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CASE STUDY

Using musculoskeletal modeling to evaluate the effect of ankle foot orthosis tuning on musculotendon dynamics: a case study

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Abstract

Purpose: This case study examines the influence of an ankle foot orthosis footwear combination (AFO-FC) on musculotendon lengths and gait kinematics and kinetics after right thrombotic stroke resulting in left hemiplegia. *Methods*: Gait analysis was performed over three visits where the subject walked with an AFO-FC with two shank-to-vertical angle (SVA) alignments, a posterior leaf spring AFO (PLS AFO), and shoes alone. Biomechanical and musculoskeletal modeling was used to evaluate musculotendon lengths, kinematics, and kinetics for each condition. *Results*: The AFO-FC improved walking speed and non-paretic kinematics compared to the PLS AFO and shoes alone. The operating length of the paretic gastrocnemius decreased with the AFO-FC improving knee kinematics in swing, but not stance. As the SVA of the AFO-FC was reduced from 15° to 12°, internal ankle plantar flexor moment increased. *Conclusions*: Musculoskeletal modeling demonstrated that the AFO-FC altered gastrocnemius operating length during post-stroke hemiplegic gait. Using these tools to evaluate muscle operating lengths can provide insight into underlying mechanisms that may improve gait and guide future AFO-FC design.

Keywords

Ankle foot orthoses, gait, muscle length, musculoskeletal modeling, tuning

History

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➤ Implications for Rehabilitation

- Modeling musculotendon operating lengths during movement has the potential to inform how ankle foot orthoses (AFO) affect tight muscles and improve mobility after stroke.
- Adjusting shank-to-vertical angle (SVA) of the AFO-footwear combination (AFO-FC) has the potential to improve gait kinematics by controlling length of the pathologic gastrocnemius and maximizing internal ankle plantar flexor moment of individuals with neuromuscular disorders.

Introduction

Stroke negatively affects mobility with 50% of stroke survivors achieving only a limited level of functional ambulation [1]. To achieve better outcomes we need an improved understanding of the mechanisms that hinder mobility and better methods for prescribing and optimizing function of assistive devices. Ankle foot orthoses (AFOs) are an assistive device commonly used to improve gait after stroke, with many designs available to provide support and alignment, compensate for muscle weakness, and help prevent secondary musculoskeletal deformities. Recently, ankle foot orthosis footwear combinations (AFO-FCs) have been suggested to improve gait for individuals with neuromuscular problems [2–6]. Ankle foot orthosis footwear combinations comprise a rigid, non-articulated AFO set at an ankle angle (AA) predicated on muscle length [7], a shank-to-vertical angle (SVA) modified by intrinsic or extrinsic heel wedges to center the knee over the middle of the foot during mid-stance [8], and footwear modified to allow stance phase roll-over given restriction of ankle and possibly metatarsophalangeal joint motion [9]. By dynamically adjusting the SVA and rocker profile of the footwear, orthotists can ''tune'' the sagittal plane orientation of the vertical ground reaction force vector with respect to the knee and hip during terminal stance and pre-swing [2,10]. Tuning an AFO-FC was previously shown to improve walking speed, knee kinematics, and knee pain in an individual after stroke [11] and walking speed, step length, and cadence in eight individuals after stroke [3].

The efficacy of AFO-FCs is thought to be related to musculotendon dynamics during gait [10]; however, the impact of AFO-FCs on muscle function during gait remains unclear. Contracture, spasticity, and increased tone are common after stroke and can contribute to pathologic gait patterns [12]. For example, contracture or spasticity of the gastrocnemius, which crosses both the knee and ankle, may contribute to reduced push-off in terminal stance, excessive knee flexion in stance, and inadequate knee flexion in swing [13,14]. If the gastrocnemius is too tight to achieve full knee extension and the 10–20 degrees of ankle dorsiflexion required during terminal stance, compensations, such as increasing ankle plantar flexion or knee flexion

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must occur. Tuning an AFO-FC to reduce the operating length of the gastrocnemius during gait may help to reduce the effect of contracture and spasticity on these abnormal kinematics, but the impact of AFO-FCs on musculotendon operating lengths has not been previously investigated.

