Engineering Evaluation of Post-Stroke Gait Using a Wearable G-Walk Sensor Under Different Ankle-Foot Orthosis Conditions: A Longitudinal Case Study

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ORIGINAL STUDY

Engineering Evaluation of Post-Stroke Gait Using a Wearable G-Walk Sensor Under Different Ankle-Foot Orthosis Conditions: A Longitudinal Case Study

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ABSTRACT

The gait profile of post-stroke patients is typically one of reduced speed, asymmetry and decreased functional mobility. Ankle–foot orthoses (AFOs) are commonly prescribed to enhance gait stability and promote safer ambulation; however, within-person longitudinal gait changes across multiple orthotic conditions have not yet been quantitatively characterized using wearable motion analysis systems. The objective of this study was to perform a longitudinal assessment of spatiotemporal gait parameters through a wearable G-Walk inertial measurement unit (IMU) with three walking conditions: without orthosis, Conventional custom-made ankle foot orthosis AFO and Prefabricated posterior leaf spring AFO. Two functional tasks, normal walking and Timed Up and Go (TUG), were performed for each condition by a single post-stroke participant during two test sessions four months apart. Spatiotemporal key parameters such as gait speed, step length, cadence, and completion time were extracted and compared between the two time points. The gait analysis revealed trends towards increased observed gait symmetry and general functional performance with orthotics compared to walking without an AFO. Results: Longitudinal comparisons indicated that walking speed and step length in the second assessment session was higher. While the conventional custom-made AFO showed higher improvements in stability and temporal organization of gait, the PLS AFO had moderate characteristics of dynamic progression of gait. Results indicate that wearable gait analysis systems have the potential to provide objective measures of longitudinal gait adaptations and could provide useful biomechanical information for orthotic assessment and rehabilitation planning in post-stroke individuals. Further studies with larger groups of participants need to confirm these observations.

Keywords: Post-stroke gait, G-Walk, Wearable gait analysis, Ankle-foot orthosis (AFO), Spatiotemporal parameters, Longitudinal assessment, Case study

1. Introduction

Gait impairment ranks as one of the most common functional limitations among survivors [1]. and stroke is one of the leading global causes of long-term disability as shown in Fig. 1, stroke affects motor control pathways. Post-stroke gait is often characterized by slowed walking speed, balance deficits, inter-limb asymmetry and motor control deficiencies [2, 3]. These impairments, foot drop due to weakness or delayed activation of ankle dorsiflexor muscles is especially common and strongly correlated with loss of functional mobility and higher risk of falls [4, 5]. Beyond its clinical presentation, post-stroke gait disturbance poses an intricate biomechanical dilemma characterized by abnormal joint coordination, suboptimal movement strategy and divergent loading [6]. These adaptations frequently result in compensatory strategies, extended double-support phases, and enhanced energy cost during ambulation. Chronic gait

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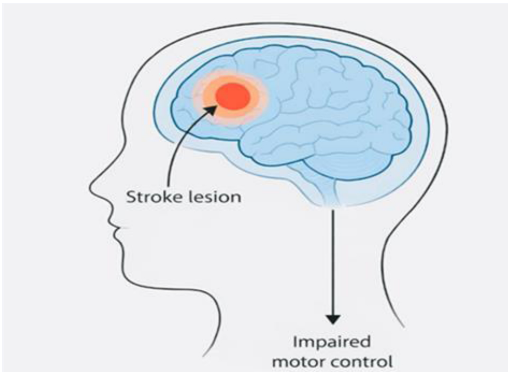

Fig. 1. Stroke-related brain injury can disrupt motor control pathways involved in gait and functional ambulation.

asymmetry can lead to chronic musculoskeletal stress and decrease overall walking efficiency over time [7].

