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Title: Kinematic features of rear-foot motion using anterior and posterior AFOs in stroke patients with hemiplegic gait

Article Type: Original Article

Keywords: Orthotic Devices; Stroke; Biomechanics; Gait

Corresponding Author: Dr. Simon F.T. Tang,

Corresponding Author's Institution:

First Author: Chih-Chi Chen

Order of Authors: Chih-Chi Chen; Wei-Hsien Hong; Chin-Man Wang; Chih-Kuang Chen; Katie Pei-Hsuan Wu; Chao-Fu Kang; Simon F.T. Tang

Abstract: Title: Kinematic features of rear-foot motion using anterior and posterior AFOs in stroke patients with hemiplegic gait

Running head: A-AFO and P-AFO use in hemiplegic gait

Key Words: Orthotic devices, Stroke, Biomechanics, Gait.

Objective: To evaluate the kinematic features of rear-foot motion during gait in hemiplegic stroke patients, using anterior ankle foot orthoses (A-AFOs), posterior AFOs (P-AFOs), and no orthotic assistance.

Design: Crossover design with randomization for the interventions.

Setting: A rehabilitation centre for adults with neurological disorders.

Participants: Fourteen patients with hemiplegia due to stroke and eleven able-bodied subjects.

Interventions: Subjects with hemiplegia were measured walking under 3 conditions with randomized sequences: (1) with an A-AFO, (2) with a P-AFO, and (3) without an AFO. Control subjects were measured walking without AFO to provide a normative reference.

Main Outcome Measures: Rear-foot kinematic change in the sagittal, coronal, and transverse planes.

Results: In the sagittal plane, as compared to walking with an A-AFO or without an AFO, the P-AFO significantly decreased plantarflexion to neutral at initial heel contact ($P = 0.001$) and the swing phase ($P < 0.001$), and increased dorsiflexion at the stance phase ($P = 0.002$). In the coronal plane, the A-AFO significantly increased maximal eversion to neutral (less inversion) at the stance phase ($P = 0.025$), and decreased the maximal inversion angle at the swing phase when compared with using no AFO ($P = 0.005$). The P-AFO also decreased the maximal inversion angle at the swing phase as compared to no

AFO (P = 0.005). In the transverse plane, when compared with walking without an AFO, the A-AFO and P-AFO decreased the adduction angle significantly at initial heel contact (P = 0.004).

Conclusions: For post-stroke hemiplegic gait, the P-AFO was better than the A-AFO in enhancing rear-foot dorsiflexion during the whole gait cycle. The A-AFO was superior to the P-AFO in correcting excessive rear-foot inversion at the stance phase. Both the A-AFOs and P-AFOs helped correct an inverted foot at the swing phase.

Key words: Orthotic Devices, Stroke, Biomechanics, Gait.

Dear Dr. Rodgers,

Thank you for your email telling me that the Editorial Board sees merit in my manuscript. Also I would like to thank Archives of PMR for finding two such outstanding and reasonable reviewers for me. Comments from the two reviewers were indeed very helpful. Revising the manuscript according to the comments from reviewers certainly made the manuscript more presentable.

We revised the manuscript as suggestion and focused on the areas as you pointed out, 1. Clarify comparison of kinematic variables between conditions, 2. Provide additional information about subjects and 3. Provide more description of the A-AFO.

The manuscript has been read by a native English speaker and edited for grammar errors. I hope you and the reviewers will like the revisions I have done. It will certainly be my greatest honor if this manuscript can be published in the renowned Archives of PMR.

Enclosed below you will find our replies to both reviews. We also made detailed comparison lists before and after revision for reviewers to easily review. Please allow us let one of our members as co-authors (Chao-Fu Kang, MD) because he helped a lot in revised this manuscript.

Thank you again. Please feel free to contact me at anytime if I can be of any further assistance. Take care!

Simon FT Tang
Professor and Program Director
Department of Physical Medicine and Rehabilitation,
Chang Gung Memorial Hospital
5, Fu-Hsin ST., Kwei-Shan, Tao-Yuan County, 333, Taiwan

Replies to Reviewer 1

➔As suggested by reviewer 1, we have checked all manuscript, clarified the comparisons and modulate those confusing statements.

➔Methods: We have added a more detailed description about the A-AFO. We have also corrected the typing errors about the P-AFO. We also added a description to explain why we let subjects walking barefoot with AFO.

➔Results: A table is now constructed as suggested. The table clearly provides information on the sex, age, time since stroke, involved side, Brunnstrom stage, muscle tone, use of assistive device, and prior AFO use.

➔A detailed comparison list before and after revision for reviewer 1 is listed in the following page.

Comparison List for Reviewer 1

Suggestion 1:

The comparison of kinematic variables between conditions often is not clear. Often times, the variable is described as "increased" or decreased" , but it is not clear what the value is being compared to. Examples are: page 7, line114-115; 116-117; 119; p8 129-130, and abstract. These are specific examples but the authors should check and clarify all comparisons.

Reply: We have checked all manuscript and clarify the comparison as following:

Before Revision	**After revision**
Abstract **Results** At initial heel contact, the rear-foot showed increased dorsiflexion while wearing P-AFOs (*P*=0.001). During the stance phase, wearing the P-AFO increased the dorsiflexion angle more significantly than wearing the A-AFO or nothing (*P*=0.002). The A-AFO lessened inversion and increased the maximal eversion angle (*P*=0.025). During the swing phase, decreased maximal plantarflexion and an increased dorsiflexion angle were noted only wearing the P-AFO (*P*<0.001). With both the A-AFO and P-AFO, the inversion angle was significantly decreased as compared to wearing nothing (*P*=0.005). **Conclusions** A-AFOs were superior in correcting excessive rear-foot inversion, while P-AFOs had the advantage in enhancing rear-foot dorsiflexion. P-AFOs also helped correct an inverted foot at the swing phase.	**Abstract** **Results** In the sagittal plane, as compared to walking with an A-AFO or without an AFO, the P-AFO significantly decreased plantarflexion to neutral at initial heel contact (*P* = 0.001) and the swing phase (*P* < 0.001), and increased dorsiflexion at the stance phase (*P* = 0.002). In the coronal plane, the A-AFO significantly increased maximal eversion to neutral (less inversion) at the stance phase (*P* = 0.025), and decreased the maximal inversion angle at the swing phase when compared with using no AFO (*P* = 0.005). The P-AFO also decreased the maximal inversion angle at the swing phase as compared to no AFO (*P* = 0.005). In the transverse plane, when compared with walking without an AFO, the A-AFO and P-AFO decreased the adduction angle significantly at initial heel contact (*P* = 0.004).