A muscle's operating length is defined as the length of the muscle-tendon unit from origin to insertion during movement. Estimating a muscle's operating length requires knowledge of not only joint angles, but also musculoskeletal geometry, such as, segment length, muscle moment arms, and musculotendon paths. Thus, estimating a muscle's operating length during movements, such as walking is challenging, especially for bi-articular muscles like the gastrocnemius. Recent advances in musculoskeletal modeling and simulation have created detailed models of the musculoskeletal system that can be used to estimate muscle operating lengths [15]. For example, musculoskeletal modeling has been used to evaluate the length of the hamstrings during crouch gait, a common gait pathology among children with cerebral palsy, and has been used to predict surgical outcomes after hamstring lengthening [16,17]. It is thought that orthotists can adjust AFOs to alter the operating length of the gastrocnemius and other muscles during gait [18], so understanding how musculotendon operating lengths change with AFO-FCs may improve orthotic prescription, design, and tuning.

This case study evaluated whether tuning an AFO-FC altered musculotendon operating lengths and contributed to improved kinematics during gait. We evaluated a subject with left hemiplegia post-stroke who presented with gastrocnemius contracture and a stiff-knee gait. Evaluations were conducted over three visits while walking with shoes alone, a posterior leaf spring AFO (PLS AFO), and an AFO-FC with two shank-to-vertical angles. We hypothesized that the AFO-FC would decrease gastrocnemius operating length and improve knee kinematics during gait.

Methods

Subject

A 56–year-old male (height = 190 cm, weight = 88.5 kg), who sustained a right middle cerebral artery injury with subsequent left hemiplegia was first evaluated using instrumented gait analysis 11 months post-stroke. The Clinical exam indicated that the subject had restricted passive ankle range of motion on the left due to gastrocnemius shortening: 10° dorsiflexion (knee at 90° flexion) and 5° plantar flexion (knee at 0°). The left knee also had 5° hyperextension. The university's Institutional Review Board approved this study and written informed consent was obtained from the subject prior to participation.

Orthotic conditions

The subject visited the motion analysis laboratory on three occasions. As part of his preceding clinical care the subject had been provided an off-the-shelf polypropylene PLS AFO. At the first visit (11 months post-stroke), his gait was assessed with the PLS AFO. The subject was also fitted with a custom polypropylene AFO-FC with an ankle angle of 8° plantar flexion (based on passive ankle range of motion with the knee extended) and an SVA of 15° after tuning (Figure 1). The AFO-FC was tuned by a certified orthotist with over 20 years of experience in the orthotic management of individuals post-stroke. The subject wore this AFO-FC full-time for 5 months between the first and second visit. At the second visit (16 months post-stroke), the subject's gait was evaluated with the same AFO-FC.

Based upon this analysis, the AFO-FC was adjusted (i.e. re-tuned) by the same orthotist, reducing the SVA from 15° to 12° by removing material from beneath the heel of the shoe. This was done to improve the sagittal plane orientation of the vertical ground reaction force vector with respect to the knee joint such that greater knee extension might be achieved in terminal stance. The subject returned 1 month later (17 months post-stroke) to evaluate the re-tuned AFO-FC, which was worn full-time during the intervening month. During this final visit, the subject's gait was also evaluated with shoes alone to determine if gait had changed due to recovery compared to the initial visit. The subject walked with a quad cane when using the PLS AFO and shoes alone but ambulated without an assistive device when the AFO-FC was worn. At the first visit, the subject refused to walk with shoes alone, which is why the PLS AFO was used as the comparison condition. At the final visit, the subject agreed to walk with shoes alone, suggesting some level of recovery and improvement in comfort and confidence in walking without AFOs. Unfortunately, the PLS AFO was no longer available for testing at the final visit.

