DEVELOPMENT OF A LOW-COST PROSTHETIC SWING-PHASE MECHANISM

Alex Furse, Tony Liang, William Cleghorn and Jan Andrysek
The Institute of Biomaterials and Biomedical Engineering, University of Toronto,
Mechanical and Industrial Engineering, University of Toronto,
& Bloorview Research Institute, Bloorview Kids Rehab

INTRODUCTION

Developing countries have very high rates of amputation for many reasons; poor health care, sub-standard working conditions and unsafe methods of transportation can all lead to significant injury resulting in the loss of a limb. [1] Current and past zones of conflict exacerbate the issue since injuries from combat and residual land mines further increase the number of amputations. Disabilities are often amplified in developing countries where health care and infrastructure may not be sufficient to accommodate those with disabilities. In developing countries, an estimated three to four million people require prostheses [1]. A low-cost, highly-functional prosthetic knee joint, combined with an adequate distribution network and clinical/technical support could help many of those in need.

A number of accessible low-cost prosthetic devices have been developed, although, most only provide basic function and lack technology that assist the patient during swing-phase. A prosthetic swing-phase mechanism simulates the action of the upper leg musculature to aid in improved gait function. More specifically, swing-phase mechanisms limit the maximum knee flexion and allow the shank to smoothly decelerate into full extension without impact. [2] Without swing-phase control, numerous gait deviations can result, increasing energy demands and gait asymmetry. [3]

Various systems have been developed to mimic the action of muscles that act about the knee. Swing-phase control mechanisms typically consist of friction or damping control, extension assist and an extension cushion. Extension assist usually takes the form of a mechanical spring while damping is produced by a pneumatic or hydraulic cylinder. These devices attempt to generate moments about the knee to cause the shank-foot to swing through space with a motion pattern which approximates that of an average able-bodied person. [2] Figure 1 displays knee moment patterns of three setups including a friction only system, a spring with friction system and a hydraulic system.

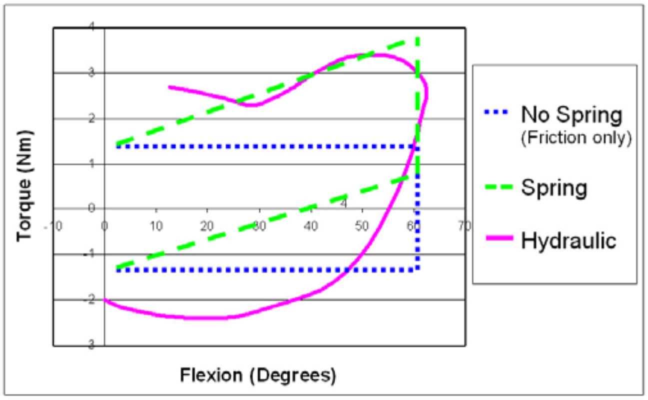

Figure 1: Swing-Phase Control Mechanisms Knee Moment Patterns

Although pneumatic and hydraulic units approximate normal gait closely, they are expensive and require ongoing maintenance. [4] This is an issue for patients in developing countries who often live in rural areas and have to travel great distances to reach prosthetic repair centres. Furthermore, failure of hydraulic knees can be difficult to asses by the patient and early detection is challenging. Failures in hydraulic knee units can result in oil leakage and loss of support, bringing about embarrassing and dangerous situations for the amputee. [5]

Numerous studies have been published focusing on the assessment of swing-phase control mechanisms. Most of these studies focus on the performance of hydraulic and pneumatic systems and their ability to allow users to walk efficiently over a range of speeds. [4, 6] The primary objective of this study was to show that low-cost swing-phase technology can help improve gait function by allowing patients to achieve faster gait, lower heel-rise and a more symmetrical gait, and decreased terminal impact. Furthermore, we aim to gain quantitative data about the gait deviation associated with terminal impact. Several publications recognize the negative effects of terminal impact on amputees, [7-9] although only a small number of studies have attempted to evaluate it [10,11], and none specifically by quantifying the impact accelerations.

METHODOLOGY

The Design

The low-cost prosthetic knee to be evaluated in this study was developed by Bloorview Research Institute (BRI). The low-cost knee (LC Knee) is based on a single-axis mechanism composed of injection moldable polymers. [12] Unlike other low cost devices, the prosthetic knee's novel stance phase locking technology allows users to attain higher levels of function while maintaining stability. As shown in figure 2, the LC Knee utilizes three mechanisms to achieve swing-phase control.