Ankle–foot orthoses (AFOs) are frequently prescribed for the management of foot drop and/or to improve stability while walking during post-stroke rehabilitation [8–10]. By providing external support to the ankle joint, AFOs work to improve toe clearance in swing phase, stability at the ankle with stance to facilitate safe and efficient gait patterns through external support to the joint. Orthotic interventions in stroke populations have reported on improvements in walking speed, step length, cadence and balance. Multiple factors are known to influence the biomechanical effectiveness of an AFO, such as its structural design and level of customization [11, 12]. The effectiveness of an AFO from a biomechanical perspective is influenced by its design characteristics and degree of customization [13]. Custom-made AFOs are designed according to an individual's anatomical structure and functional disabilities, while prefabricated AFOs offer a more general support with less individualized adjustment [14]. There is some evidence that customized orthotic design can provide greater control of ankle range-of-motion, enhanced load redistribution and improved gait symmetry compared to off-the-shelf devices [15, 16]. Recent advances in wearable instruments have enabled objective, precise quantification of spatiotemporal gait parameters for real-world applications both clinically and in research environments [17]. Inertial measurement unit (IMU) based systems like the G-Walk provide a reliable assessment of walking speed, cadence, step length and functional mobility tasks performed under various walking conditions [18, 19]. While these technologies are being increasingly used, evidence on their longitudinal use to track compliance and adherence to orthotics during long-term rehabilitation is limited. Wearable gait analysis technologies and ankle–foot orthoses are gaining popularity in stroke rehabilitation. However, there is limited evidence for the longitudinal biomechanical comparison of conventional custom-made AFOs and prefabricated posterior leaf spring (PLS) AFOs in the same post-stroke individual. Much of the previous studies have focused on short-term assessments or cross-sectional comparisons, but the temporal adaptations in gait performance under different orthotic conditions have not been sufficiently explored. Additionally, the use of wearable IMU-based systems, such as the G-Walk, to monitor long-term functional changes associated with different AFO designs has been somewhat underexplored. Thus, there is a need for longitudinal case-based studies to objectively evaluate gait performance over time under various orthotic interventions. From an engineering perspective, wearable inertial measurement unit (IMU) systems provide an effective quantitative approach for capturing human movement dynamics and evaluating gait biomechanics under different assistive device conditions. The aim of this study was to characterize spatiotemporal gait during a longitudinal assessment with the wearable G-Walk system in three orthotic conditions (without orthosis, traditional AFO and ready-made posterior leaf spring AFO) in a post-stroke case-study [14, 20–22]. This study aims to provide objective evidence for informed orthotic prescription through long-term rehabilitation monitoring by comparing functional performance at two points in time, with four months between those evaluation sessions. This study aims to provide biomechanical insights that would facilitate more informed clinical decision-making on ankle–foot orthosis prescription [23].

2. Materials and methods

2.1. Study design

This longitudinal single-case study was conducted to evaluate the gait performance of one post-stroke participant under three walking conditions: walking without an orthosis, walking with a conventional custom-made AFO and walking with a prefabricated posterior leaf spring AFO. The participant was tested at two time points separated by four months. The study was designed to provide preliminary within-subject biomechanical comparisons of orthotic effects over time and not to generalize the findings to the broader post-stroke population.

2.2. Participant

A 60-year-old male post-stroke patient with right hemiparesis. The participant had suffered cerebrovascular accident 18 months before data acquisition, and exhibited persistent foot drop and gait asymmetry on his right side. At evaluation, the participant had a body weight of 83 kg and was clinically stable with no other neurological or musculoskeletal conditions that could interfere with their gait performance. Each assessment was carried out in a controlled clinical environment. This study was approved by the Ethical Committee of Department of Prosthetics and Orthotics Engineering, Al-Nahrain University. Written informed consent was obtained from the participant prior to data collection and participation in the study.

Between the two assessment sessions, the participant continued with the routine rehabilitation treatment, which consisted of 1-2 physiotherapy sessions per week, for a total of four months. Additionally, neuromuscular electrical stimulation (NMES) was administered at the end of each rehabilitation session within the framework of the ongoing clinical management program.

2.3. Instrumentation

Spatiotemporal gait parameters, the G-SENSOR wearable inertial measurement unit (IMU) system from G-Walk platform (BTS Bioengineering, Italy) was used. It consists of a tri-axial accelerometer, gyroscope and magnetometer that allows to detect three-dimensional trunk motions during functional activities. To estimate the body's center of mass, the sensor was positioned at the level of the fifth lumbar vertebra (L5) as shown in Fig. 2, Sensor placement using an elastic belt manufactured specifically for this study, following manufacturer specifications. Data acquisition was performed through a BTS G-Studio software interface that permitted real-time registration and later data extraction of spatiotemporal gait parameters the G-Walk system is shown in Fig. 3, the system allows for an objective assessment of gait speed, cadence, step length, stance phase and double support time with both walking and functional mobility tasks. The BTS G-Walk system has

Fig. 2. Placement of the BTS G-Sensor at the level of the fifth lumbar vertebra (L5) using an elastic belt during gait data acquisition.

