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ORIGINAL RESEARCH ARTICLE

Shank-to-Vertical Angle in Ankle-Foot Orthoses: A Comparison of Static and Dynamic Assessment in a Series of Cases

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ABSTRACT

Background: Tuning of ankle-foot orthosis footwear combinations (AFO-FC) has been shown to be effective in aligning the ground reaction force (GRF) closer to the joint rotation center of the lower limbs. The notion of "tuning" the AFO-FC is largely dependent on the shank-to-vertical angle (SVA), which is measured while the subject is static but is meant to represent the SVA in mid-stance.

Objectives: The aim of this study was to compare the SVA measured in standing position with the SVA at temporal mid-stance (TMST) in a series of cases.

Study Design: This study is a case series.

Methods: Four participants had their AFO-FC tuned to optimum SVA using video-based gait analysis with GRF overlay. Initially, the SVA was measured with the subject standing in relaxed stance on the force plate with approximately equal weight on both feet. The SVA was then assessed at TMST.

Results: The measurement of the SVA of the AFO-FC in relaxed stance seems to be the same as the measurement of the SVA in TMST.

Conclusions: Measuring the SVA of the AFO-FC in relaxed stance is an accurate way of determining the SVA at TMST.

Clinical Relevance: Ankle-foot orthosis footwear combination tuning is considered an essential aspect of AFO prescriptions. The SVA is a key principle of AFO-FC tuning. The method for determining the SVA has yet to be tested to ensure that the static measurement correlates to the dynamic measurement during gait. (*J Prosthet Orthot*. 2017;29:00–00)

KEY INDEXING TERMS: orthotic devices, AFO tuning, ankle-foot orthoses, cerebral palsy, gait, shank-to-vertical angle

Ankle-foot orthoses (AFOs) are commonly prescribed to patients in an attempt to normalize joint kinetics and kinematics during gait. It is clear from the available literature that different designs of AFOs can significantly affect the kinetics and kinematics of gait.[1–30] Patients with pathological gait have abnormal lower-limb kinematics, particularly at the shank segment (see Winters et al.[31] and Rodda et al.[32] for classification of gait in cerebral palsy, and Owen[33,37,42,43,46] for details on abnormal shank kinematics). Attempting to normalize the shank kinematics offers a greater chance of optimum thigh and trunk kinematics and knee and hip kinetics.[33,34] Tuning the AFO and the footwear combination (AFO-FC) has been demonstrated to optimize the ground reaction force (GRF) during gait[33–37] and has been recognized as an essential aspect of clinical practice.[37–43] Ankle-foot orthoses tuning can be defined as the process whereby fine adjustments are made to the design of the AFO-FC to optimize its performance during gait. The term biomechanical optimization is used to encompass the whole process of designing, aligning, and tuning the AFO-FC.[37,43,47]

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THE SHANK-TO-VERTICAL ANGLE

The shank-to-vertical angle (SVA) can be described as the angle of the shank relative to the vertical, measured in the sagittal plane. The SVA is described as inclined if the shank is inclined forward from the vertical and reclined if it is reclined backward from the vertical. It is described in degrees, with vertical being 0°. The line in the sagittal plane of the anterior aspect of the tibia is used to represent the line of the shank.[37,43,47] Owen[37,43,47] indicated that anthropometric measures dictate that an SVA between 10° and 12° inclined from the vertical brings the knee joint center over the middle of the foot during mid-stance in normal subjects. There is only a small range of SVA where it is possible to incline the thigh, maintain a vertical trunk, and balance. It is 7° to 15° inclined, 10° to 12° being the optimum position.[36,43,47]

An SVA of 10° to 12° at mid-stance is important for the following reasons[37]:

1. It contributes to stability in stance by placing the knee joint center over the center of the foot, which is creating a stable distal support mechanism. This creates a stable distal support mechanism in the form of a triangle.
2. It facilitates ballistic movement of the thigh, pelvis, and trunk. Soleus is restraining the forward movement of the

shank, and momentum carries the thigh, pelvis, and trunk forward to extend the knee.
3. It dictates thigh, pelvis, trunk, and head kinematics.
4. It facilitates appropriate GRF alignment to the knee and hip and switching of moments from flexion to extension moments at the knee and hip.
5. It may contribute to conservation of energy.

Pratt et al.[44] investigated the SVA and the moment arm at the knee joint on 11 healthy children in an attempt to establish a baseline for AFO-FC tuning. The research reported a mean SVA at temporal mid-stance (TMST) of 11.4° ± 3.4° in the barefoot condition and 10.5° ± 3.6° in the shod condition, thus providing support for Owen's[37,43,47] indication of the position of the SVA during mid-stance. More recently, Kerkum et al.[48] looked at the SVA as a parameter to evaluate tuning of AFOs; their study on adults demonstrated that the SVA is responsive to changes in AFO-FC heel height, which resulted in an increase in lower-limb joint flexion angles and net internal extension moments. This is in line with findings from other studies.[34,35,49] However, it is assumed that the static SVA of the AFOFC will closely mimic the dynamic SVA at TMST, although there is no evidence of this in the current literature.