Before Revision	After revision
Abstract-Conclusions A-AFOs were superior in correcting excessive rear-foot inversion, while P-AFOs had the advantage in enhancing rear-foot dorsiflexion. P-AFOs also helped correct an inverted foot at the swing phase.	**Abstract-Conclusions** For post-stroke hemiplegic gait, the P-AFO was better than the A-AFO in enhancing rear-foot dorsiflexion during the whole gait cycle. The A-AFO was superior to the P-AFO in correcting excessive rear-foot inversion at the stance phase. Both the A-AFOs and P-AFOs helped correct an inverted foot at the swing phase.

Before Revision	After revision
Results (Page 7, line 114-119) At initial heel contact, the rear-foot showed increased dorsiflexion while wearing P-AFOs. The subjects showed a trend in decreasing the inversion rear-foot angle after wearing A-AFOs, but it was not significant (*P*=0.064). Wearing the A-AFO and the P-AFO decreased the adduction angle significantly. During the stance phase, wearing the P-AFO increased the dorsiflexion angle more significantly than wearing the A-AFO or nothing. The A-AFO lessened inversion and increased the maximal eversion angle. There was no significant difference in the maximal abduction angle in any of the AFO trials. During the swing phase, decreased maximal plantarflexion and an increased dorsiflexion angle were noted only wearing the P-AFO. With both the A-AFO and P-AFO, the inversion angle was significantly decreased as compared to wearing nothing. No significant difference could be seen in the abduction and adduction angles with or without the A-AFO or P-AFO.	**Results (page 8, line 136-146)** In the sagittal plane, as compared to walking with an A-AFO or without an AFO, the P-AFO significantly decreased plantarflexion to neutral at initial heel contact and the swing phase and increased dorsiflexion at the stance phase. In the coronal plane, the A-AFO significantly increased maximal eversion to neutral (less inversion) at the stance phase and decreased the maximal inversion angle at the swing phase when compared with not using an AFO. The P-AFO also decreased the maximal inversion angle at the swing phase when compared with not using an AFO. In the transverse plane, as compared to walking without an AFO, the A-AFO and P-AFO conditions decreased the adduction angle significantly at initial heel contact. There were no significant differences in maximal adduction and the maximal abduction angles among the three AFO conditions during the stance and swing phases respectively.

Before Revision	After revision
Discussion (p8 125-131) Our aim in this study was to assess the kinematic characteristics of rear-foot joint change during gait in hemiplegic stroke patients using A-AFOs, P-AFOs, and no orthotic assistance. Previously, the choice of anterior or posterior AFO was often based on the practitioner's experience and the patients' preference. In both the stance and the swing phases, our results showed that A-AFOs were superior in correcting excessive rear-foot inversion, while P-AFOs had the advantage in enhancing rear-foot dorsiflexion. P-AFOs also helped correct an inverted foot at the swing phase.	**Discussion** (p9 148-158) The incidence of equinovarus foot in stabilized vascular hemiplegia was reported to be about 18%.[17] The equinovarus foot shifts weight bearing from the heel to the lateral plantar surface, which can cause loss of balance and reduce walking safety. This condition also has a strong correlation to the presence of claw toes.[18, 19] An AFO has often been prescribed to facilitate ankle control for the equinus and/or varus foot. This study investigated the kinematic change in rear-foot joint control during gait in hemiplegic stroke patients using A-AFOs, P-AFOs, and no AFO assistance. As compared to using no AFO, the A-AFO decreased rear-foot inversion at the stance and swing phases. The P-AFO increased rear-foot dorsiflexion during the whole gait cycle in comparison with the A-AFO and P-AFO. The P-AFO also decreased rear-foot inversion at the swing phase as compared to using no AFO.

Suggestion 2:

In addition, in some locations, the comparison of the A-AFO to other conditions seems misleading. For example, the paper reads, 'our results showed that the A-AFOs were superior in correcting excessive rear foot inversion." (129-130; 171), but elsewhere (lines 134-136) the text indicates there were no differences in gait parameters between the brace conditions after statistical analysis.

Reply: We have clarified the comparison and modulate these confusing statements.

Before revision	**After revision**
Discussion (line 134-136) After wearing either A-AFOs or P-AFOs, we noted no significant difference in the gait parameters after statistical analysis.	**Discussion** (p10 line 161-162) After wearing either A-AFOs or P-AFOs, we noted no significant difference in walking speed, step length and cycle time after statistical analysis.

Suggestion 3.

The paper correctly states in several locations that brace selection will be dependent upon the patient's motor control and gait patterns (i.e., line 198). However, the study does not adequately describe the clinical characteristics of the people with a history of stroke to allow interpretation of the results. The authors should provide additional information about subjects; for example, severity of deficits (some type of standardized measure), tone, use of assistive device, and prior AFO use.

Reply:

We have added a table 1 to provide more detailed information about the subjects.

Table 1: Information about stroke subjects with hemiplegia

Subject Number	Sex	Age(y)	Years and months since stroke	Involved Side R/L	Brunnstrom stage of involved lower limb	Ankle MAS	Use of assistive device	Prior AFO use
1	M	47	5y6m	L	V	3	N	Y(A-AFO)
2	M	51	3y8m	L	IV	3	N	Y(A-AFO)
3	M	47	3y9m	R	V	1+	N	N
4	M	67	2y5m	L	IV	1+	N	N
5	M	60	7m	R	III-IV	3	N	Y(A-AFO)
6	M	53	5y4m	R	V	2	N	N
7	M	53	8m	L	III	2	N	N
8	M	51	3y4m	R	III	3	N	Y(A-AFO)
9	M	43	10m	L	V	2	N	Y(A-AFO)
10	M	70	5m	R	V	1+	N	N
11	W	49	2m	R	IV	2	N	Y(A-AFO)
12	W	56	2y2m	R	IV	2	N	Y(A-AFO)
13	W	72	1y	R	V	2	N	N
14	W	71	4y4m	L	IV	1+	N	Y(A-AFO)

MAS: Modified Ashworth Scale. N: no, Y: yes.

Suggestion 4, The A-AFO will not be familiar to many readers, and although it has been described elsewhere in the literature, it should be described in greater detail here; ie, specific anatomical boundaries of trim line, rationale for design.

Reply: We have added a more detailed description about the A-AFO.

Before revision	**After revision**
Method Nil (not mentioned before revision)	**Method** (p4 48-58) The A-AFO was made of a low temperature 3.2 mm thick thermoplastic material, Orfit.[a] A piece of thermoplastic was cut in the shape of a bottle cap opener (fig 1). The pretibial and ankle parts were padded with closed-cell foam, Kushionflex padding.[b] Subjects were asked to sit with their knee in a 90 degree flexion and their ankle in a neutral position. After softening the thermoplastic in a hot water tank (60°C), the anterior AFO was molded directly to the subject's lower limb, with her or his foot going through the hole in the bottle cap opener section. The sole part was 6 cm in width, with its anterior trim line just behind the metatarsal heads. The foot and ankle portions were folded to form the medial and lateral bars. The upper part was molded onto the ankle and lower half of the tibia without covering the medial and lateral malleoli. Velcro straps[c] were placed at the ankle level and upper part of the orthosis (see fig 2). Usually, we can make an A-AFO within half an hour.

