

Direct measurement of plantarflexion resistive moments and angular positions of an articulated ankle–foot orthosis while walking in individuals post stroke: A preliminary study

Toshiki Kobayashi^{1,2}, Michael S Orendurff¹, Madeline L Singer³, Wayne K Daly¹, Lucas S Lincoln¹, Fan Gao⁴ and K Bo Foreman³

Abstract

The plantarflexion resistive moments of an articulated ankle–foot orthosis play an important role in improving gait in individuals post stroke. However, the evidence regarding their magnitude required from the articulated ankle–foot orthosis to improve walking is still limited. Therefore, the primary aim of this study was to directly measure the plantarflexion resistive moments and the joint angular positions while walking using a prototype instrumented articulated ankle–foot orthosis in five individuals post stroke. The secondary aim was to investigate their moment–angle relationship by changing its preset plantarflexion stiffness. Each subject was fitted with the instrumented articulated ankle–foot orthosis and walked on a treadmill under four different preset plantarflexion stiffness conditions (0.35 N·m/°, 0.51 N·m/°, 0.87 N·m/°, and 1.27 N·m/°). For each subject, the plantarflexion resistive moments and the joint angular positions of five continuous gait cycles were extracted and averaged for each condition. Data were plotted and presented as case series. Both plantarflexion resistive moments and joint angular positions of the ankle–foot orthosis changed according to the preset plantarflexion stiffness in all subjects. Using the instrumented articulated ankle–foot orthosis could potentially advance the understanding of the biomechanics of an ankle–foot orthosis, as well as contribute to more evidence-based orthotic care of patients.

Keywords

Ankle–foot orthosis (AFO), gait analysis, hemiplegia, orthotics, stiffness

Date received: 10 November 2015; accepted: 23 February 2016

Introduction

Ankle–foot orthoses (AFOs) improve gait in individuals post stroke.¹ Typically, they are classified as either articulated or non-articulated AFOs.² Articulated AFOs have joints, while non-articulated AFOs lack joints and are generally made of a single piece of material (e.g. plastics or carbons). One of the advantages of an articulated AFO is that certain types (e.g. AFO with oil-damper joint) have the benefit of being able to tune the plantarflexion resistive moment independent of dorsiflexion resistive moment.³ This characteristic is especially important when investigating the effects of a specific resistive moment generated from an AFO on kinematics and kinetics of gait.^{4–6}

The plantarflexion resistive moment of an articulated AFO plays an important role in achieving heel contact at the beginning of stance and foot clearance during swing in individuals post stroke.^{7,8} Preservation

¹Orthocare Innovations, Mountlake Terrace, USA

²Department of Prosthetics and Orthotics, Faculty of Health Sciences, Hokkaido University of Science, Sapporo, Japan

³Department of Physical Therapy, University of Utah, Salt Lake City, USA

⁴Department of Health Care Sciences, School of Health Professions, University of Texas Southwestern Medical Center, Dallas, TX, USA

Corresponding author:

Toshiki Kobayashi, Department of Prosthetics and Orthotics, Faculty of Health Sciences, Hokkaido University of Science, 7-15-4-1 Maeda, Teine, Sapporo, Hokkaido, 006-8585, Japan.

Email: kobayashi-t@hus.ac.jp; toshiki42@gmail.com



of heel contact using an AFO has been shown to provide improvements with gait.^{3,9} The plantarflexion resistive moment can be measured directly using a load cell that is integrated into a joint^{7,10} or indirectly using a three-dimensional motion analysis system and a bench measurement of a moment–angle relationship of an AFO.¹¹ The moment–angle relationship of an AFO has traditionally been measured statically on the bench.^{12–14} However, the bench measurements have generally overlooked influences of anatomical structures¹⁵ and the data regarding the relationship between the plantarflexion resistive moments and angular positions of an articulated AFO while walking are still very limited. This information would be valuable to understanding the mechanical contribution of the AFO in improving gait and for designing AFOs. To address this, the primary aim of the study was to directly measure the plantarflexion resistive moments and the joint angular positions while walking using a custom instrumented articulated AFO in individuals post stroke. The secondary aim was to investigate the moment–angle relationship of the AFO by changing its preset plantarflexion stiffness.