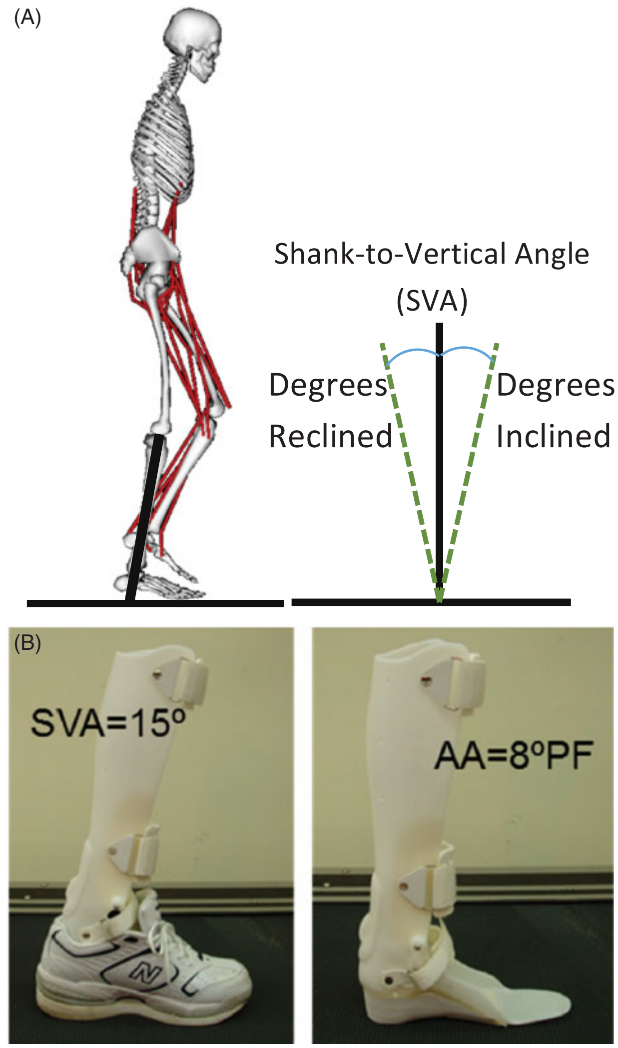

Figure 1. (A) Shank-to-vertical angle (SVA) is defined as being either reclined or inclined. During normal walking, the SVA at midstance is 10° inclined. (B) Alignment of the AFO-FC showing ankle angle (AA) set at 8° plantar flexion and SVA of 15° inclination when the orthosis is placed inside a modified shoe.

Gait analysis

An eight-camera real-time motion capture system (Motion Analysis Corporation, Santa Rosa, CA) was used to acquire three-dimensional marker data at 120 Hz. Markers were placed on the subject by the same investigator for all analyses based on a modified Helen-Hayes marker set [19]. Ground reaction forces were acquired at 960 Hz using six force plates (Advanced Mechanical Technology Inc., Watertown, MA).

Musculoskeletal modeling

OpenSim, an open-source musculoskeletal modeling and simulation software platform [20], was used to calculate gait kinematics and estimate musculotendon lengths. A generic musculoskeletal model with 19 degrees of freedom and 92 muscles [15] was scaled to the subject based upon anatomical landmarks. For each trial, inverse kinematics was used to calculate joint angles, minimizing the distance between the three-dimensional marker trajectories from gait analysis and virtual markers placed on the model.

Musculotendon operating lengths of major lower-limb muscles were calculated from the distance of each muscle's path from origin to insertion during the gait cycle. Muscle paths are based upon cadaveric and imaging data and have previously been used to evaluate muscle lengths and velocities in unimpaired individuals and individuals with neurological disorders [17]. To facilitate comparison with unimpaired individuals, musculotendon lengths were normalized by the length of each muscle with the hip, knee, and ankle joints in the anatomic position. The maximum operating length of the gastrocnemius was also estimated by calculating the length of the gastrocnemius with the knee in full extension and the ankle dorsiflexed to the maximum angle measured during the clinical exam. Joint kinetics were calculated using inverse dynamics. Joint kinematics, kinetics, and musculotendon operating lengths were normalized to 101 points for each gait cycle and averaged over a minimum of nine gait cycles for each condition.

Musculotendon operating lengths have previously been shown to be dependent on walking speed [21]. Hence, results were compared to previously collected kinematics and musculotendon lengths of a group of unimpaired subjects walking at very slow speeds ($N = 8$, data available at: https://simtk.org/home/mspeed-walksims) [22].

Results

Compared to unimpaired individuals, the subject walked with inadequate hip extension, excessive stance phase knee flexion, reduced stance phase ankle dorsiflexion, and reduced swing phase knee flexion on the paretic side when wearing shoes alone or the PLS AFO (Figure 2A–C). On the non-paretic side, hip, knee, and ankle kinematics were also abnormal with shoes alone and PLS AFO, with a prolonged support time (Figure 2D–F). For the same conditions (shoes alone and PLS AFO), the paretic side hamstrings operated at near normal maximum length at initial contact (Figure 3A, solid and dotted gray lines), while paretic side gastrocnemius length (Figure 3B, solid and dotted gray lines) was reduced during stance phase compared to unimpaired gait. Maximum paretic side gastrocnemius length in terminal