Suggestion 5, The paper states that P-AFO trim lines were anterior to both malleoli (line 55), but such a trim line seems quite restrictive and different from Fig 1. Please clarify.

Reply: We have corrected the typing errors and added more description about the P-AFO.

Before revision	**After revision**
Method (p4 52-55) The AFO extended distally under the toes and covered the mediolateral border of the foot. Proximally, it covered the posterior portion of the leg to 5 cm below the fibular head. The trim lines were anterior to both malleoli. Three straps crossed the anterior upper tibia, front of the ankle, and the mid-foot area (See fig 1).	**Method** (p4 59-67) We used leaf-spring AFO in comparison with A-AFO not only because it is commonly used in clinical situations but it dose not cover malleoli, which is similar to the A-AFO. Each P-AFO was fabricated using polypropylene with the ankle in a neutral position. The footplate was cut to the metatarsal head. Proximally, it covered the posterior portion of the leg to 5 cm below the fibular head. The medial and lateral trim lines over the ankle were posterior to both malleoli. Three straps crossed the proximal end of shank, the front of the ankle, and the mid-foot area (see fig 2). We used three straps to hold the P-AFO instead of standard single strap at the upper shank because we let subjects walk barefoot with P-AFO without shoes assistance.

Suggestion 6, Why did subjects walk barefoot with P-AFO? In America, walking barefoot with a P-AFO would be very unusual.

Reply: We added a description to explain why we let subjects walking barefoot with P-AFO.

Before revision	**After revision**
Nil (not mentioned before revision)	**Method.** (P5 68-70) The decision to analyze subjects walking barefoot with AFOs was based upon: (1) our need to know the real function of the AFO without the assistance of a shoe; and, (2) our interest in conforming to the custom in Asia countries of walking barefoot indoors.

Replies to Reviewer 2

➔Introduction: As suggested by reviewer 2, we have added the suggested references to expose the interest of AFOS.

➔Methods: We made a hole at P-AFO to allow calcaneal marker directly placed on the skin. Thank you for reminding us to add the important description. We also added pictures to clarify the marker position.

➔Results: We have corrected the typing error in table 3.

➔Discussions: Thank you for your kindly suggestion. We have added the references and a discussion of risk of walking with equinovarus foot as your suggestion.

➔A detailed comparison list before and after revision for reviewer 2 is listed in the following page.

Comparison List for Reviewer 2

Reviewer 2

Suggestion 1.

Introduction:

Previous pertinent literature: page2, line15 to 24: The following article is missing in the references to expose the interest of AFOS: Ann Readapt Med Phys. 2008 Apr;51(3):147-53. Epub 2008 Jan 7.[Assessment of the Chignon dynamic ankle-foot orthosis using instrumented gait analysis in hemiparetic adults]. Bleyenheuft C, Caty G, Lejeune T, Detrembleur C.

Reply: We have added the suggested references to expose the interest of AFOS.

Before revision	After revision
Introduction (P2 19-22) Several studies evaluated the effects of posterior AFOs (P-AFOs) on stroke patients and demonstrated improvement in gait parameters including stride length, gait velocity and cadence,[4-6] gait stability,[4] balance control,[7] energy cost of walking,[8] and functional status.[5]	**Introduction** (P2 19-22) Several studies evaluated the effects of P-AFOs on stroke patients and demonstrated improvement in gait parameters including stride length, gait velocity and cadence,[4-6] gait stability,[4] balance control,[7] energy cost of walking,[8, 9] and functional status.[5] Reference 9.Bleyenheuft C, Caty G, Lejeune T, Detrembleur C. Assessment of the Chignon dynamic ankle-foot orthosis using instrumented gait analysis in hemiparetic adults. Ann Readapt Med Phys 2008;51(3):154-60.

Suggestion 2.

Methods : p5 line 63-65. it seems the posterior marker is placed on the p-AFO. In this condition, are the authors sure that the kinematic data show the mobility of the foot rather the mobility of the P-AFO. Please discuss this point.

Reply:

We made a hole at P-AFO to allow calcaneal marker directly placed on the skin. We have added the picture and statement in the methods.

Before revision	**After revision**
Method –Equipment (p5 62-64) A marker was placed on the midline of the calcaneal posterior process, and, with the subject standing, individual markers were also placed on the medial and lateral sides of the calcaneus in a plane parallel to the ground (fig 2).	**Method –Equipment** (p5 80-81) We made one hole in each P-AFO to allow placement of the calcaneal markers directly onto the skin (fig 2).

Suggestion 3.

P7 line 111 : the authors wrote that the stroke patients showed less maximal plantarflexion than the healthy control group, but the table 3 does not show that. Is there an error in the table 3?

Reply. We have corrected table 3 as following.

Table 3. Rear-foot kinematics during gait for the involved limb of stroke subjects an control subjects walking barefoot with their self-selected comfortable walking speec

Gait phase	Initial heel contact	Stance phase	Swing phase
Sagittal plane	Plantarflexion	Maximal Dorsiflexion	Maximal Plantarflexion
Angle			
Control	6.3±4.7	-8.6±2.9	8.4±3.6
Stroke	8.5±5.7	-2.4±6.4	5.4±4.0
P-value	0.307	0.018*	0.048*
Coronal plane	Inversion	Maximal Eversion	Maximal Inversion
Angle			
Control	-1.4±2.8	-4.6±3.0	7.7±2.6
Stroke	8.2±4.5	4.4±5.0	10.5±4.7
P -value	<0.001**	<0.001**	0.177
Transverse plane	Adduction	Maximal Adduction	Maximal Abduction
Angle			
Control	1.2±3.6	11.3±4.5	7.7±2.6
Stroke	8.9±4.3	11.5±5.5	3.7±5.4
P -value	<0.001**	0.850	0.118

*: $P < 0.05$; **: $P < 0.01$; plantarflexio (+), dorsiflexion (-); inversion (+), eversion (-); adduction (+), abduction (-).

