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Mechanical Properties of Shock-Absorbing Pylons Used in Transtibial Prostheses

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Prosthetic manufacturers have developed shock-absorbing pylons to attenuate the transient forces of foot-ground contact in order to supplement the residual capacity of lower limb amputees. The purpose of this study was to measure the elastic and damping properties of two frequently prescribed pylons (the ICON™ Shock Pylon and the Mercury TT Pyramid Pylon) at frequencies enveloping those observed during gait using pseudo-static compressive and dynamic cyclic testing methods. Results showed that the spring constants were linear functions of deformation (ranging from 74 to 110 N/mm and 91 to 157 N/mm for the ICON and the TT Pylons, respectively) while the damping force was a function of the square root of velocity combined with a coulomb element ($1.6\dot{x}^{0.5}+21$ *and* $7.4\dot{x}^{0.5}+102$ *N for the ICON and the TT Pylon, respectively).* [DOI: 10.1115/1.1645865]

Introduction

Transient forces arising from foot-ground contact have been implicated in the initiation and progression of osteoarthritis [1,2], low back disorders [3], and injuries related to muscle tears, stress fractures, and skin ulcers [4,5]. Interventions that attenuate these transient forces, specifically shoe insoles, have been shown to reduce the incidence of injuries in intact individuals [6,7]. Lower limb amputees, who by definition have reduced shock-absorbing capacity, may be prescribed prosthetic components such as shock-absorbing pylons (SAPs) that are intended to supplement their residual ability. Unfortunately, little is known about the efficacy and performance of shock-absorbing pylons.

The purpose of this study was to measure elastic and damping properties of two commonly prescribed shock-absorbing pylons at frequencies enveloping those observed during walking gait [8]. When coupled with forthcoming outcome measures identifying amputees' mobility, level of fatigue and pain, and perceived prosthesis comfort as a function of componentry, the results of this study will provide the engineering-based explanations to support observed outcomes.

Materials and Methods

Prosthetic manufacturers have developed SAPs that, in contrast to conventional rigid pylons, allow for axial energy dissipation. Only translational energy dissipation, in the long axis of the pylon, was considered in this study. Using prescription frequency at the Veterans Affairs Puget Sound Health Care System (VAPSHCS; Seattle, WA) as a guideline, two SAPs were selected for testing: the ICON™ Shock Pylon (Ossur, Reykjavik, Iceland) and the Mercury™ TT (Telescopic Torsion) Pyramid Pylon (Chas A. Blatchford & Sons, Ltd., Hampshire, England, UK). Each pylon can be configured by a prosthetist with the appropriate die compression spring based upon the amputee's weight and activity level. For this study, four ICON pylons were each outfitted with one of the manufacturer's four stiffest springs (in order of increasing stiffness; i4, i5, i6, and i7) and three TT Pylons with one of the three available springs (in order of increasing stiffness; Purple, White, and Black) to reflect the somewhat heavier body mass of VAPSHCS patients [9,10].

Pseudo-static compressive testing was performed with an MTS (Model 858 Bionix™; MTS System Corporation, Eden Prairie, MN), in displacement control, to determine spring constant values. A constant deformation rate of 0.5 mm/s, starting at the unloaded state (0 mm) and ending near the maximum displacement (15 mm or 12.5 mm for the ICON and TT Pylons, respectively), followed by a return to the unloaded state was applied to each pylon. Force and displacement measurements were sampled at 20 Hz with a 16-bit data acquisition board. A least squares linear fit

Table 1 Dynamic cyclic testing protocol

Frequency (Hz)	Step Size (Hz)	Peak-to-peak Displacement (mm)
0.1, 0.5–4	0.5	9
5–15	1	3
16–25	1	2
26–55	1	1
60–100	5	1 (except i5, 0.5)

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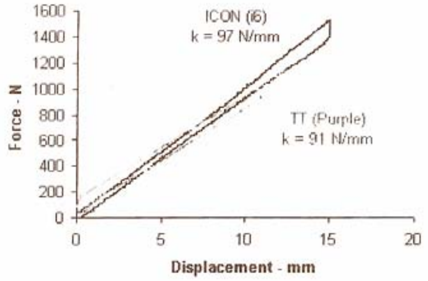

Fig. 1 Typical force versus displacement loading and unloading curves for the ICON and TT Pylon. The ICON was outfitted with an i6 spring and the TT Pylon with a Purple spring.

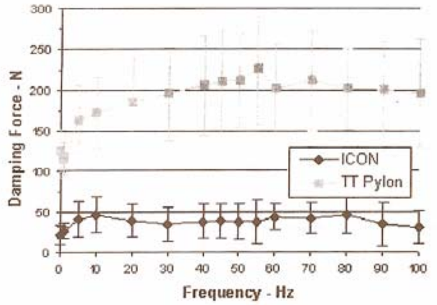

Fig. 2 Damping force versus frequency for the ICON (n=4, mean ± S.D.) and TT Pylon (n=3, mean ± S.D.). Trend lines, R^2 values, and equations represent the result of a least squares linear fit of each data set.