Figure 2: LC Knee Swing-Phase Control Mechanisms

Tightening the nut on the bolt that passes through the center of the knee axis enables adjustment of the compression between the knees articulating faces thereby allowing friction control. The elastomeric bumpers reduce impact between the knees contact surfaces at the end of swing-phase. The spring system helps in reducing maximum flexion and assists swinging the shank forward during extension. The LC Knee can be setup with one of two spring systems. One consists of a single compression spring, and the other is composed of a novel dual spring system. The dual spring system utilizes two springs in series with different spring coefficients to better approximate the action of the leg musculature during flexion and extension.

Computational Model and Mechanical Testing

A computation model developed at the Bloorview Research Institute was used to simulate the action of the LC Knee. The program coded in Matlab was executed to optimize the mechanical swing-phase control of the LC Knee by matching it as best as possible to previously attained prosthetic hydraulic knee moment data. [13] These data were obtained using a kinematic simulator that mechanically simulated the action of swing-phase using gait lab data collected from an above-knee amputee. The kinematic simulator setup can be seen in figure 3. The amount of flexion was controlled by altering the sinusoidal drive linkage. Changing the voltage input to the motor allowed control of the rotational speed thereby setting the frequency at which the prosthetic knee flexes and extends. The kinematic simulator outputs, torque and position, were used to plot knee torque vs. flexion graphs. The computational model then predicted spring constants and friction levels for both the single and dual spring systems that most closely matched the hydraulic knee moment data by the root mean square deviation method.

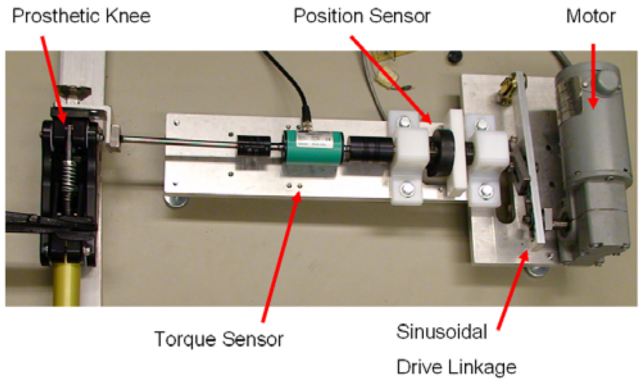

Figure 3: Kinematics Simulator

A friction control knob for the LC Knee was created to allow more precise control of the friction levels during clinical testing. By tightening the knob to set incremental values and looking at the subsequent changes in torque output from the kinematics simulator, we were able to establish two levels of friction, low (0.75Nm) and high (1.5Nm), for the clinical testing.

Clinical Testing

To validate the results of the computational model clinical testing with an above-knee amputee was completed. The subject was 18 years old, weighed 72.5 kg and was 177 cm tall. The amputee was fitted with a LC Knee and allowed to use the leg for at least a month prior to testing. Ethics for the study was approved by the Bloorview Research Ethics Board. The clinical testing included a series of 20-meter walk tests utilizing a mobile computer setup connected to goniometers (Biometrics Ltd. SG150) and an accelerometer (Silicon Designs Inc. 25G) mounted on the sound and prosthetic limbs. The goniometers measured knee flexion angle and time and the accelerometer measured terminal impact accelerations. The participant completed twenty trials with different low-cost swing-phase setups at two walking speeds. The setups included changing friction levels, incorporating a secondary extension bumper and incorporating five different spring systems (No Spring, Single Spring, Single Stiff Spring, Dual Spring and Dual Stiff Spring) on gait and prosthetic performance.

RESULTS

Computational Model and Mechanical Testing

The program recommended spring constants and friction levels at the two walking speeds for both spring systems to be used in the clinical testing. Table 1 displays a summary of the optimized output.

Table 1. Computation Model Output Summary

Spring System	Walking Speed	Spring Constant (N/m)	Friction (Nm)
Single	Self Selected	5000	1.4
	Fast Walk	7500	1.8
Dual	Self Selected	1500 & 19500	1.4
	Fast Walk	3500 & 19500	1.8

Figure 4 illustrates the torque vs. flexion curves of the optimized single and dual spring systems at self selected walking speed. The program results confirmed the hypothesis that a dual spring system could better match the torque curve of a hydraulic system when the root mean square deviation was minimized. The dual spring system with the 1500 N/m and 19500 N/m springs performed best when considering both self selected and fast walk walking speeds.