Suggestion 4. Discussion: P8 line126-132 : Since the main result is the importance of the varus-foot stabilization with A-AFO it could be interesting to discuss the incidence of varus equinus and value its consequences on gait (see references below): Claw toes in hemiplegic patients after stroke.Laurent G, Valentini F, Loiseau K, Hennebelle D, Robain G.Ann Phys Rehabil Med. 2010 Mar;53(2):77-85. Epub 2010 Jan 13. English, French. PMID: 20097630 [PubMed - indexed for MEDLINE]
Epidemiology of pes varus and/or equinus one year after a first cerebral hemisphere stroke: apropos of a cohort of 86 patients] Verdié C, Daviet JC, Borie MJ, Popielarz S, Munoz M, Salle JY, Rebeyrotte I, Dudognon P. Ann Readapt Med Phys. 2004 Mar;47(2):81-6.

Reply: We have added the references and a discussion of risk of walking with equinovarus foot.

Before revision	**After revision**
Discussion (p8 126-132) Nil (not mentioned before revision)	**Discussion** (p9 148-151) The incidence of equinovarus foot in stabilized vascular hemiplegia was reported to be about 18%.[17] The equinovarus foot shifts weight bearing from the heel to the lateral plantar surface, which can cause loss of balance and reduce walking safety. This condition also has a strong correlation to the presence of claw toes.[18, 19] **Reference** 17. Verdie C, Daviet JC, Borie MJ, Popielarz S, Munoz M, Salle JY et al. [Epidemiology of pes varus and/or equinus one year after a first cerebral hemisphere stroke: apropos of a cohort of 86 patients]. Ann Readapt Med Phys 2004;47(2):81-6. 19. Laurent G, Valentini F, Loiseau K, Hennebelle D, Robain G. Claw toes in hemiplegic patients after stroke. Ann Phys Rehabil Med 2010;53(2):77-85.

Suggestion 5. Moreover, since the A-AFO is superior in correcting excessive rear-foot inversion, a discussion of risk of walking with a varus-equinus foot could be interesting.

Reply:

Besides the discussion of altered rear-foot kinematics in hemiplegic gait and its consequences in altered gait pattern (p11 181-184). We have added a discussion of risk of walking with equinovarus foot as your suggestion.

Before revision	After revision
Nil (not mentioned before revision)	**Discussion** (p9 149-151) The equinovarus foot shifts weight bearing from the heel to the lateral plantar surface, which can cause loss of balance and reduce walking safety. This condition also has a strong correlation to the presence of claw toes.[18, 19]

*Title page with author details

Word counts for the main text: 2969, Word counts for Abstract: 333.

Title: **Kinematic features of rear-foot motion using anterior and posterior AFOs in stroke patients with hemiplegic gait**

Names and affiliations of the authors: Chih-Chi Chen, MD[1], Wei-Hsien Hong, PHD[2], Chin-Man Wang MD[1], Chih-Kuang Chen, MD[1], Katie Pei-Hsuan Wu, MD[1] , Chao-Fu Kang, MD[1] & Simon F.T. Tang, MD[1]

From the [1.] Department of Physical Medicine and Rehabilitation, Chang Gung Memorial Hospital and Chang Gung University, Linkou and [2.] School of Sports Medicine, China Medical University, Taichung, Taiwan

Running head: A-AFO and P-AFO use in hemiplegic gait

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Corresponding author:

Professor Simon F.T. Tang, MD

Department of Physical Medicine & Rehabilitation
Chang Gung Memorial Hospital & Chang Gung University Taoyuan, Taiwan
5, Fu-Hsin St, Kwei-Shan, Tao-Yuan, 333, Taiwan
Tel: +886-3-328-1200 ext. 3846
Fax:+886-3-327-4850
E-mail: fttang@adm.cgmh.org.tw
bluegirl5477@yahoo.com.tw

Title: **Kinematic features of rear-foot motion using anterior and posterior AFOs in stroke patients with hemiplegic gait**

Running head: A-AFO and P-AFO use in hemiplegic gait

Key words: Orthotic Devices, Stroke, Biomechanics, Gait.

Introduction

Stroke patients often have upper motor neuron syndrome with a resultant loss of strength and dexterity, impaired motor control, increased spasticity, hyperreflexia, co-contraction, and spastic dystonia in the affected limbs. These conditions result in inappropriate and involuntary posturing and contribute to abnormal gait pattern and impaired walking ability.[1] Clinically, we can identify more than one type of gait pattern across stroke patients, such as the equinus and equinovarus gaits, indicating that people who have suffered strokes need to use different strategies to achieve the goal of walking.[2]

AFOs are often prescribed to stroke patients and are designed to provide mediolateral ankle stability during stance and adequate toe clearance during swing and to promote heel strike.[3] Conventional plastic AFOs have a posterior leaf-type design, and are fabricated by a lamination or vacuum-forming technique over a positive plaster model of the limb.[4] A-AFOs are low-temperature ankle foot orthoses commonly used in Asian countries for convenience when walking indoors. Several studies evaluated the effects of P-AFOs on stroke patients and demonstrated improvement in gait parameters including stride length, gait velocity and cadence,[4-6] gait stability,[4] balance control,[7] energy cost of walking,[8, 9] and functional status.[5] Some studies evaluated the A-AFO function and suggested that A-AFOs also work effectively for gait parameters,[10] walking ability,[11] and balance control[12] in hemiplegic stroke patients.

Since ankle motor control in stroke patients is variable, and the designs of A-AFOs and P-AFOs are different, we speculated that different post-stroke gait patterns could benefit from different AFO types. We analyzed the shank-calcaneus rotation angle, as representative of rear-foot movement, by means of a 3-dimensional motion analysis system.[13] To our knowledge, this is the first study to compare the kinematic changes in rear-foot movement during gait in hemiplegic stroke patients using either A-AFOs or P-AFOs.

Methods

Subjects

For this study, we recruited 14 stroke subjects with hemiplegia. The inclusion criteria for the study group were as follows: (1) diagnosis of unilateral hemiplegia caused by either hemorrhagic or ischemic stroke; (2) ability to follow simple verbal commands or instructions; and, (3) ability to ambulate independently. Subjects were excluded if they had any of the following conditions: (1) medical problems other than stroke that would interfere with their gait; or, (2) foot-related premorbid or comorbid orthopedic problems. All patients underwent neuroimaging studies, including computed tomography or magnetic resonance imaging of the brain to confirm the diagnosis of stroke at an early stage. We also recruited 11 normal subjects, who had no known neurological and orthopedic impairments, to serve as our control group. This study was approved by the local medical ethics and the human clinical trial committees (Chang Gung Memorial Hospital, Taiwan), and all participants signed the informed consent.