Methods

Subjects

Five individuals post stroke (two females/three males; 62(9) years old; 6(2) years since stroke incidence) participated in this study. Their mean(SD) height was 1.73(0.12) m and their mean(SD) body mass was 90(20) kg. Their maximum manual passive ankle dorsiflexion angles while a knee joint was kept in extension ranged from 5° to 10° of dorsiflexion. To be included in the study, participants had to be more than six-months post-stroke with hemiplegia and have the ability to walk on a treadmill with the use of an AFO without an assistive device. Exclusion criteria were any confounding injury, and musculoskeletal or cognitive problems that would limit the ability to walk on the treadmill.

Gait analysis

A prototype instrumented articulated AFO with a load cell (LC201-75, Omegadyne Inc., Sunbury, OH, USA) and a linear potentiometer (ZX-PA-1.5-B, UniMeasure, Corvallis, OR, USA) was developed. The plantarflexion resistive moments of the articulated AFO were adjustable by exchanging a compression spring (72611, 72437, 72412, Century Spring Corp., Los Angeles, CA, USA) or changing the spring's position relative to the joint center (Figure 1). The mass of the AFO including the shoe was 2 kg. The compression spring was situated in the posterior aspect of the AFO

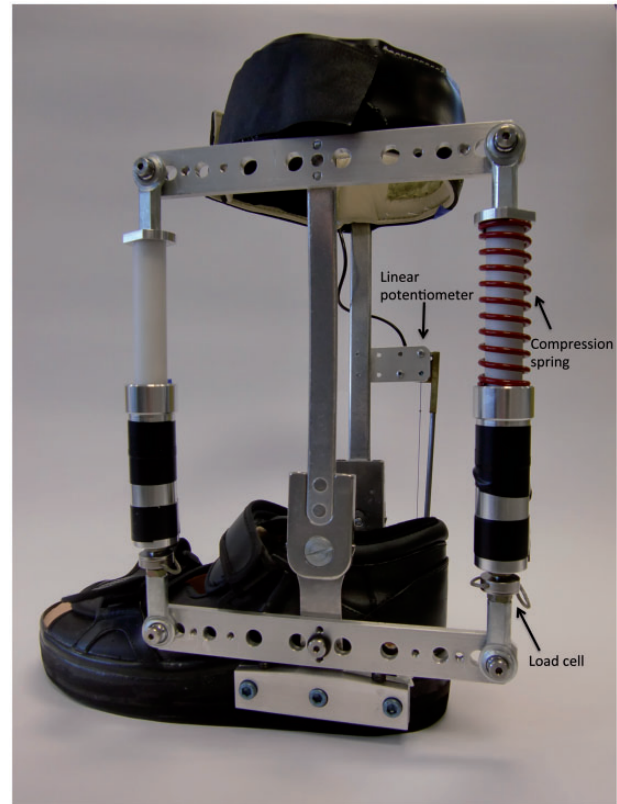


Figure 1. An instrumented articulated ankle-foot orthosis. The load cell measures force generated by the compression spring and is used to calculate the plantarflexion resistive moments, while the linear potentiometer measures the joint angular positions.

and the load cell measured its force, while the linear potentiometer measured the angular position of the joint. The plantarflexion resistive moments were calculated by multiplying the force measured by the load cell and its perpendicular distance from the joint center. The plantarflexion resistive moments and the plantarflexion angles were defined as negative. The data from the load cell and the linear potentiometer were collected at 100 Hz and sent wirelessly to a computer via Bluetooth. No spring was placed in the anterior aspect, thus the AFO did not generate spring induced dorsiflexion resistive moments.

After informed consent was obtained for this Institutional Review Board approved study, each subject was fitted with the instrumented articulated AFO. The subject was secured in a harness for safety. Data collection was performed under four levels of plantarflexion stiffness preset on the AFO: 0.35 N·m/° (S1), 0.51 N·m/° (S2), 0.87 N·m/° (S3) and 1.27 N·m/° (S4). They were determined based on a previous work on an AFO with oil-damper joint (Gait Solution: Pacific Supply, Osaka, Japan).³ Each subject walked on a split-belt treadmill at a self-selected gait speed.

The order of the four conditions was randomized for the walking trials. Each subject was allowed to rest if necessary between trials and given a short acclimatization period to walk on the treadmill under each condition before data collection. The initial angle of the AFO joint was adjusted in the range of 5° to 10° of dorsiflexion. The initial angle is the angle at which the spring starts to engage and generate the plantarflexion resistive moment.