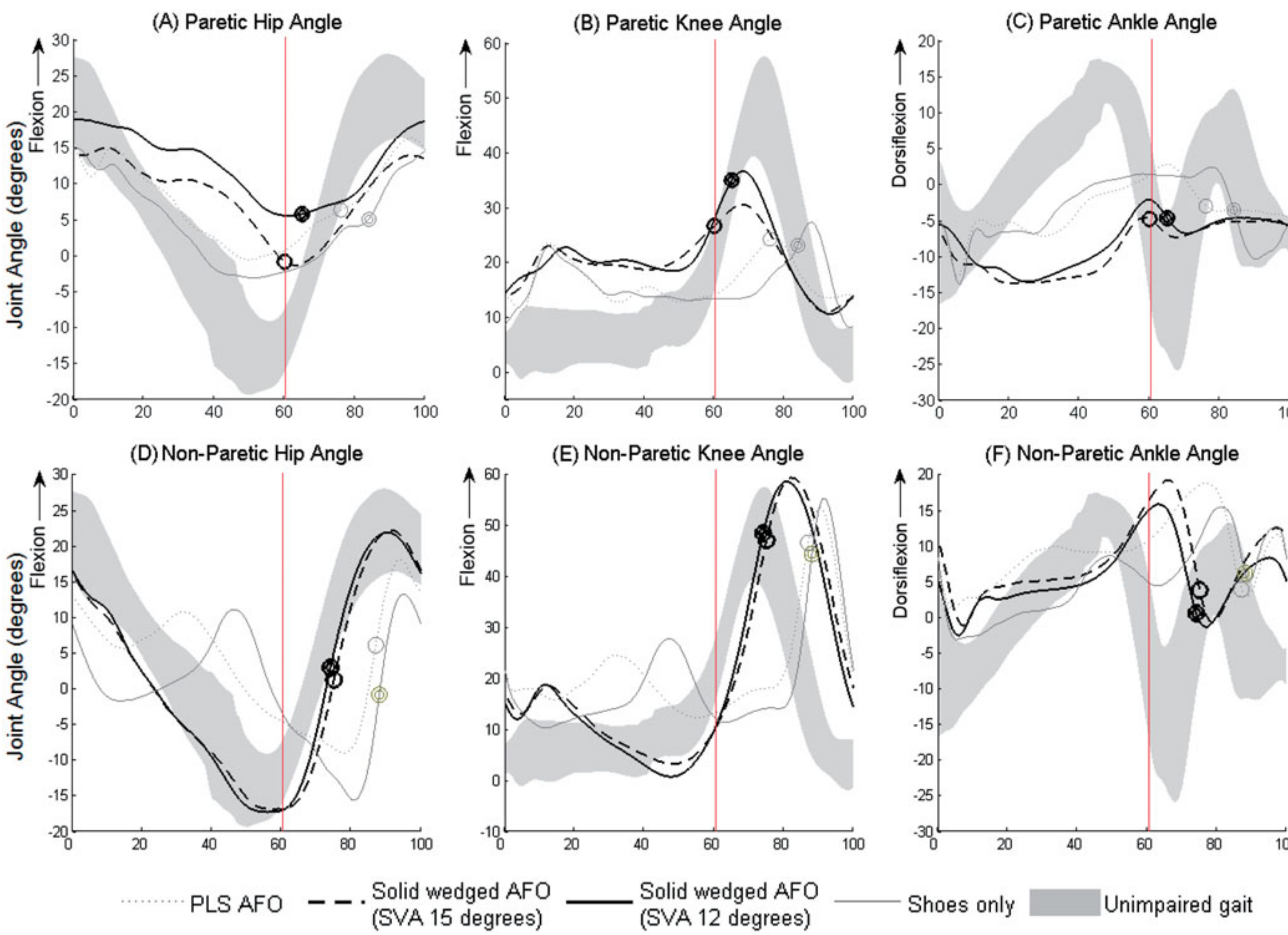

Figure 2. Average sagittal plane kinematics at the hip, knee, and ankle of the non-paretic and paretic sides with shoes alone (solid gray line), PLS AFO (dotted gray line), AFO-FC with 15° SVA (dotted black line) and AFO-FC with 12° SVA (solid black line) normalized to one gait cycle. The gray shaded band depicts the average ± one standard deviation of unimpaired gait at very slow speeds. Circles and vertical lines indicate toe-off for each condition for the subject with stroke and unimpaired individuals, respectively. Positive values of hip and knee angles are flexion and positive values of ankle angle are dorsiflexion.