AFO design

A-AFOs and P-AFOs for the study were custom-made for each subject by a certified orthotist. Fabrication of an anterior AFO was well documented in our previous study.[11] The A-AFO was made of a low temperature 3.2 mm thick thermoplastic material, Orfit.[a] A piece of thermoplastic was cut in the shape of a bottle cap opener (fig 1). The pretibial and ankle parts were padded with closed-cell foam, Kushionflex padding.[b] Subjects were asked to sit with their knee in a 90 degree flexion and their ankle in a neutral position. After softening the thermoplastic in a hot water tank (60°C), the anterior AFO was molded directly to the subject's lower limb, with her or his foot going through the hole in the bottle cap opener section. The sole part was 6 cm in width, with its anterior trim line just behind the metatarsal heads. The foot and ankle portions were folded to form the medial and lateral bars. The upper part was molded onto the ankle and lower half of the tibia without covering the medial and lateral malleoli. Velcro straps[c] were placed at the ankle level and upper part of the orthosis (see fig 2). Usually, we can make an A-AFO within half an hour.

The P-AFO used in this study was the plastic leaf-spring AFO[14]. We used leaf-spring AFO in comparison with A-AFO not only because it is commonly used in clinical situations but it dose not cover malleoli, which is similar to the A-AFO. Each P-AFO was fabricated using polypropylene with the ankle in a neutral position. The footplate was cut to the metatarsal head. Proximally, it covered the posterior portion of the leg to 5 cm below the fibular head. The medial and lateral trim lines over the ankle were posterior to both malleoli. Three straps crossed the proximal end of shank, the front of the ankle, and the mid-foot area (see fig 2). We used three straps to hold the P-AFO instead of standard single strap at the upper shank because we let subjects walk barefoot with P-AFO without shoes assistance. The decision to analyze subjects walking barefoot with AFOs was based upon: (1) our need to know the real function of the AFO without the assistance of a shoe; and, (2) our interest in conforming to the custom in Asia countries of walking barefoot indoors.

Equipment

A Vicon motion analysis system[c] was used to collect the kinematic data. The Vicon MS system included 8 infrared cameras for acquiring, at a rate of 100Hz, the kinematic trajectories of the reflective markers attached to the subject's lower limbs. We placed 7 spherical retro-reflective markers (diameter 1.4 cm) directly on the subject's affected-side calcaneus and shank. Two markers were placed on the medial and lateral tibial condyles, and 2 markers were also placed on the medial and lateral malleoli. A marker was placed on the midline of the calcaneal posterior process, and, with the subject standing, individual markers were also placed on the medial and lateral sides of the calcaneus in a plane parallel to the ground. We made one hole in each P-AFO to allow placement of the calcaneal markers directly onto the skin (fig 2). Three-dimensional marker trajectories were used to determine the rear-foot motion angles in the sagittal (dorsiflexion–plantarflexion), coronal (inversion–eversion), and transverse (abduction–adduction) planes.

Data collection

We evaluated and recorded stroke participants' motor recovery and ankle muscle tone using a Brunnstrom stage[15] and modified Ashworth Scale (MAS),[16] respectively. All subjects practiced walking with and without the orthosis before we performed the gait analysis. Each subject was asked to stand still for one second to allow all of the cameras to record the markers to analyze the subject's initial anatomical position. Each subject was then measured walking at a self-selected, comfortable speed in each of three orthotic trials (barefoot without an AFO, with a P-AFO, and with an A-AFO) during the same session. The order of the three trials was randomized. Subjects were allowed to rest for 5 minutes between trials. The walkway was carpeted to avoid any discomfort when the subjects walked barefoot without an AFO. To reduce measurement errors during gait analysis, data were collected from three successful trials. The data from these three trials were averaged and the results were used for the statistical analysis.

Data analysis

A LabView software package[d] was designed to analyze rear-foot motion. A joint coordinate system examined the relative rotation matrices of the marker reference frames on the calcaneus with respect to those on the shank. The neutral position was defined as the standing position. The calculated rotation matrices in the neutral position were used to correct the joint. Euler angles were used to define the three-dimensional relative joint angular motion. From this neutral position, the distal segment was assumed to move through three successive finite rotations to attain its new configuration. The first rotation was dorsiflexion–plantarflexion about the z-axis of the proximal segment, followed by inversion–eversion about a rotated floating x-axis. Finally, the third rotation was the abduction–adduction rotation about the distal to proximal direction (y-axis) of the distal segment. The temporal and spatial gait parameters were computed, including walking speed, step length, cycle time, and angles of the rear-foot joint.

Statistical Analysis

We used SPSS version 12 software[e] for the statistical analysis. Group differences in age, body height, and body mass were compared using an independent t-test. Gender differences between the groups were determined using a χ2 test. The gait parameters were compared using repeated measures analysis of variance (ANOVA) to determine significant differences among the AFOs and groups. *Post hoc* Bonferroni tests were used to evaluate the significance of pairwise comparisons between the AFOs. The level of significance used was $P < 0.05$.

Results

Descriptive information regarding the 14 participants with hemiplegia is listed in table 1. Comparisons of demographic data, including age, gender, body height, and body weight between the stroke and normative subjects are listed in table 2. The hemiplegic stroke subjects walked at a significantly slower, self-selected, comfortable walking speed, had decreased step length, and longer cycle times than the control group. When comparing the A-AFO, P-AFO, and barefoot conditions in the hemiplegic stroke subjects, there was no significant difference in the self-selected, comfortable walking speeds, step lengths, and cycle times (see table 3).

Rear-foot kinematic changes during gait in both the stroke and normal subjects when barefoot are shown in table 4 and figure 3. At initial heel contact, the rear-foot movement of the stroke patients showed increased inversion and adduction in comparison with the healthy control subjects. During the stance phase, the stroke patients showed less dorsiflexion and more inversion in the rear-foot angle. During the swing phase, the rear-foot of the stroke patients showed less maximal plantarflexion and less dorsiflexion than the healthy control group. Actually, they all showed the gait pattern as equinovarus gait.

Comparisons of the rear-foot angular motions in hemiplegic stroke subjects in the A-AFO, P-AFO, and without AFO conditions are shown in figures 3 and 4. In the sagittal plane, as compared to walking with an A-AFO or without an AFO, the P-AFO significantly decreased plantarflexion to neutral at initial heel contact and the swing phase and increased dorsiflexion at the stance phase. In the coronal plane, the A-AFO significantly increased maximal eversion to neutral (less inversion) at the stance phase and decreased the maximal inversion angle at the swing phase when compared with not using an AFO. The P-AFO also decreased the maximal inversion angle at the swing phase when compared with not using an AFO. In the transverse plane, as compared to walking without an AFO, the A-AFO and P-AFO conditions decreased the adduction angle significantly at initial heel contact. There were no significant differences in maximal adduction and the maximal abduction angles among the three AFO conditions during the stance and swing phases respectively.