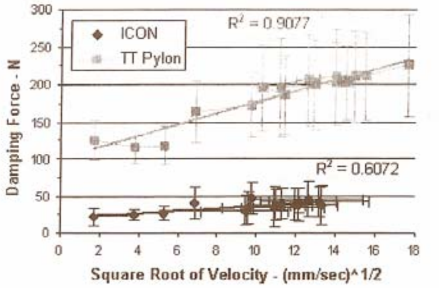

Fig. 3 Damping force versus square root of velocity for ICON (n=4, mean ± S.D.) and TT Pylon (n=3, mean ± S.D.)

of the force versus displacement loading and unloading curves was used to quantify each pylon spring constant (k).

Dynamic cyclic testing was performed on an MTS (Model 810 High Rate), in displacement control, to determine damping constants and kinetic friction force values. Ten and a half haversine cycles (5 sinusoidal peaks), starting at either a 1 or 2 mm offset (pre-load), was applied to each pylon at the frequencies and peak-to-peak displacements listed in Table 1. Force and displacement measurements were sampled at at least 40 times the haversine frequency.

The pylon was modeled as a linear spring in parallel with both a frictional element and a nonlinear viscous damper. Steady state displacement at the midpoint of the upward stroke (typically from the 3rd sinusoid) and the corresponding force at each frequency tested were used to solve for the velocity at the midpoint displacement ($\dot{x}$). These values in combination with the linear spring constant were used in a lumped parameter model (Eq. (1)) to determine the damping constant (c) and the kinetic friction force (F_f) for each pylon.

$$F=kx+c\dot{x}^{0.5}+F_f \tag{1}$$

Results

The loading and unloading curves were linear over the displacement range for all the pylons tested (Fig. 1). The calculated spring constants for the ICON with i4–i7 springs were 74, 82, 97, and 110 N/mm, respectively. The calculated spring constants for the TT Pylon with Purple, White, and Black springs were 91, 114, and 157 N/mm, respectively.

Damping force as a function of frequency showed greater magnitude for the TT Pylon than for the ICON (Fig. 2). Damping force versus the square root of velocity (Fig. 3) revealed a reasonable curve fit for the TT Pylon ($R^2=0.9077$) but some un-modeled error for the ICON ($R^2=0.6072$). Table 2 contains the calculated damping constants, kinetic friction force values, and coefficient of friction values for the ICON and TT Pylon. The coefficient of friction values for each pylon were obtained from the manufacturer (TT Pylon) or the manufacturer of the sliding surfaces (ICON) using data from bench top situations replicating the sliding surfaces as closely as possible [11,12]. The damping constant and kinetic friction force for the TT Pylon were almost five times those of the ICON, while the estimated coefficient of friction for the ICON's sliding surfaces was 2.5 times that for the TT Pylon's sliding surfaces.

Discussion

The mechanical testing methods outlined in this paper utilized pseudo-static compressive and dynamic cyclic approaches to characterize two commercially available shock-absorbing pylons. The pseudo-static compression tests generated parallelogram-shaped hysteresis loops and showed that each pylon/spring combination had linear elastic properties throughout the tested displacement ranges. Only the TT Pylon spring constant values are available from the manufacturer; the values presented here are 16, 5.6, and 14% different from those of the manufacturer for the Purple, White, and Black springs, respectively [10]. Differences in the spring constant values could be attributed to differences in the manufacturing lots and/or testing methodologies. The TT Pylon

Table 2 Damping constants, kinetic friction force values, and coefficient of friction values for the ICON and TT Pylon

Pylon	Damping Constant ($N/\sqrt{mm/s}$)	Kinetic Friction Force (N)	Coefficient of Friction (Dimensionless)
ICON	1.6	21	0.20
TT Pylon	7.4	102	0.08

exhibited larger damping force over the frequency range of walking gait than the ICON, and each pylon has a trend of increasing damping with an increase in velocity. Although the curve fit of the ICON's damping force is not an ideal approximation, a compromise in model simplicity versus fitness was reached with the particular nonlinear model chosen.

A limitation of this study was that the pylons were tested under axial loads instead of the typical combination of axial loads, bending moments, and rotational moments experienced during locomotion. Testing under only axial loads could have underestimated the measured kinetic friction force. However, the multi-axial loading experienced by the SAPs during walking is extremely difficult to simulate in vitro. Human subject in vivo testing, while allowing observation of actual performance under multi-axial loading conditions, is time intensive and expensive requiring large sample populations due to the inherent variability within and across subjects.

The results presented here can be compared with the mechanical testing results of a different SAP, namely the Re-Flex Vertical Shock Pylon (VSP). Miller and Childress [13] used similar pseudo-static test methods to obtain spring constants for two Re-Flex VSPs, one recommended for a 61 kg subject and the other for an 82 kg subject, of 49.4 and 91.4 kN/m, respectively. Their dynamic testing approach used a free response technique where a step unloading was simulated to obtain a damping ratio for each pylon. Resonance frequencies of 21.3 and 23.9 Hz and pylon damping ratios of 0.2897 and 0.3844 were calculated for the two SAPs.