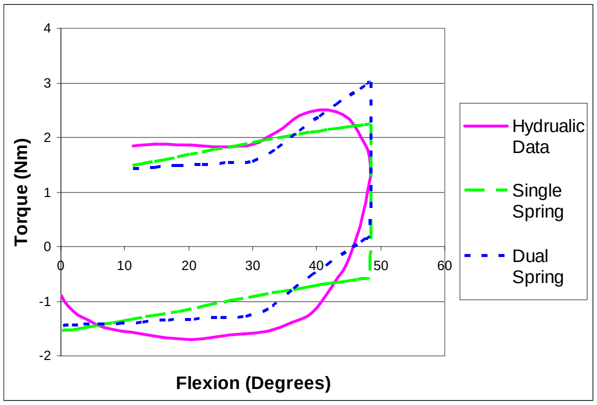

Figure 4: Program Output - Optimized Spring Systems

Clinical Testing

It is apparent from the results of this study that swing-phase mechanisms greatly aid in improving gait. On average the participant attained a 9% increase (0.2 m/s) in velocity when a spring system was integrated. Maximum flexion decreased on average by 11% (10 degrees) to provide more normal kinematics. As shown in figure 5, adding swing-phase control mechanisms significantly improved gait symmetry (shown in terms of the gait symmetry index [14]) by reducing prosthetic heel-rise to better match the intact limb. Incorporating spring systems reduced terminal impact on average by 14% (3 g) while removing the secondary elastomeric bumper resulted in the largest terminal impact accelerations, with a 17% (4 g) decrement.

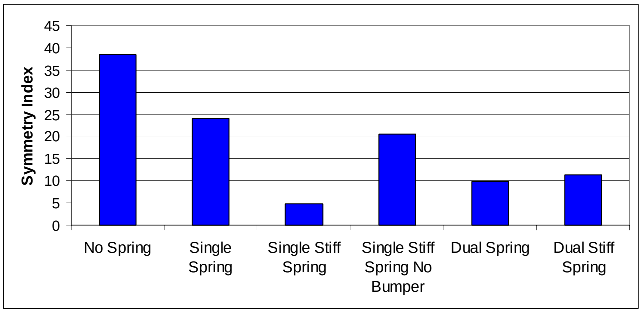

Figure 5: Spring System Evaluation – Gait Symmetry

Comparing the spring systems it is clear that the dual spring systems were best overall. The dual spring systems allowed the participant to achieve high walking velocities with low maximum flexion values and were most effective at reducing terminal impact. The stiff dual spring system enabled the highest walking velocities at 1.34 m/s for self selected and 1.71 m/s for fast walk. For the self-selected walking speed with low friction condition, the less stiff dual spring system reduced terminal impact by 38% compared to the no spring setup, 14% better than the single spring systems. (see figure 6)

It is evident from the study results that friction also plays a pivotal role in enhancing gait characteristics. The high friction condition resulted in both lower maximum flexion and terminal impact while enabling the user to maintain high walking velocities. As shown in figure 6, when friction was increased the stiff dual spring system performed best.

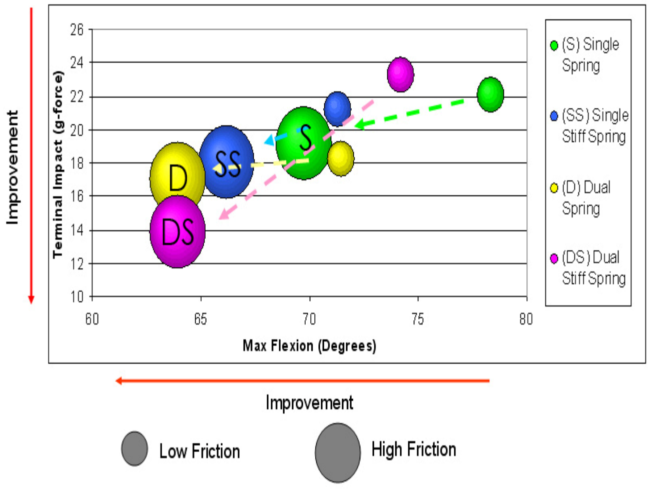

Figure 6: Spring System Evaluation – Friction

DISCUSSION

Increased walking velocity is a common goal of many areas of rehabilitation, as it is considered indicative of overall improvements in mobility function. [15, 16] Increased gait velocity is also associated with higher-end prosthetic components. [17, 18] The swing-phase control mechanisms allowed the user to attain higher velocities, more symmetrical gait, decreased unwanted heel-rise, and reduced terminal impact.

The dual spring system, two springs in series, as predicted by a computational model out-performed the single spring system. The dual spring system's greatest improvement was in lowering terminal impact. This is achieved by the deactivation of the stiff spring and activation of the less stiff spring during the last 20 degrees of swing before full knee extension that allows the shank to decelerate and hit the bumper at a lower velocity. (see figure 7) Providing sufficient shock absorption to amputees through the addition of specialized prosthetic components, such as shock absorbing pylons, has been shown to increase comfort, gait performance and prevent joint and back problems in the long-term. [19] Therefore, the same benefits may be realized by reducing terminal impact.