Fig. 3. BTS G-Sensor (G-Walk system) inertial measurement unit (IMU) and elastic mounting belt used for spatiotemporal gait analy**sis.**

been shown to provide valid and reliable measurements of spatiotemporal gait parameters in healthy individuals and neurological populations in previous studies. The system has indicated good agreement with laboratory-based gait analysis techniques and has been widely used for the objective assessment of walking performance, balance and functional mobility. Hence, it was considered as an appropriate tool for longitudinal gait assessment in the present case study. [19, 21, 22].

2.4. Experimental conditions

Gait assessments were performed under three walking conditions:

1. Walking without orthosis (Without AFO)
2. Walking with a traditional custom-made AFO
3. Walking with a prefabricated posterior leaf spring (PLS) AFO

All conditions were tested during two separate assessment sessions:

- Time Point 1 (T1)
- Time Point 2 (T2) after four months

2.5. Outcome measures

The following spatiotemporal parameters were extracted:

- Gait speed (m/s)
- Step length (m)
- Cadence (steps/min)
- Stance phase (%)
- Double support time (%)

2.6. Functional tasks

The functional test was conducted three times for each walking condition at each assessment session.

The mean of the three trials was used for analysis in order to minimize trial-to-trial variability. Two functional tasks were performed under each walking condition:

- Normal Walking Test (over a predefined straight pathway).
- Time Up and Go Test (TUG).

2.6.1. Normal walking test

Participants walked at a self-selected comfortable speed along a straight walkway that was pre-defined. Testing was performed over a standard distance of six meters. The G-Walk sensor was fixed at the L5 level, and data were measured continuously throughout the walking trial. Each condition was repeated and the mean value of spatiotemporal parameters recorded was used for analysis.

2.6.2. Timed up and go (TUG) test

The authors evaluated functional mobility using the Timed Up and Go (TUG) protocol. The subject was instructed to stand up from a sitting position, walk 6 meters in front to turn back, and return to sit down. All gait parameters were recorded with the G-Walk system (the total duration of a task and spatiotemporal parameters). Each trial was repeated and the average value is used for comparison to ensure measurement consistency.

3. Results

Results from the longitudinal gait assessment are reported through functional task and walking condition. Comparison of spatiotemporal parameters compared between the two time points (T1 and T2) across the three conditions based on G-Walk system.

3.1. Normal walking test

A comparison of spatiotemporal parameters during normal walking test across the three walking conditions and two assessment sessions is presented below.

3.1.1. Without AFO

A normal walking test without orthosis was performed to assess the participant's spatiotemporal gait parameters, the spatiotemporal gait parameters for normal walking without an orthosis are presented in Table 1.

Without the orthotic device, there was a notable improvement between T1 and T2 in normal walking. The gait speed was improved by 14.1% and cadence by (7.1%), respectively. Furthermore, gait cycle duration was decreased bilaterally (−11.3% on the left; −17.1% on the right), reflecting enhanced temporal efficiency and walking cadences after four months.

Table 1. Spatiotemporal parameters during normal walking without AFO.

Parameter	T1	T2	% Change
Gait Speed (m/s)	0.78	0.89	+14.1%
Cadence (steps/min)	82.96	88.85	+7.1%
Gait Cycle Duration – Left (s)	1.60	1.42	−11.3%
Gait Cycle Duration – Right (s)	1.70	1.41	−17.1%

3.1.2. Traditional AFO

A normal walking test with Traditional custom-made AFO was performed to assess the participant's spatiotemporal gait parameters, spatiotemporal parameters during normal walking with the conventional custom-made AFO are shown in Table 2.

Table 2. Spatiotemporal parameters during normal walking with conventional (custom made AFO).