Discussion

The incidence of equinovarus foot in stabilized vascular hemiplegia was reported to be about 18%.[17] The equinovarus foot shifts weight bearing from the heel to the lateral plantar surface, which can cause loss of balance and reduce walking safety. This condition also has a strong correlation to the presence of claw toes.[18, 19] An AFO has often been prescribed to facilitate ankle control for the equinus and/or varus foot. This study investigated the kinematic change in rear-foot joint control during gait in hemiplegic stroke patients using A-AFOs, P-AFOs, and no AFO assistance. As compared to using no AFO, the A-AFO decreased rear-foot inversion at the stance and swing phases. The P-AFO increased rear-foot dorsiflexion during the whole gait cycle in comparison with the A-AFO and

P-AFO. The P-AFO also decreased rear-foot inversion at the swing phase as compared to using no AFO.

In comparison with the normal controls in our study, the stroke subjects showed significantly decreased gait parameters including walking speed, step length, and cycle time. After wearing either the A-AFOs or P-AFOs, we noted no significant differences in the walking speed, step lengths, and cycle times after statistical analysis. Such results were not compatible with the previously mentioned studies,[4-6] but were similar to other studies.[1, 20, 21] The relatively small number of cases, variable improvement in patients' wearing different types of AFO, (improvement in gait speed when wearing A-AFOs as opposed to decreases in gait speed when wearing P-AFOs or vice versa), may explain the insignificant statistical results. According to the study of Perry et al, a difference of 20 cm/s in walking speed was defined as clinically significant.[22] Even though some studies showed an improvement in gait speed in stroke patients after wearing AFOs, most of the improvements were too small to reach clinical significance.[5]

In healthy subjects, the rear-foot tended to plantarflex at initial heel contact, and then dorsiflex during the stance phase and mid-swing phase in the sagittal plane. In the coronal plane, the rear-foot inverted at initial heel contact and then everted until terminal stance when it inverted. These findings are compatible with previous studies.[12,15] W. Liu et al evaluated rear-foot kinematic changes in healthy subjects and found that repeatable patterns between subjects can be observed in dorsiflexion/plantarflexion and inversion/eversion, suggesting that these characteristic changes are essential for efficient level walking. The inconsistent kinematic changes in the abduction/adduction angle between the studies may be explained by the angle's secondary importance to level walking. Each individual may adopts his/her own strategy and his/her specific motion characteristics.[23]

We noted that hemiplegic stroke subjects have altered rear-foot kinematics during gait, such as rear-foot inversion and adduction at initial heel contact. It has been suggested that foot eversion during the stance phase provides shock absorption on floor impact.[24] Increased rear-foot inversion at initial heel contact only offers shock absorption from the toe and lateral border of the foot, but increases the stress on the contact area.[25] During the stance phase, rear-foot control in the hemiplegic stroke patients became more plantarflexed and still inverted. This plantarflexion and rear-foot inversion may interfere with adequate pushing motion generation during propulsion.[26] During the swing phase of stroke subjects, the rear-foot remained in the plantarflexion position and could not accomplish dorsiflexion well. Inadequate dorsiflexion may interfere with foot clearance. Perry found that the hemiplegic stroke patients had inadequate shock absorption at heel strike, poor control of momentum during stance, and inadequate excursion of the paretic limb during swing.[27] Our study suggests that these observations may be explained by the abnormal kinematic changes in rear-foot control in our stroke patients.

After hemiplegic stroke subjects wore the two types of AFOs, their rear-foot control at initial heel contact was in a more dorsiflexed position with P-AFOs as compared to the A-AFOs and no AFO, and was less adducted with both the A-AFOs and P-AFOs when compared to using no AFO. During the stance phase, the P-AFO increased the dorsiflexion angle when compared with the A-AFO and no AFO, while the A-AFO corrected an inverted rear-foot more effectively when compared with not using an AFO. At the swing phase, the P-AFO kept the rear-foot in the dorsiflexion position in comparison with the A-AFO and no AFO, and both the A-AFO and P-AFO decreased the inverted angle as compared to using no AFO. The kinematic findings for the P-AFO in the sagittal plane were compatible with Stefania Fatone et al's study, which showed that all patients tested with P-AFOs with different AFO alignments and foot-plate lengths were able to decrease their plantar flexion of the ankle at initial contact and mid-swing.[1] Our study also suggested that the A-AFOs had a greater effect on inverted rear-foot control than the P-AFOs and going barefoot, especially in the stance phase.

We speculated that the different effects of AFO type on the rear-foot kinematic change may relate to the design differences. The P-AFO, with its sole extending the length from heel to sulcus and posterior reinforcement to stiffen its plantar flexion resistance feature, may prevent ankle plantarflexion effectively. Their medial and lateral trim lines posterior to both malleoli allowed sufficient flexibility and helped dorsiflexion effectively but helped less in controlling inverted ankle. The A-AFO, with its small sole band just under the metatarsal and lack of posterior reinforcement, may have limited its ability to prevent plantarflexion. However, its continuous coverage from the metatarsal and tarsal to shank may fix the subtalar joint and prevent rear-foot inversion more effectively. Although the rear-foot kinematics after AFO correction were still different from those of the normal subjects, the A-AFOs and P-AFOs did play a role in correcting and normalizing the rear-foot angle of hemiplegic subjects after statistical analysis. Such change may contribute to the functional improvement noted in previously mentioned studies in gait stability, balance control, energy cost, and patients' function. Other integrated strategies are still needed to improve stroke patients' gait pattern.[28]

There are some limitations in this study. First, a relatively small number of cases were recruited for this study. Second, the healthy control group did not walk as slowly as the stroke subjects, given that forcing such a slow speed on a healthy person would result in unnatural gait patterns and thereby increase the variables. Third, we studied the rear-foot kinematic change as representative of the ankle joint, since it can be easily marked and compared well with the typical ankle gait analysis [13]. Fourth, we only analyzed the posterior leaf-spring AFO, which provide little effects in controlling inverted ankle, in representative of P-AFO in this study. Further study should evaluate the rear-foot, mid-foot, and fore-foot motions under different AFO designs and conditions.

Conclusions

The results of our study suggested that for post-stroke hemiplegic gait, the P-AFO was better than A-AFO in enhancing rear-foot dorsiflexion during the whole gait cycle. The A-AFO was superior to the P-AFO in correcting excessive rear-foot inversion at the stance phase. Both the A-AFOs and P-AFOs helped correct inverted foot at the swing phase. The choice between A-AFO and P-AFO should not only be made by considering the patients' preference and the practitioners' expertise, but should also be based on the patients' motor control and resultant gait characteristics. We report our results here in anticipation that they will be applied to AFO selection in hemiplegic stroke patients.