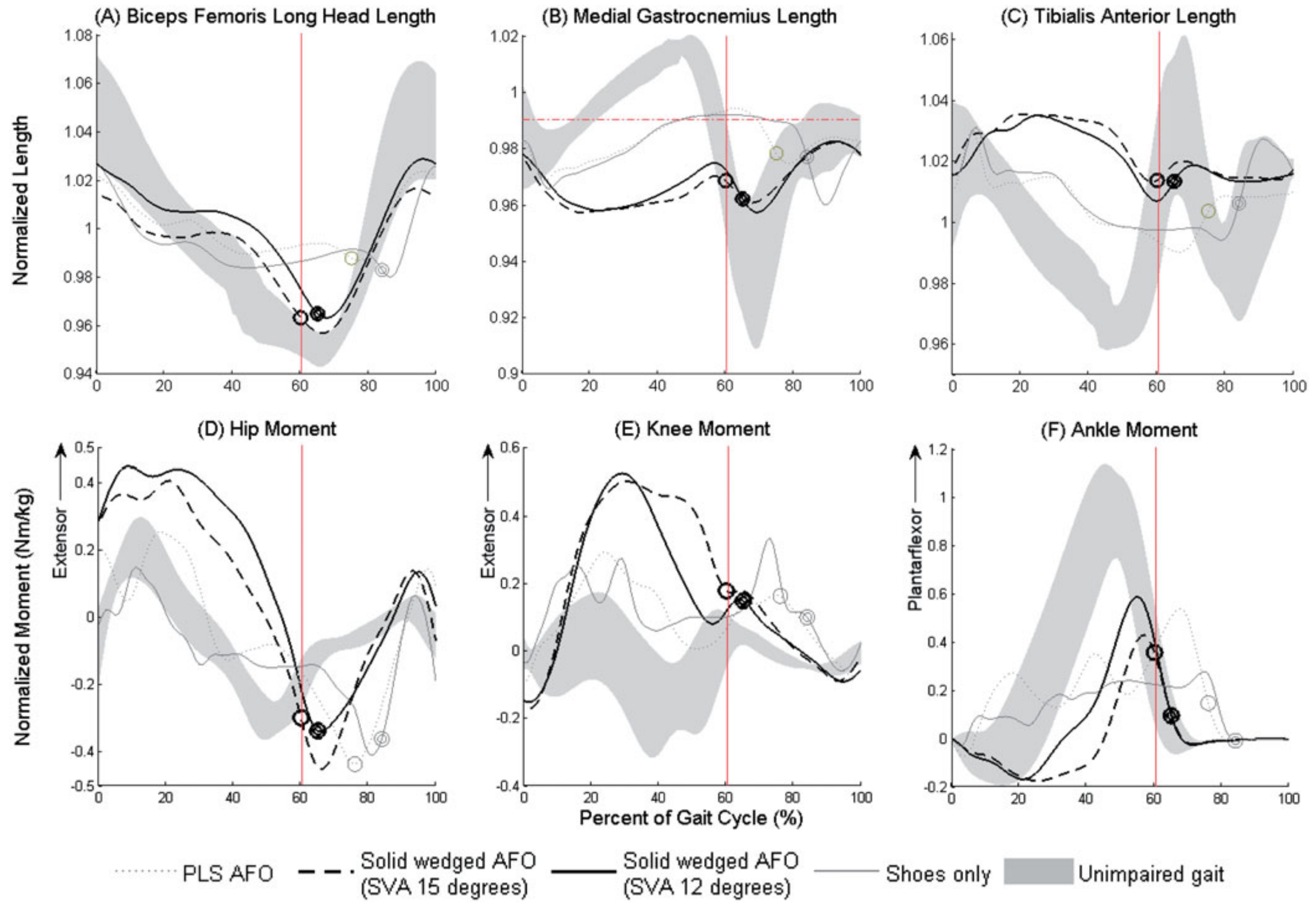

Figure 3. Average musculotendon operating length on the paretic side for the biceps femoris long head (A), medial gastrocnemius (B), and tibialis anterior (C) during trials with shoes alone (solid gray line), PLS AFO (dotted gray line), AFO-FC with SVA of 15° (dotted black line), and AFO-FC with SVA of 12° (solid black line) normalized to one gait cycle. The gray shaded band depicts the average ± one standard deviation of musculotendon operating lengths during very slow unimpaired gait. Circles and vertical lines indicate toe-off for each condition for the subject with stroke and unimpaired individuals, respectively. The horizontal dash-dot line in (B) depicts gastrocnemius length at maximum ankle dorsiflexion with the knee extended from the clinical exam. Musculotendon lengths were normalized by the length of each muscle in the anatomic position. Also shown are average sagittal plane internal joint moments at the hip (D), knee (E), and ankle (F) of the paretic side with shoes alone (solid gray line), PLS AFO (dotted gray line), AFO-FC with 15° SVA (dotted black line) and AFO-FC with 12° SVA (solid black line) normalized to one gait cycle.

stance was similar to the maximum length measured during passive ankle dorsiflexion in the clinical exam (Figure 3B, dash dot horizontal line).

Paretic limb kinematics at the hip, knee, and ankle improved with the AFO-FC at the second and third visits (Figure 2A–C). The AFO-FC reduced support time and improved joint motion on the non-paretic side compared to gait with shoes alone and the PLS AFO. At the second visit, the AFO-FC with SVA of 15° reduced toe-off time from 88 to 76% of the gait cycle on the non-paretic side and 77 to 61% of the gait cycle on the paretic side. Knee range of motion remained less than unimpaired gait, but improved from 19.3° and 13.4° with shoes alone and the PLS AFO, respectively, to 26.1° in the AFO-FC with SVA of 12° at the final visit.

