STRUCTURAL PROPERTIES AND VISCOELASTIC MODELING OF DYNAMIC ELASTIC RESPONSE PROSTHETIC FEET

Mark D. Geil

Health and Performance Sciences, Georgia Institute of Technology, Atlanta, Georgia
Email: mark.geil@oip.gatech.edu

INTRODUCTION

Dynamic Elastic Response (DER) prosthetic feet are designed to assist the lower-limb amputee by storing energy in the stance phase of gait and returning a portion of that energy at toe-off to assist in limb progression. Since the introduction of a very few DER designs in the mid-1980s, the number of manufacturers and designs has expanded rapidly.

Several articles compare kinematic, kinetic, and metabolic parameters of various DER feet in gait. Few articles compare material and structural properties. This project compared structural properties and employed a new viscoelastic modeling technique to objectively compare 11 different conventional and DER prosthetic feet independent of the amputee.

METHODS

Material tests of prosthetic feet were performed on an Instron (Canton, MA) 8521 Servohydraulic Material Testing Machine. The feet tested represent the majority of prosthetics prescriptions for prosthetic feet and included multiple samples of: Seattle Voyager and Lightfoot, College Park TruStep, Ohio Willow Wood Carbon Copy HP, Kingsley Steplite Flattie and Steplite Strider, Otto Bock Dynamic Plus, and the Flex Foot Variflex.

Sinusoidal cyclic loading tests were conducted at 1 Hz. Constant strain rate tests were conducted at strain rates of 0.1 mm/sec, 1 mm/sec, and 10 mm/sec. Stress-relaxation and creep tests were also conducted. Feet were tested to a maximum of 800 N, based on recommendations for fatigue testing by Toh, et al. (1993) and results for vertical propulsive force in Arya, et al. (1995).

Each foot was connected to the Instron machine using a custom-machined device with a standard inverted pyramid adapter. The tests were performed with each foot placed at the maximum plantarflexion allowed by the inverted pyramid. Two sheets of Teflon were placed on the testing surface to minimize friction.

Data were analyzed using a program previously developed by Geil et al. (1997) to determine the viscoelastic model coefficients. Each foot was modeled as a Standard Linear Solid (SLS) consisting of a series spring and damper connected in parallel with a second spring. Spring and damper coefficients were determined using differential equation solutions found in Wang et al. (1997). Data from creep, stress-relaxation, and constant strain rate tests were compared to predicted values from these equations, and the root mean square (RMS) error was calculated. Total RMS for each test was minimized by iteratively changing the SLS model coefficients.

RESULTS AND DISCUSSION

Tests revealed marked differences in structural properties of prosthetic feet both in stiffness and viscoelasticity. Each foot tested in cyclic loading revealed energy loss due to hysteresis. The feet varied in stiffness and required different testing amplitudes to achieve the 100 N minimum and 800 N maximum in the cyclic testing.

Energy was calculated as the integral of force versus displacement. The College Park feet showed the greatest loading and unloading energy, and the Flex foot showed the least. Hysteresis was calculated as the difference in loading energy (input energy) versus unloading energy and as a percentage of input energy. The College Park feet showed the largest percentage loss, and the Otto Bock and Kingsley feet showed the least (Fig. 1). Percentage loss and actual energy loss in Joules were generally correlated, but the Flex foot showed the fifth highest percentage loss with the lowest actual energy loss.

Average total RMS error for actual results versus predicted results was 0.0105. The most accurately modeled feet were the SACH (0.004341). The least accurate were the Flex foot (0.0281) and the College Park feet (0.0176). This indicates that the SLS model might not be as appropriate for the

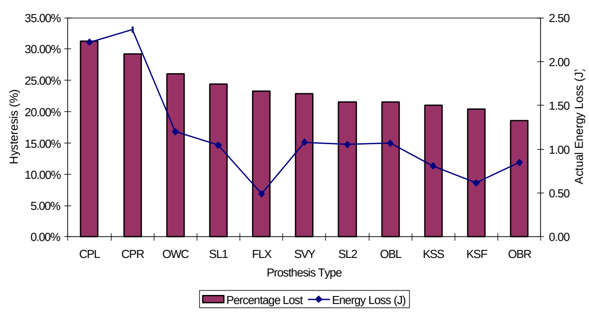

Figure 1: Amount of energy loss (J, line) and energy loss expressed as a percentage of input energy (vertical columns) for each foot under 1 Hz sinusoidal loading between 100 N and 800 N.

Flex and College Park feet. The highest parallel spring coefficient was found on the only pediatric foot tested, a Seattle Light (SL1). Only the Flex foot showed a higher series spring stiffness than parallel, suggesting again that this foot might require a different viscoelastic model. Although the College Park feet showed the greatest energy loss, they also showed the smallest damping coefficients, also indicating the possibility of an inappropriate model.

Amputees use the structural properties of DER feet differently in gait. The measured hysteresis and viscoelastic properties are independent of variations in loading rates, frequencies, and amounts and will be useful in evaluation of functional gait results to determine how much of the measured parameters might be due to inter- and intra-subject variation. Furthermore, analysis of such variation and its effects on the function of each foot will provide valuable design insight. These material and structural property results should be coupled with an extensive functional gait analysis of each foot.

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ACKNOWLEDGMENTS

This work was supported by the Atlanta VA Rehab R&D Center. The generous donation of prostheses from each manufacturer is appreciated.