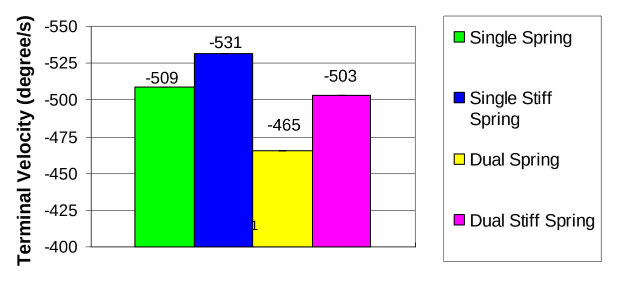

Figure 7: Average Terminal Velocity

As hypothesized, incorporating friction and a spring system resulted in improved gait function. The new dual spring mechanism is simple, improves prosthetic function, and is ideal for use in low-cost and peadiatric prostheses, where size and cost may be constrained. Future work aims to apply a larger sample size to investigate the generalizability of these results.

ACKNOWLEDGEMENTS

The authors would like to thank
- The studies participant
- Staff at Bloorview Research Institute
- Prof. L. H. Shu and Prof. A. Mihailidis for their valuable insight

Funding for this project was supplied by NERSC, CIHR and the Bloorview Graduate Scholarship

REFERENCES

[1] D. Cummings, "Prosthetics in the developing world: a review of the literature," *Prosthet.Orthot.Int.* 20, 51-60, 1996.

[2] C. Radcliffe, "Above-knee prosthetics: The Knud Jansen Lecture", New York, 1977.

[3] N. Berger, "Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles," Chapter 14 - Analysis of Amputee Gait, Mosby-Year Book; 2 Sub edition, 1992.

[4] R. Whitesides, and T. Volatile, "Mauch S.N.S. Hydraulic Knee Units in Above-knee Amputees: A Long-term Follow-up Study," *Clinical Orthopedics*, 1985.

[5] J. Davenport, and C. Mechefske, "Experimental Investigation of the Decaying Performance of Hydraulic Knee Controllers," Victorian University of Technology, 1998.

[6] C. Stewart, "Swing phase and its Control in the Trans-Femoral Amputee," University of Strathclyde, September, 1995.

[7] M. Schuch, "Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles," Chapter 20 - Transfemoral Amputation: Prosthetic Management, Mosby-Year Book; 2 Sub edition, 1992.

[8] H. Uustal and E. Baerga, "Prosthetics and Orthotics," NCBI: Physical Medicine and Rehabilitation Board Review, Demos Medical Publishing, Inc., New York, 2004.

[9] G. Hunter and J. MacKillop, "Prosthetic fitting of adult lower limb amputees following trauma and peripheral vascular disease," *Current Orthopaedics*, 11, 275-280, 1997.

[10] S. Nakamura and S. Sawamura, HRC adjustable pneumatic swing-phase control knee, *Prosthetics and Orthotics International*, 2, 137-142, 1978.

[11] J. Andrysek, and S. Redekop, "Role of internal friction in the attenuation of terminal impact noise in above-knee prostheses," Bloorview Research Institute, Conference Paper

[12] J. Andrysek et al. "A new stance-phase controlled prosthetic knee joint for low-income countries." Proceedings of the 13th World Congress of the International Society for Prosthetics and Orthotics, Germany, 2010.

[13] J. Andrysek and G. Chau "A self-energizing electromechanical swing-phase controlled knee joint prostheses: Feasibility study," *IEEE Trans Biomed Eng*, 54(12):2276–83, 2007.

[14] Robinson, R., User of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. J. Manipulative Physiol. Ther. 10:172-176 (1987)

[15] E. Paap, N. van Der, P. Helders, and T. Takken, "Physiologic response of the six-minute walk test in children with juvenile idiopathic arthritis," *Arthritis Rheum* 53, 351-356, 2005.

[16] M. van Loo, M. Moseley, J. Bosman, R. de Bie, and L. Hassett, "Test-re-test reliability of walking speed, step length and step width measurement after traumatic brain injury: a pilot study," *Brain Inj.* 18, 1041-1048, 2004.

[17] D. Brooks, J. Parsons, J. Hunter, M. Devlin, and J. Walker, "The 2-minute walk test as a measure of functional improvement in persons with lower limb amputation," *Arch Phys Med Rehabil*. 82, 1478-1483, 2001.

[18] D. Brooks, , J. Hunter, J. Parsons, E. Livsey, J. Squirt, and M. Devlin, "Reliability of the two-minute walk test in individuals with transtibial amputation," *Arch Phys Med Rehabil*. 83, 1562-1565, 2001.

[19] R. Konz and S. Gard, "The effect of a shock-absorbing pylon on the gait of persons with unilateral transtibial amputation," *Journal of Rehabilitation Research and Development*, Vol. 40, No. 2, 109–124, 2003.