Musculotendon operating lengths and joint moments on the paretic side were altered with the AFO-FCs (Figure 3A–C). In contrast to the shoes alone and PLS AFO conditions, the medial gastrocnemius did not exceed the maximum passive gastrocnemius length with the AFO-FCs because of the fixed plantar flexion angle. Although gastrocnemius operating length was reduced, paretic side knee extension during stance did not improve with the AFO-FCs (Figure 2B, solid and dotted black lines). However, changing the AFO-FC's SVA from 15° to 12° improved knee flexion during swing. Knee flexion during swing increased from 30.4° to 36.5° after re-tuning the AFO-FC. Hip flexion at heel contact improved from 14.1° to 18.8° with the retuned AFO-FC, but overall range of motion decreased. Reducing the AFO-FC's SVA from 15° to 12° also increased the internal ankle plantar flexor moment and decreased the internal knee extensor moment during terminal stance, helping to decrease the stiff-knee gait pattern.

Walking speed was also significantly improved with the AFO-FC. The subject's speed was 0.20 and 0.26 m/s (0.07 and 0.09 non-dimensional velocity) with the shoes alone and PLS AFO, respectively. With the initial AFO-FC, the speed was 0.59 m/s (0.21 non-dimensional velocity) and improved to 0.66 m/s (0.24 non-dimensional velocity) when the AFO-FC was re-tuned to an SVA of 12°. However, these speeds are still substantially less than the unimpaired subjects' very slow speed, which had an average non-dimensionalized velocity of 0.54 ± 0.04 (Table 1).

Discussion

In this case study, we used musculoskeletal modeling to evaluate the influence of AFO-FCs on musculotendon lengths and gait kinematics and kinetics. Our results indicate that the AFO-FC reduced gastrocnemius operating length during gait and improved walking speed, stiff-knee gait, and non-paretic limb kinematics compared to both shoes alone and a PLS AFO. Since the PLS AFO was not retested on the subject at the end of the study, we

Table 1. Temporal-spatial and kinematic changes in gait with each condition.

	First visit (11 months post-stroke) PLS AFO	Second visit (16 months post-stroke) AFO-FC (SVA 15°)	Third visit (17 months post-stroke)	
			AFO-FC (SVA 12°)	Shoe only
Stride length (cm)	45.5	72.8	76.0	47.3
Non-dimensional velocity*	0.09	0.21	0.24	0.07
Walking speed (meters/s)	0.26	0.59	0.66	0.20
Cadence (steps/min)	68.8	98.0	104.2	50.1
Step width (cm)	27.7	23.7	23.7	32.8
Paretic toe-off time (%)	77	61	66	85
Paretic hip range of motion (°)	17	16.4	13.4	18.1
Paretic knee range of motion (°)	13.4	19.7	26.1	19.3
Paretic ankle range of motion (°)	15.7	9.2	11.4	16.4