The plantarflexion resistive moments and the joint angular positions of five continuous gait cycles (initial contact (0%) to next initial contact (100%) of the leg wearing the AFO) were extracted and averaged for each condition in each subject. They were subsequently plotted and presented as case series for each subject as follows: 1) the plantarflexion resistive moments normalized to gait cycle (Figure 2); 2) the joint angular positions normalized to gait cycle (Figure 2); and 3) the plantarflexion resistive moments versus the joint angular positions (Figure 3).

Results

Plantarflexion resistive moments

All subjects showed a systematic change in the plantarflexion resistive moments (Figure 2). The gait speed ranged from 0.11 m/s to 0.22 m/s (Figure 2). The average and standard deviations of the peak plantarflexion resistive moments of the five subjects for each condition were as follows: $-3.52(1.92)$ N·m for S1, $-5.49(2.81)$ N·m for S2, $-7.31(4.18)$ N·m for S3, $-10.31(6.53)$ N·m for S4.

Joint angular positions

The angular positions showed some changes, but they were less systematic (Figure 2). The average and standard deviations of the peak plantarflexion angles of the five subjects for each condition were as follows: $-2.78(5.15)^{\circ}$ for S1, $-2.95(4.95)^{\circ}$ for S2, $-1.02(5.14)^{\circ}$ for S3, $-0.19(4.75)^{\circ}$ for S4.

Moments versus angles relationship

Figure 3 depicts the relationship between the plantarflexion resistive moments and the joint angular positions. Each condition demonstrated a distinctive hysteresis curve in all subjects.

Discussion

The plantarflexion resistive moments and the joint angular positions were directly measured using the instrumented articulated AFO while walking in

individuals post stroke and their relationships were presented as case series. Both the peak plantarflexion resistive moment and the peak plantarflexion angle changed according to the preset plantarflexion stiffness of the AFO (Figure 2). The AFO improved initial contact and loading response by enabling plantarflexion from a dorsiflexed position. The plantarflexion resistive moment of the AFO functioned as dorsiflexors in normal gait. But it impeded push-off during pre-swing as it could not actively plantarflex. During swing phase, the AFO tended to maintain the ankle in a dorsiflexed position. The outcome of this study is important because there is a lack of data on the relationship between the physical properties of AFOs and gait. It is very difficult to measure the load applied by a conventional AFO, and we have achieved this with a simpler mechanical design.

The load cell measures the compressive load on the spring and this is a direct function of the ankle. Therefore, the moment-angle relationship of the AFO is predictable on the bench. However, the actual amount of plantarflexion resistive moment and joint angular position of the AFO during gait is not predictable for each individual with stroke. The hysteresis component, presumably due to frictional losses between the AFO and the leg, would be a little higher during gait due to the more complex load system (Figure 3). This measurement would reflect individual differences in the influences of anatomical structures, such as contracture and spasticity of the ankle joint while walking. Thus, we were not just measuring the properties of the AFO using the human subjects in place of some machine to load the AFO. Theoretically, the instrumented articulated AFO could provide information on the range of motion and/or required resistive moments for individuals walking post stroke. Current clinical routine to determine the AFO's stiffness is based on experiences of clinicians and trial-and-error. The direct measurement technique may potentially contribute to improving gait with an articulated AFO for individual patients in the future. However, further work, such as comparison of the moment-angle data to other gait data collected with a motion capture system, is required for this endeavor.

Tuning stiffness of the AFO is clinically believed important. This study showed how changing its stiffness would affect the range of motion of the ankle joint in individuals with stroke. Our previous work demonstrated that stiffness of the AFO would affect kinematics and kinetics of ankle and knee joints while walking in individuals with stroke.⁴⁻⁶ However, its evidence is still limited, and the AFO's stiffness is generally determined based on experiences of clinicians and trial-and-error. This is because it is still not known how much stiffness is required from the AFO to improve