Parameter	T1	T2	% Change
Gait Speed (m/s)	0.78	0.81	+3.8%
Cadence (steps/min)	73.25	88.37	+20.6%
Gait Cycle Duration – Left (s)	1.66	1.46	−12.0%
Gait Cycle Duration – Right (s)	1.71	1.43	−16.4%

Moderate improvements in T2 were seen during normal walking with the conventional custom-made AFO. Gait speed slightly improved by a (3.8%) increase, while cadence showed an impressive rise of (20.6%). Furthermore, the gait cycle duration was shorter on both sides, reflecting a more efficient temporal pattern with respect to gait and rhythm of walking across four months.

3.1.3. Readymade posterior leaf spring (PLS) AFO

A normal walking test with readymade Posterior Leaf Spring (PLS) AFO was performed to assess the participant's spatiotemporal gait parameters, the spatiotemporal gait parameters with the prefabricated PLS AFO are presented in Table 3.

Table 3. Spatiotemporal parameters during normal walking with PLS AFO.

Parameter	T1	T2	% Change
Gait Speed (m/s)	0.80	0.78	−2.5%
Cadence (steps/min)	82.19	80.98	−1.5%
Gait Cycle Duration – Left (s)	1.52	1.42	−6.6%
Gait Cycle Duration – Right (s)	1.62	1.53	−5.6%

For the PLS AFO during typical walking, only small differences were index between the two timepoints. Although there was a small bilateral reduction in gait cycle duration, both gait speed and cadence were lower at T2. These results reveal comparable walking performance at a four-month follow-up visit examined in the prefabricated orthotic condition.

3.1.4. Comparative analysis across walking conditions

During the normal walking task, all three walking conditions showed different temporal patterns of change over the four-month period. During the no-AFO condition, gait speed (+14.1%) and cadence (+7.1%), with a notable decrease in gait cycle duration bilaterally, suggesting that over time use of an AFO can confer benefits to overall walking efficiency. There was moderate increase in gait speed (+3.8%) and marked improvement in cadence (+20.6 %) with the conventional custom-made AFO condition, amongst a decreased duration of the gait cycle. The changes suggest improved rhythmicity and temporal organization of gait with the custom orthotic support. In comparison, the performance of the posterior leaf spring (PLS) AFO condition remained relatively consistent across sessions. Although gait cycle duration decreased slightly, both gait speed and cadence were only approximately 5% lower at T2, thus there was a limited amount of longitudinal change for these parameters compared to the other conditions. The overall temporal enhancements seen between without-AFO and conventional AFO conditions were observed greater than improvements observed through prefabricated PLS device during the normal gait walking task.

3.2. Timed up and go (TUG) test

Functional mobility, including transitional movements and dynamic turning ability under three walking conditions at the two assessment time points was assessed using the Timed Up and Go (TUG) test. The subsequent tables outline the temporal parameters that were extracted for each orthotic condition (No AFO, Conventional AFO and PLS AFO), directly supporting longitudinal comparison between T1 and T2.

3.2.1. Timed up and go (Without AFO)

Timed Up and Go (TUG) test was conducted to evaluate the participant's functional mobility and dynamic balance during a commonly executed daily task, during this test the patient stood up from a sitting position, walked forward a short distance, turned around, walked back to the chair and sat down again without orthosis, the Timed Up and Go (TUG) parameters without orthotic support are presented in Table 4.

Table 4. Timed up and go parameters – without AFO condition.

Parameter	T1 (s)	T2 (s)	% Change
Total TUG Duration	22.33	11.50	−48.5%
Sit-to-Stand	2.20	2.50	+13.6%
Stand-to-Sit	1.70	1.60	-5.88%
Mid Turning	5.00	3.10	−38.0%
End Turning	2.64	2.84	+7.6%

During the Timed Up and Go test without orthotic support, total test duration increased slightly at T2 (+3.6%), indicating a marginal reduction in overall functional mobility performance over the four-month interval. Sit-to-stand and stand-to-sit phases suggest increased durations, suggesting greater transitional demand. In contrast, end-turning duration decreased notably, while mid-turning time remained relatively stable. These findings indicate phase-specific temporal variability rather than a uniform longitudinal change in functional mobility under the no-AFO condition.

3.2.2. Timed up and Go (Traditional AFO orthosis)

Timed Up and Go (TUG) test was conducted to evaluate the participant's functional mobility and dynamic balance during a commonly executed daily task, during this test the patient stood up from a sitting position, walked forward a short distance, turned around, walked back to the chair and sat down again with traditional AFO orthosis, the TUG parameters under the traditional custom-made AFO condition are shown in Table 5.