Miller and Childress recognized the limitation of their model and implied it might only be useful for predicting the response at the resonant frequency. In this current study, the spring constants for the ICON and the TT Pylon were calculated and shown to be fairly linear over the displacement range tested. Damping force was shown to be a function of the square root of velocity and contains a coulomb element.

Conclusions

The objective of this study was to measure the spring and damping properties of two commonly prescribed SAPs at frequencies enveloping those observed during human locomotion. Testing was done using two different testing protocols: pseudo-static compressive and dynamic cyclic testing. Spring constant values for the pylons tested were linear across the displacement range. Both pylons tested had increasing damping related to an increase in the square root of velocity, while the TT Pylon produced larger damping forces than the ICON across the frequency range of gait. Coefficient of friction values were estimated from manufacturers' data with the ICON's 2.5 times greater than the TT Pylon's. When coupled with a forthcoming outcomes study identifying amputees' mobility, fatigue, pain, and perceived level of comfort as related to prosthetic componentry, the results from this study will facilitate the understanding of these measures with engineering-based explanations.

Acknowledgments

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References

[1] Radin, E. L., Orr, R. B., Kelman, J. L., Paul, I. L., and Rose, R. M., 1982, "Effect of Prolonged Walking on Concrete on the Knees of Sheep," J. Biomech., **15**(7), pp. 487–492.
[2] Radin, E. L., Ehrlich, M. G., Chernack, R., Abernethy, P., Paul, I. L., and Rose, R. M., 1978, "Effect of Repetitive Impulsive Loading on the Knee Joints of Rabbits," Clin. Orthop., **131**(March–April), pp. 288–293.
[3] Sandover, J., 1983, "Dynamic Loading as a Possible Source of Low-Back Disorders," Spine, **8**(6), pp. 652–658.
[4] Brand, P. W., 1988, *Repetitive Stress in the Development of Diabetic Foot Ulcers*, C. V. Mosby and St. Louis, MO, pp. 83–90.
[5] Whittle, M. W., 1999, "Generation and Attenuation of Transient Impulsive Forces Beneath the Foot: A Review," Gait Posture, **10**(3), pp. 264–275.
[6] Schwellnus, M. P., Jordaan, G., and Noakes, T. D., 1990, "Prevention of Common Overuse Injuries by the Use of Shock Absorbing Insoles. A Prospective Study," Am. J. Sports Med., **18**(6), pp. 636–641.
[7] Smith, W., Walter, Jr., J., and Bailey, M., 1985, "Effects of Insoles in Coast Guard Basic Training Footwear," J. Am. Podiatr Med. Assoc., **75**(12), pp. 644–647.
[8] Gillespie, K. A., and Dickey, J. P., 2003, "Determination of the Effectiveness of Materials in Attenuating High Frequency Shock During Gait Using Filterbank Analysis," Clin. Biomech. (Bristol, Avon), **18**(1), pp. 50–59.
[9] Anonymous, 1999, "ICON™ Shock Pylon," TI 040 Rev. C, Flex-Foot, Inc., Aliso Viejo, CA.
[10] Anonymous, 1999, "Fitting Instructions TT (Telescopic Torsion) Pyramid Pylon," 938061/04-1198, Chas A Blatchford & Sons, Ltd., Hampshire, England, UK.
[11] Cativo, J. J., 2002, "Email Regarding ICON's Coefficient of Friction," Personal Communication, February 26, 2002, Saint Gobain Performance Plastics, Bristol, RI.
[12] Smart, C., 2002, "Email #2 Regarding the TT Pylon," Personal Conversation, February 21, 2002, Chas A Blatchford & Sons, Ltd., Hampshire, England, UK.
[13] Miller, L. A., and Childress, D. S., 1997, "Analysis of a Vertical Compliance Prosthetic Foot," J. Rehabil. Res. Dev., **34**(1), pp. 52–57.

Preparation of On-Axis Cylindrical Trabecular Bone Specimens Using Micro-CT Imaging

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The Orientation of trabecular bone specimens for mechanical testing must be carefully controlled. A method for accurately preparing on-axis cylindrical specimens using high-resolution micro-CT imaging was developed. Sixteen cylindrical specimens were prepared from eight bovine tibiae. High-resolution finite element models were generated from micro-CT images of parallelepipeds and used to determine the principal material coordinate system of each parallelepiped. A cylindrical specimen was then machined with a diamond coring bit. The resulting specimens were scanned again to evaluate the orientation. The average deviation between the principal fabric orientation and the longitudinal axis of the cylindrical specimen was only $4.70\pm 3.11^\circ$*.*
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Keywords: Trabecular bone, Orthotropy, Mechanical testing

Introduction

Trabecular bone is anisotropic in both modulus [1,2] and strength [3,4]. Due to this anisotropy, mechanical testing must be performed along the principal elastic directions of the trabecular structure. Otherwise the results of measurements will be influenced by material constants associated with multiple material directions [5,6]. For a deviation of 10°, the average errors for Poisson's ratios and Young's moduli can be 12% and 9% respectively for trabecular bone from human tibiae [5].

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