasi-linear viscoelastic (QLV) model proposed by Fung [4].

Experimental analysis was performed on the Niagara Foot keel, a dynamic-response passive prosthetic foot system made of a thermoplastic polymer [5]. Two phases of mechanical testing were performed at specific loads and shank angles using the system shown in Figure 1. A ramp-and-hold test was used to extract model parameters and a cyclic testing protocol was used to validate model predictions.

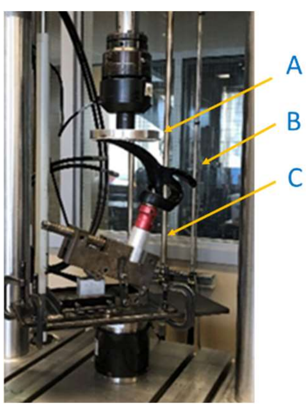


***Figure 1: NFK assembled for testing in MTS Bionix™ Model 370.02 Universal Testing Machine.*** ***A****: Test platen with low-friction surface simulating ground contact. Platen descends vertically under displacement control while force is measured.* ***B****: Prosthetic component (Niagara Foot M2 V22) fixed to standard pyramid adapter.* ***C****: Positioning vice to orient prosthesis to shank angle based on ISO 10328 [6].*

Three parameters (*Q,R,S*) for were extracted for the standard linear solid model (Equation 1) and nine ($P_1, P_2, P_3, A, B, C, D, E, F$) for the QLV model (Equation 2) by minimizing least squared residuals. These parameters were then used to numerically integrate cyclic displacement functions, $x(t)$, to predict expected force responses, *F(t),* in the validation tests.

***(1) SLS Model:***

$$Y(t) = Q + Re^{-St}$$

$$\text{where } F(t) = \int_0^t Y(t-\tau)\frac{\partial x(\tau)}{\partial \tau}\,d\tau$$

***(2) QLV Model:***

$$F^e(x) = P_1x^3 + P_2x^2 + P_3x$$

$$G(t) = Ae^{-Bt} + Ce^{-Dt} + Ee^{-Ft}$$

$$\text{where } F(t) = \int_0^t G(t-\tau)\frac{\partial F^e_{x(\tau)}}{\partial x}\frac{\partial x(\tau)}{\partial \tau}\,d\tau$$

## Results and Discussion

Typical normalized force-relaxation results are shown in Figure 2a. In all cases, the QLV model showed a better fit than the SLS model due to the presence of multiple time constants in the reduced relaxation response, *G(t)*.

Similarly, non-linear force-deflection responses were better fit by the QLV cubic model, $F^e(x)$ (Figure 2b).

The QLV model predicted a reasonably accurate dynamic force response of the during loading (±7.4N) and unloading phases (±14N) when subject to a axial displacement of 15 mm (Figure 2c). However, the method was inaccurate in predicting the response of the system during loading (±50N) and unloading (± 31N) when subject to axial displacements greater than 15 mm.

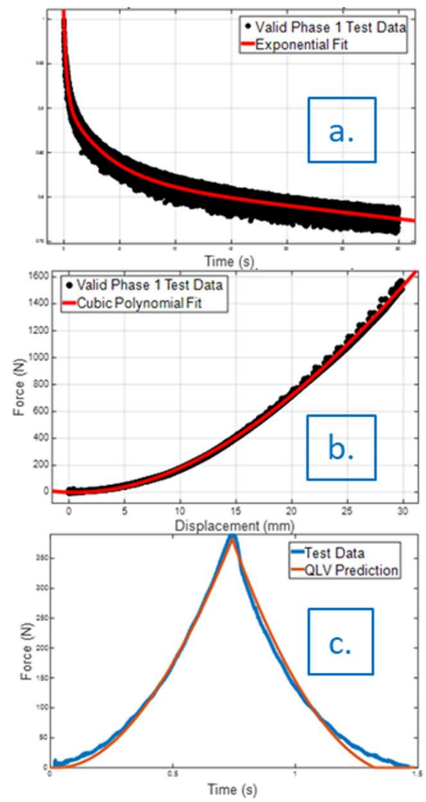


***Figure 2: Parameter Extraction and Validation for QLV Model.***

## Significance

QLV modelling methods reasonably predict the loading response of a typical prosthetic foot but lack of agreement in the unloading phase may limit their application. As such, comprehensive finite element models may produce better results when predicting energy management in these systems.

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## References

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