PLS AFO = posterior leaf spring ankle foot orthosis; AFO-FC = ankle foot orthosis-footwear combination; SVA = shank-to-vertical angle.
*The non-dimensional velocity normalizes walking velocity by $\sqrt{gL_{leg}}$, where g is gravity and L_{leg} is subject leg length.

cannot rule out the possibility that some of the improvement seen in the AFO-FC conditions were the result of motor recovery over time and that further improvements in gait with the PLS AFO may have also been achieved at the final visit. However, stance phase kinematics were highly similar between walking with shoes alone and PLS AFO, suggesting that the PLS AFO had minimal effects on gait kinematics and the subject used a similar gait pattern without AFO-FCs at the initial visit (11 months after stroke) and final visit (17 months after stroke). Given that PLS AFOs are designed primarily to assist swing phase ankle alignment, this similarity was unsurprising.

We had hypothesized that a shortened gastrocnemius was contributing to impaired knee motion and that reducing gastrocnemius operating length during gait with an AFO-FC would improve knee kinematics. Our hypothesis was partially supported by our results: we demonstrated that the gastrocnemius was operating at its maximum length during gait with the PLS AFO and shoes alone; while the AFO-FC reduced gastrocnemius operating length, knee kinematics improved in swing, but not stance.

Sagittal plane joint moments provide insight into the mechanisms underlying changes in knee kinematics. First, since gastrocnemius operating length was reduced throughout the gait cycle to below the subject's maximum length based on clinical exam, a shortened gastrocnemius no longer contributed to inadequate dorsiflexion or excessive knee flexion in stance. However, reducing the effect of a stiff/shortened gastrocnemius does not directly translate to improved knee kinematics. In swing, maximum knee flexion is largely dependent upon ankle and knee moments in terminal stance. With the AFO-FCs, the subject had greater internal ankle plantar flexor and knee extensor moments in terminal stance than with shoes alone (Figure 3E and F), which helped improve knee flexion in swing. With the initial AFO-FC (SVA of 15°), the internal ankle plantar flexor moment increased in terminal stance, but there was also an excessive internal knee extensor moment. Reducing the SVA from 15° to 12° shifted the orientation of the ground reaction force such that the internal ankle plantar flexor moment increased and the internal knee extensor moment decreased, improving knee flexion in swing [23]. This demonstrates the importance of tuning the SVA of AFO-FCs and that even a small change in SVA can have a dramatic effect on knee kinetics.

In stance, knee extension did not improve with the AFO-FCs, even though the gastrocnemius operating length was reduced. With shoes and the PLS AFO, the gastrocnemius was operating at its maximum length and likely contributed to inadequate ankle dorsiflexion and knee extension. While, the AFO-FC dramatically changed the dynamics of the ankle joint, a reduced gastrocnemius operating length did not translate to improved ankle and knee kinematics in stance. In unimpaired gait, the ankle plantar flexors play an important role in helping to extend the knee through dynamic coupling: ankle plantar flexion-knee extension couple [23,24]. In an AFO-FC, the ankle is held rigid and the ankle plantar flexor muscles can no longer contribute to knee extension acceleration. Furthermore, as SVA increases, the forward tilt of the shank causes greater knee flexion and increases the internal knee extensor moment required to maintain a stable posture. Additionally, increasing SVA shortens the foot lever, similar to high heels, creating a smaller effective moment arm about the ankle [25]. These changes highlight the complex, interacting factors that must be considered when tuning orthoses.

Conclusion

This case study illustrates how musculoskeletal modeling can be used to evaluate the role of individual muscles during walking, informing orthotic design to improve gait. We quantified changes in musculotendon lengths, kinematics, and kinetics when wearing an AFO-FC. The AFO-FC reduced gastrocnemius length, but did not improve knee extension in stance compared to shoes alone and the PLS AFO. However, overall gait improved with the AFO-FC, including faster walking speed and reduced stiff-knee gait. Further studies are needed to determine if changes in gastrocnemius operating length and effects on joint moments during gait are consistent across multiple subjects, as well as evaluate differences between orthotic designs. We believe finding the balance between optimizing musculotendon operating lengths and lower extremity joint moments can help improve orthotic designs.

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Declaration of interest

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