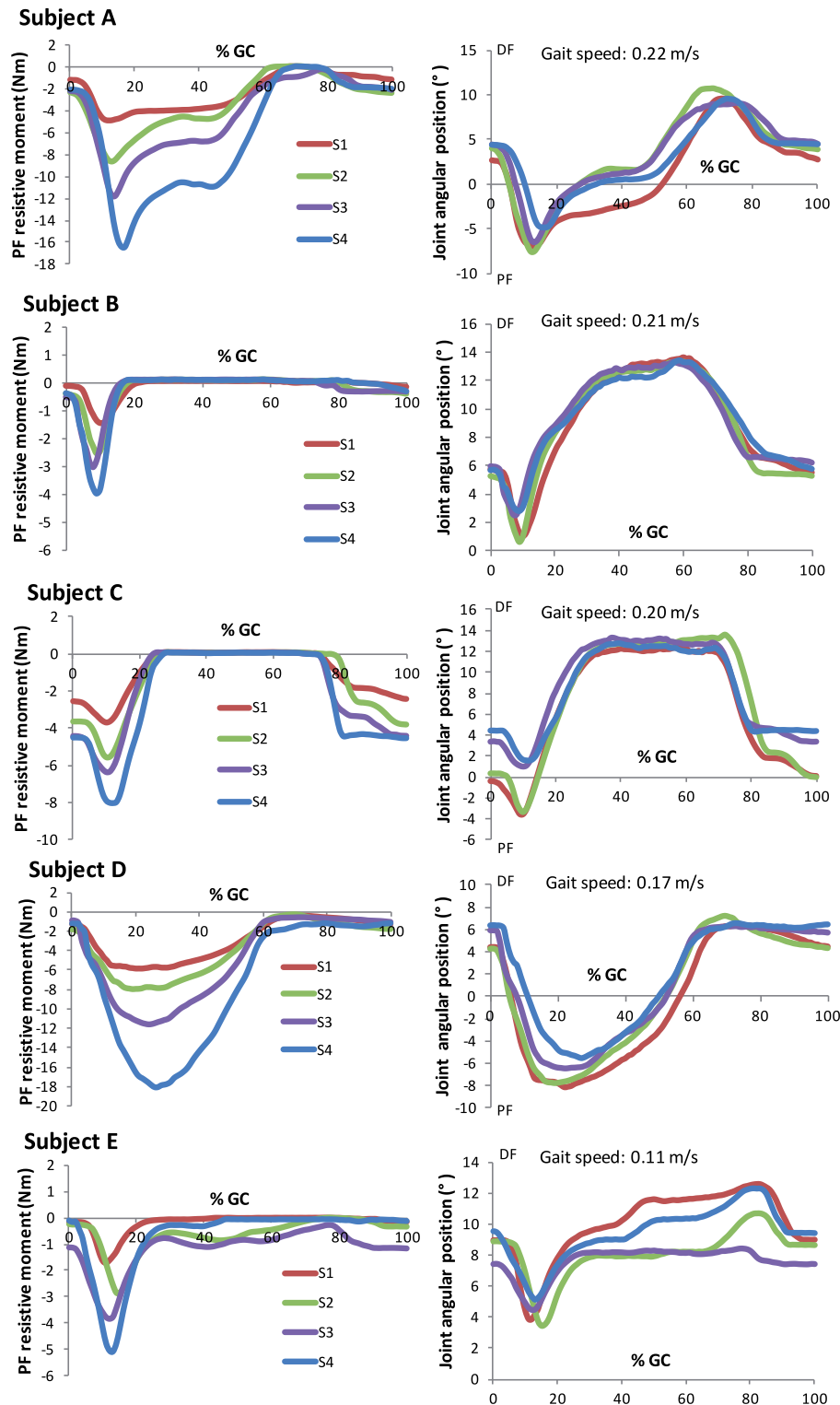


Figure 2. The mean plantarflexion resistive moments and the mean joint angular positions of five continuous gait cycles measured by the instrumented articulated ankle-foot orthosis. They were normalized to gait cycle in each subject and presented as case series. The plantarflexion stiffness preset on the instrumented articulated ankle-foot orthosis increased in the order of S1 ($0.35 \text{ N}\cdot\text{m}/^\circ$) < S2 ($0.51 \text{ N}\cdot\text{m}/^\circ$) < S3 ($0.87 \text{ N}\cdot\text{m}/^\circ$) < S4 ($1.27 \text{ N}\cdot\text{m}/^\circ$). Plantarflexion resistive moments and plantarflexion angles were defined as negative. A gait speed of each subject is presented within the figure. Initial contact of the gait cycle corresponds to 0% of the gait cycle. DF: dorsiflexion; % GC: % gait cycle; PF: plantarflexion