Acknowledgement:

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Figure Legends

Figure 1. A piece of thermoplastic was cut in the shape of a bottle cap opener

Figure 2. The arrangement of markers on the shank and calcaneus in anterior AFO (A, B) and posterior AFO (C, D) conditions

Figure 3. Angular motion of rear-foot in both groups: plantarflexion (+); dorsiflexion (-); inversion (+); eversion (-); adduction (+); abduction (-); Asterisks (*) indicate points in the gait cycle where the difference in angles with and without AFOs was significantly different. Vertical lines indicate mean toe-off for each cycle with and without AFOs. The solid line shows toe-off for the A-AFO trial, the dash line for the P-AFO trial, and the dot line for toe-off without an AFO.

Figure 4. Angular comparisons of rear-foot with and without AFOs. *: $P<0.05$; plantarflexion (+), dorsiflexion (-); inversion (+), eversion (-); adduction (+), abduction (-).

Table 1

Table 1: Information about stroke subjects with hemiplegia

Subject Number	Sex	Age(y)	Years and months since stroke	Involved Side R/L	Brunnstrom stage of involved lower limb	Ankle MAS	Use of assistive device	Prior AFO use
1	M	47	5y6m	L	V	3	N	Y(A-AFO)
2	M	51	3y8m	L	IV	3	N	Y(A-AFO)
3	M	47	3y9m	R	V	1+	N	N
4	M	67	2y5m	L	IV	1+	N	N
5	M	60	7m	R	III-IV	3	N	Y(A-AFO)
6	M	53	5y4m	R	V	2	N	N
7	M	53	8m	L	III	2	N	N
8	M	51	3y4m	R	III	3	N	Y(A-AFO)
9	M	43	10m	L	V	2	N	Y(A-AFO)
10	W	70	5m	R	V	1+	N	N
11	W	49	2m	R	IV	2	N	Y(A-AFO)
12	W	56	2y2m	R	IV	2	N	Y(A-AFO)
13	W	72	1y	R	V	2	N	N
14	W	71	4y4m	L	IV	1+	N	Y(A-AFO)

MAS:Modified Ashworth Scale. N: no, Y: yes.

Table 2

Table 2. Comparisons of demographic data between stroke and normative subjects

Groups Demographic data	Stroke subjects (n=14)	Normal subjects (n=11)	*P* value
Age (years)	56.4 ± 9.8	55.6 ± 8.2	0.842
Gender (Men/Women)	9/5	5/6	0.435
Body height (cm)	161.0 ±9.5	158.3 ± 5.6	0.415
Body mass (kg)	64.0 ± 9.7	60.9 ± 9.9	0.439

.

Table 3

Table 3. Gait parameters of AFO conditions in stroke subjects and normal subjects

	Stroke patients			Normal subjects
Plane	A-AFO	P-AFO	Barefoot	Barefoot
Speed (%BH/sec)	32.8±11.1	31.6±10.9	31.9±11.6	66.5±3.9
Step length (%BH)	9.6±6.2	9.2±5.9	9.8±6.6	29.4±4.1
Cycle time (sec)	4.0±1.4	4.2±1.4	3.9±1.5	2.2±0.3

Table 4

Table 4. Rear-foot kinematics during gait for the involved limb of stroke subjects and control subjects walking barefoot with their self-selected, comfortable walking speed.

Gait phase	Initial heel contact	Stance phase	Swing phase
Sagittal plane	Plantarflexion	Maximal Dorsiflexion	Maximal Plantarflexion
Angle (degree)			
Control	6.3±4.7	-8.6±2.9	8.4±3.6
Stroke	8.5±5.7	-2.4±6.4	5.4±4.0
P-value	0.307	0.018*	0.048*
Coronal plane	Inversion	Maximal Eversion	Maximal Inversion
Angle (degree)			
Control	-1.4±2.8	-4.6±3.0	7.7±2.6
Stroke	8.2±4.5	4.4±5.0	10.5±4.7
P -value	<0.001**	<0.001**	0.177
Transverse plane	Adduction	Maximal Adduction	Maximal Abduction
Angle (degree)			
Control	1.2±3.6	11.3±4.5	7.7±2.6
Stroke	8.9±4.3	11.5±5.5	3.7±5.4
P -value	<0.001**	0.850	0.118

*: $P < 0.05$; **: $P < 0.01$; plantarflexio (+), dorsiflexion (-); inversion (+), eversion (-); adduction (+), abduction (-).