Table 5. Timed up and go parameters – conventional AFO condition.

Parameter	T1 (s)	T2 (s)	% Change
Total TUG Duration	28.70	29.73	+3.6%
Sit-to-Stand	2.40	2.90	+20.8%
Stand-to-Sit	2.50	3.50	+40.0%
Mid Turning	3.33	3.28	−1.5%
End Turning	3.05	1.10	−63.9%

The total test duration decreased substantially (−48.5%) at T2 as compared to the initial Time Up and Go completion with the conventional custom-made AFO, suggesting an overall enhanced ability in functional mobility performance over four months. The mid-turning duration considerably acceptable dynamic the total test duration decreased substantially (−48.5%) at T2 as compared to the initial Time Up and Go completion with the conventional custom-made AFO, suggesting an overall enhanced ability in functional mobility performance over four months. The mid-turning duration considerably acceptable dynamic rotational control improvement. The sit-to-stand duration was marginally extended, whereas the stand-to-sit data at T2 was very close to the initial assessment T1. These results suggest that there is noticeable longitudinal improvement in functional mobility on the standard orthosis condition.

3.2.3. Timed up and go (PLS AFO)

Timed Up and Go (TUG) test was conducted to evaluate the participant's functional mobility and dynamic balance during a commonly executed daily task, during this test the patient stood up from a sitting position, walked forward a short distance, turned around, walked back to the chair and sat down again with prefabricated PLS AFO, the TUG parameters for the PLS AFO condition are presented in Table 6.

Table 6. Timed up and go parameters – PLS AFO condition.

Parameter	T1 (s)	T2 (s)	% Change
Total TUG Duration	15.13	25.59	+69.1%
Sit-to-Stand	1.09	2.40	+120.2%
Stand-to-Sit	2.40	2.30	−4.2%
Mid Turning	3.50	4.60	+31.4%
End Turning	3.00	2.77	−7.7%

In the Timed Up and Go tests using the prefabricated posterior Leaf Spring (PLS) AFO, the total test duration at T2 was observed increased (+69.1%) yielding a noticeable overall reduction in functional mobility performance over four months. Only sit-to-stand and mid-turning phases had observed higher durations, with stand-to-sit and end-turning times being less affected. These results indicating decreased efficiency in transitional and rotational subcomponents of functional mobility under the prefabricated orthotic condition at follow up.

3.2.4. Comparative analysis of TUG performance across conditions

Between the three conditions, unique longitudinal trajectories were noted during Timed Up and Go performance. The traditional custom-made AFO had the most improvement with a large decrease in total test duration (−48.5%) which was mainly due to decreased mid-turning time. The no-AFO condition only slightly increased total duration (+ 3.6%), and thus indicate relatively preserved functional mobility with little phase-specific variation. Vice versa was observed for the prefabricated PLS AFO, where a noticeable increase in total TUG duration (+69.1%) occurred at T2 compared to baseline with an evident increase in transitional and turning phases. In conclusion, the conventional AFO condition indicates best longitudinal functional mobility outcome, whereas prefabricated device had less efficient during time.

4. Discussion

This is a longitudinal case report investigating the biomechanical and functional effects of three walking conditions (without orthosis, conventional custom-made AFO, prefabricated posterior leaf spring (PLS) AFO) examined over four months in a chronic post-stroke patient with right-sided hemiparesis. These findings disclosed condition-specific adaptations in the spatiotemporal patterns of performance and functional mobility, emphasizing the need for orthotic specificity when managing post-stroke gait recovery.

Findings also suggest that improvements observed in the no-AFO condition with respect to gait speed, cadence and reduced gait cycle duration during typical walking conditions could reflect ongoing neuromotor adaptation and compensatory motor learning processes. Improvements in walking economy may even occur with more chronic stroke populations due to activity-dependent neuroplasticity and task repetition [24, 25]. However, despite these changes, absolute values remained under normative ranges, in line with the common features of hemiparetic gait which includes persistent asymmetry and decreased propulsion [26].