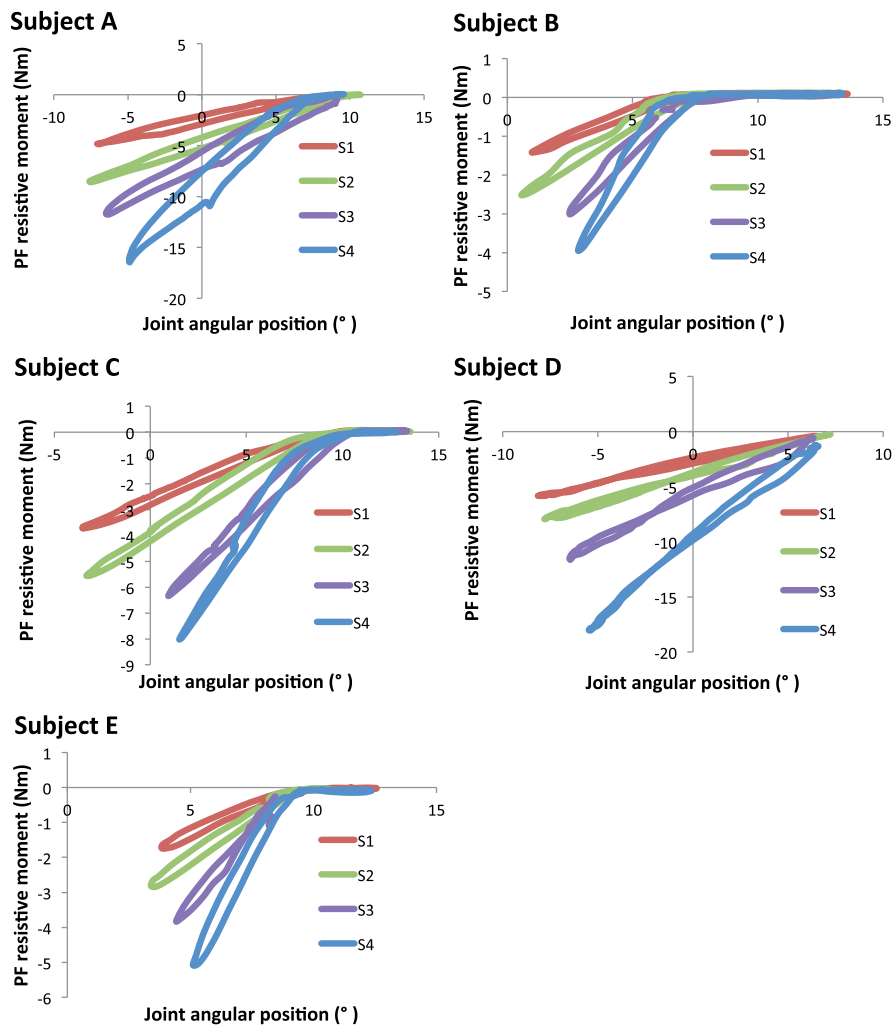


Figure 3. The relationship between the mean plantarflexion resistive moments and the mean joint angular positions of five continuous gait cycles measured by the instrumented articulated ankle-foot orthosis in each subject. The plantarflexion stiffness preset on the instrumented articulated ankle-foot orthosis increased in the order of S1 ($0.35 \text{ N}\cdot\text{m}/^\circ$) < S2 ($0.51 \text{ N}\cdot\text{m}/^\circ$) < S3 ($0.87 \text{ N}\cdot\text{m}/^\circ$) < S4 ($1.27 \text{ N}\cdot\text{m}/^\circ$). Plantarflexion resistive moments and plantarflexion angles were defined as negative.

PF: plantarflexion

gait. Our study could serve as a foundation to explore this important clinical question.

The data presented in this study are preliminary, and a larger scale study is needed to verify the outcome in a more generalized stroke population. The experiment was performed on the treadmill with subjects wearing the instrumented articulated AFO, and they tended to walk very cautiously. This resulted in slow gait speeds. It is also important to investigate the relationship between the data obtained from the instrumented AFO and gait patterns and further explore how the AFO's stiffness affects gait of patients with stroke. For instance, the time sequential graphs of plantarflexion resistance moment of subjects A and D showed prolonged plantarflexion resistance moment in stance (Figure 2). This meant that the subjects showed

continuous plantarflexion in most duration in stance. This would indicate that these subjects tended to walk with hyperextension of the knee.