Figure 1

Figure 2

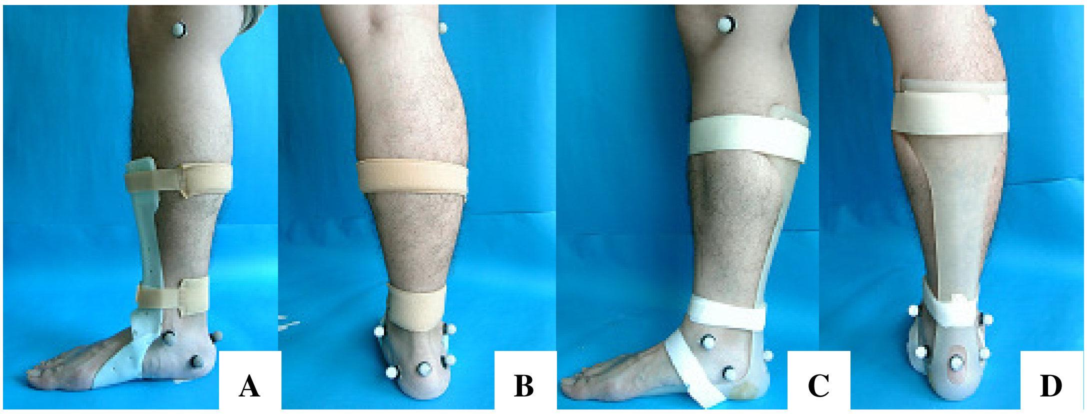
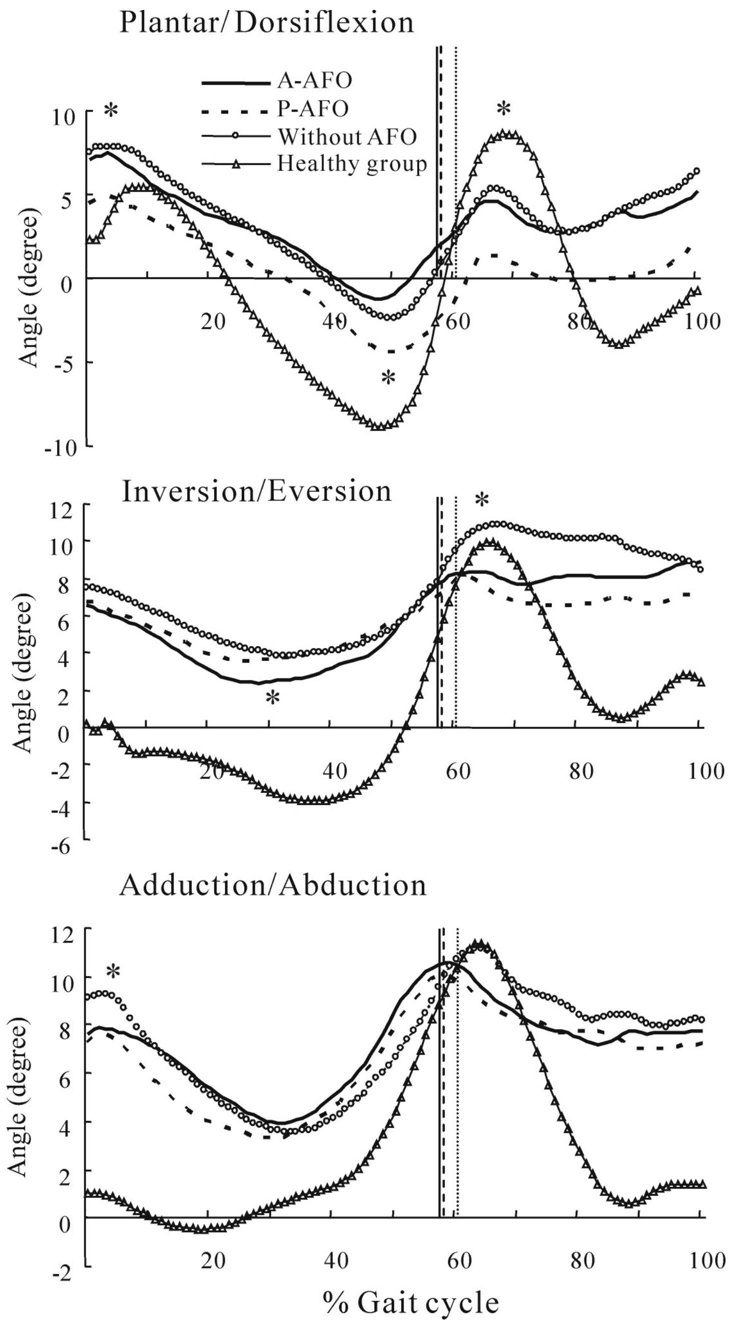
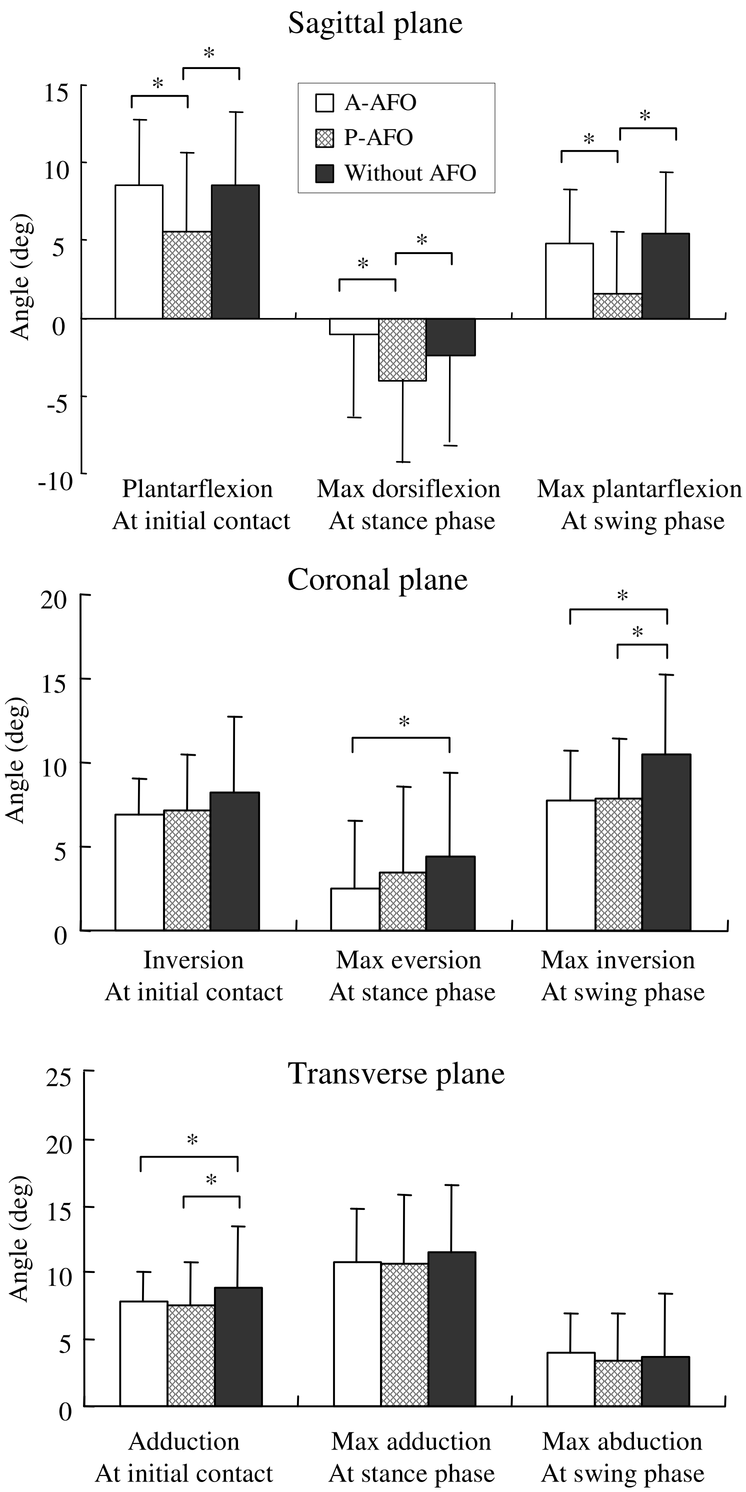


Figure 3



Plantar/Dorsiflexion
A-AFO
P-AFO
Without AFO
Healthy group
Angle (degree)
10
5
0
-5
-10
20
40
60
80
100
*
*
*
Inversion/Eversion
Angle (degree)
12
10
8
6
4
2
0
-2
-4
-6
20
40
60
80
100
*
*
Adduction/Abduction
Angle (degree)
12
10
8
6
4
2
0
-2
20
40
60
80
100
*
% Gait cycle

Figure 4



Sagittal plane
A-AFO
P-AFO
Without AFO
Angle (deg)
15
10
5
0
-5
-10
*
Plantarflexion
At initial contact
Max dorsiflexion
At stance phase
Max plantarflexion
At swing phase
Coronal plane
20
15
10
5
0
Inversion
At initial contact
Max eversion
At stance phase
Max inversion
At swing phase
Transverse plane
25
Adduction
At initial contact
Max adduction
At stance phase
Max abduction
At swing phase

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