It is noted that the participant received routine physiotherapy and NMES treatment throughout the follow-up period. Thus, part of the observed improvements may be attributed to the ongoing rehabilitation-related neuromotor recovery in addition to the biomechanical effects of the orthotic interventions. Therefore, the orthotic effects should be interpreted within the larger context of the participant's rehabilitation program.

Cadence and rhythm stabilization showed the best longitudinal increase in temporal organization through time using conventional custom-made AFO. Recent biomechanical studies have shown that a more tailored AFO alignment improves ankle rocker mechanics, limits excessive stance phase plantarflexion, and enhances forward progression through improved tibial progression [27]. In addition, customized stiffness profiles have also been marked to improve energy storage and return mechanisms, ultimately enhancing gait efficiency and dynamic stability [28]. These improvements in turning performance supports further evidence for orthoses that are properly tuned to enhance mediolateral control and rotational stability during complex functional tasks [29].

The better performance with the conventional custom-made AFO may be due to individual design and better anatomical fit. The custom-made orthosis was manufactured to match the participant's limb geometry and functional requirements, in contrast to the prefabricated PLS AFO, and provided enhanced ankle stabilization, improved mediolateral control, and more effective alignment of the lower limb during gait. These biomechanical properties could have contributed to the improvements observed in temporal gait organization and functional mobility during follow-up. The prefabricated

PLS AFO suggest limited longitudinal improvement in straight-line walking with a TUG time at follow-up that was observed longer. Although PLS designs indeed help facilitate dorsiflexion in swing phase, they have standardized mechanical properties that may not sufficiently address personalized impairments in proximal control, balance or power generation [30]. Recent systematic reviews have placed considerable emphasis on how the effectiveness of orthoses is strongly contingent upon patient-specific biomechanics and device-tuning, rather than generic foot-drop correction ability [31]. The extended durations of sit-to-stand and mid-turning under the PLS condition suggest elevated transitional demands, alongside decreased mechanical efficiency, when performing multi-directional tasks.

Importantly, this study emphasizes that better linear gait parameters do not translate into improved functional mobility. Functional activities like TUG require anticipatory postural adjustments, trunk coordination, and rapid directional changes that demand joint integration beyond the ankle-salvaging an approach to neuromuscular control [32]. New evidence in stroke rehabilitation suggests that orthotic interventions may exert differential effects on task-specific functional outcomes relative to steady-state walking metrics [33].

Individualized orthotics therapeutic approaches may more effectively drive the chronic stroke gait outcome longer term than off-the-shelf configurations leading to the current findings that offer clinical context for treating chronic hemiparetic. These findings support contemporary biomechanical paradigms focused on individualized orthotic prescription reliant on dynamic evaluation as opposed to device availability alone [34].

5. Study limitations

There are some limitations to the study that should be taken into consideration when interpreting the findings. First, the investigation was conducted on a single post-stroke participant, thus limiting the generalizability of the results to the larger stroke population. Second, no formal statistical analysis was conducted due to the single-subject design. Third, the follow-up period lasted only 4 months, and it may not be representative of long-term adaptations to orthotics wearing. Finally, while the participant was clinically stable during the study period, the effect of ongoing rehabilitation, daily activities and individual recovery processes cannot be completely excluded. The results should therefore be considered preliminary and require further validation in studies with larger participant cohorts.

6. Conclusion

This longitudinal case study assessed the impact of three ambulation conditions (without orthosis, with conventional custom-made ankle-foot orthosis AFO, and with prefabricated posterior leaf spring PLS AFO) on spatiotemporal gait parameters and functional mobility in a post-stroke individual across a four-month observation period. The findings indicate condition-specific adaptations. Temporal organization and rhythmic control were improved for the conventional AFO compared to no AFO over time during both normal walking conditions. In comparison, the PLS AFO condition had similar longitudinal gains or smaller. The best longitudinal improvements in the Timed Up and Go test to assess motor functional mobility were observed in the conventional custom-made AFO condition, whereas performance deteriorated over time in the PLS AFO condition. The findings of this longitudinal case study suggest that the traditional custom-made AFO may offer functional benefits to this participant over the prefabricated PLS AFO. However, these observations need to be taken with caution given the single-subject design and larger cohort studies are required before general conclusions can be drawn. This longitudinal study emphasizes the need for task-specific evaluation when prescribing ankle-foot orthoses for post-stroke individuals.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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