The instrumented articulated AFO presented in this study is a prototype, and a modified lighter and more compact version of the device is warranted in the clinical setting. It is our intention to collect data at participants' preferred gait speed on the ground and investigate the effect of AFO stiffness on their gait based on subjective comments from the participants and clinicians as well as objective kinematics and kinetics data of lower limb joints using a three-dimensional gait analysis system. These data will be compared with clinical assessments (e.g. range of motion, spasticity, and stiffness of joints) of the participants with stroke. The instrumented AFO could provide useful insight

into the dynamic behavior of the AFO to improve future designs, advance the understanding of the biomechanics of the AFO and contribute to more evidence-based orthotic care of patients.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: TK, MSO, WKD, and LSL are/were employees of Orthocare Innovations and designed the instrumented articulated AFO used in this study.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Institutes of Health, Eunice Kennedy Shriver National Institute of Child Health & Human Development (grant number 2R44HD069095).

References

1. Tyson SF, Sadeghi-Demneh E and Nester CJ. A systematic review and meta-analysis of the effect of an ankle-foot orthosis on gait biomechanics after stroke. *Clin Rehabil* 2013; 27: 879–891.
2. Hoy DJ and Reinthal MAK. *Articulated ankle foot orthosis designs (R3): Report of a Consensus Conference on the Orthotic Management of Stroke Patients*. Copenhagen, Denmark: ISPO, 2004..
3. Yamamoto S, Hagiwara A, Mizobe T, et al. Development of an ankle-foot orthosis with an oil damper. *Prosthet Orthot Int* 2005; 29: 209–219.
4. Kobayashi T, Leung AK, Akazawa Y, et al. Design of a stiffness-adjustable ankle-foot orthosis and its effect on ankle joint kinematics in patients with stroke. *Gait Posture* 2011; 33: 721–723.
5. Kobayashi T, Leung AK, Akazawa Y, et al. The effect of varying the plantarflexion resistance of an ankle-foot orthosis on knee joint kinematics in patients with stroke. *Gait Posture* 2013; 37: 457–459.
6. Singer ML, Kobayashi T, Lincoln LS, et al. The effect of ankle-foot orthosis plantarflexion stiffness on ankle and knee joint kinematics and kinetics during first and second rockers of gait in individuals with stroke. *Clin Biomech (Bristol, Avon)* 2014; 29: 1077–1080.
7. Yamamoto S, Tomokiyo N, Yasui T, et al. Effects of plantar flexion resistive moment generated by an ankle-foot orthosis with an oil damper on the gait of stroke patients: A pilot study. *Prosthet Orthot Int* 2013; 37: 212–221.
8. Kobayashi T, Singer ML, Orendurff MS, et al. The effect of changing plantarflexion resistive moment of an articulated ankle-foot orthosis on ankle and knee joint angles and moments while walking in patients post stroke. *Clin Biomech (Bristol, Avon)* 2015; 30: 775–780.
9. Nolan KJ and Yarossi M. Preservation of the first rocker is related to increases in gait speed in individuals with hemiplegia and AFO. *Clin Biomech (Bristol, Avon)* 2011; 26: 655–660.
10. Ohata K, Yasui T, Tsuboyama T, et al. Effects of an ankle-foot orthosis with oil damper on muscle activity in adults after stroke. *Gait Posture* 2011; 33: 102–107.
11. Bregman DJ, De Groot V, Van Diggele P, et al. Polypropylene ankle foot orthoses to overcome drop-foot gait in central neurological patients: A mechanical and functional evaluation. *Prosthet Orthot Int* 2010; 34: 293–304.
12. Gao F, Carlton W and Kapp S. Effects of joint alignment and type on mechanical properties of thermoplastic articulated ankle-foot orthosis. *Prosthet Orthot Int* 2011; 35: 181–189.
13. Nagaya M. Shoehorn-type ankle-foot orthoses: Prediction of flexibility. *Arch Phys Med Rehabil* 1997; 78: 82–84.
14. Sumiya T, Suzuki Y and Kasahara T. Stiffness control in posterior-type plastic ankle-foot orthoses: Effect of ankle trimline. Part 1: A device for measuring ankle moment. *Prosthet Orthot Int* 1996; 20: 129–131.
15. Kobayashi T, Leung AK and Hutchins SW. Techniques to measure rigidity of ankle-foot orthosis: A review. *J Rehabil Res Dev* 2011; 48: 565–576.