The angle of the ankle in the AFO (AAAFO) and the pitch of the heel sole differential (HSD) will determine the SVA. Detailed information on the tuning process has previously been described.[33,37,43,46,47] Various authors have used different terms to describe the angle between the shank of the tibia and the floor. Owen[37,43,46,50] used shank angle to floor (SAF); Pratt et al.[44] used shank and the vertical angle (SAV); and Hullin et al.[45] used the term foot-shank angle, all of which are synonymous with SVA.[37]

MEASURING THE SVA OF THE AFO-FC

Owen[37,43,46] advocates measuring the SVA of the AFO-FC with the subject standing on a force plate with the AFO-FC sagittal to the camera with equal weight between the heel and the toe, ensuring the GRF is in the middle of the foot. A picture is then printed and, using a goniometer, the angle between the shank and the vertical is measured; this is considered the angle of the SVA of the AFO-FC. It is assumed that the SVA of the AFO-FC measured while the subject is static will positively affect the SVA at TMST during the gait cycle; however, there is no evidence in the literature to suggest whether this is an accurate method of determining the effect of the SVA at TMST.

The aim of the SVA is to positively influence the kinetics and kinematics during gait. Therefore, it is imperative that the SVA of the AFO-FC measured statically normalizes the SVA measured dynamically at TMST. Given that this is an accepted clinical practice, the purpose of this study is to compare the measurement of the SVA of the AFO-FC statically with the measurement of the SVA dynamically at TMST in a series of cases.

METHOD

PARTICIPANTS

Four children aged between 7 and 11 years with a diagnosis of cerebral palsy, 1 with hemiplegia and 3 with diplegia, participants with a gross motor functional classification scale (GMFCS) of 2, and all of whom were long-term AFO users participated in this study (see Table 1 for anthropometric data of the participants). T1

ETHICAL APPROVAL

This study was granted ethical approval by the National Research Ethics Service (NRES) Ethics Committee West Midlands South Birmingham (reference number 12/WM/0378). All participants provided full informed oral and written consent before inclusion in the study.

PROCEDURE

Each subject was assessed by an experienced orthotist and prescribed with a bespoke solid polypropylene AFO. The AFOs (see Figure 1 and 1A) used in this study were deemed appropriate for each subject on an individual basis and ensured there was F1 no movement of the AFO in terms of deformation during stance phase (see Table 2 for AFO design details). T2

Table 1. Anthropometric data

Subject ID	CP classification	GMFCS	Weight, kg	Age, y	Height, mm	Length of gastrocnemius passively with knee extended	Bare foot gait classification
ID2	Spastic hemiplegic with right side affected	2	23.6	8	1220	5° Dorsiflexed	Group II (Winters 87)
ID4	Spastic diplegic with right side predominately affected, AFO right only	2	55.1	11	1450	90°	Group ~~II~~ (Winters 87)
ID5	Spastic diplegic	2	27.7	7	1310	90°	Group ~~III apparent equinus (Rodda 2004)~~
ID8	Spastic diplegic with right leg predominately affected AFO right only	2	25.8	9	1310	90°	Group II (Winters 87)

Figure 1. A and B, Illustrative examples of one subject's AFO.

The trimlines at the ankle finished anterior to the malleolus. The height of each AFO finished 30 mm below the fibula head. All the footplates were full length. The AAAFO was determined by an examination of the passive length of gastrocnemius with the knee extended to ensure that the resulting AFO captured the length of gastrocnemius. Where the AAAFO was in plantarflexion, a buildup was added to the AFO to achieve a vertical bench alignment, shank angle to bench (SAB). All subjects were issued with the same over-splint footwear (see Figure 2) in either black or white (Blacky style manufactured by Salts Techstep, United Kingdom).

Retroreflective markers were placed on each subject's lower limbs to mark the tibial tuberosity; fibula head; lateral knee joint; distal tibia; calcaneus; lateral malleolus; first, second, and fifth MTPJs, and the distal first phalangeal to allow identification of gait events (see Figure 3A, B).

Each participant's AFO-FC was tuned by an experienced orthotist using video equipment with GRF overlay to establish the optimum SVA of the AFO-FC. The tuning process followed Owen's algorithm.[46] Temporary wedges and, where necessary, point loading rockers (PLRs) were added to the sole of the footwear via masking tape (see Figure 3) until the optimum SVA of the AFO-FC was determined. Once the SVA of the AFO-FC was determined, the footwear was then sent for permanent modification. The participants were called back to the laboratory 3 weeks after receiving their permanently modified footwear (to allow

Table 2. AFO design for each participant

Subject ID	AAAFO	AFO	Material	Material thickness	Foot plate	Strapping	Optimum SVA
ID2	90°	Right solid AFO	Homopoly polypropylene	4.5 mm	Full length with M–L flanges distal to fifth MTPJ footplate to control forefoot abduction flexible at MTPJs to facilitate third rocker	Figure of eight at the ankle and Velcro ring, ring pull at the calf	12°
ID4	90°	Right solid AFO	Homopoly polypropylene	5 mm	~~Full length with M–L flanges distal to 5th MTPJ footplate to control forefoot abduction flexible at MTPJs to facilitate third rocker~~	Figure of eight at the ankle and Velcro ring, ring pull at the calf	12°
ID5	90°	Bilateral solid AFOs	Homopoly polypropylene	4.5 mm	Full length with carbon fiber stiffner M–L flanges distal to MTPJs to block third rocker and limit knee flexion	Figure of eight at the ankle and Velcro ring, ring pull at the calf	13°
ID8	90°	Right solid AFO	Homopoly polypropylene	4.5 mm	Full length with M–L flanges proximal to MTPJs; flexible footplate at MTPJs to facilitate third rocker	Figure of eight at the ankle and Velcro ring, ring pull at the calf	11°

Fig 2 4/C

Figure 2. Example of over-splint footwear (Blacky style manufactured by Salts Techstep, United Kingdom).

each participant to get used to walking in their tuned AFO-FC before testing) to undergo testing for this study.

MEASUREMENTS

Each participant was asked to stand on the force plate in the tuned AFO-FC with the AFO-FC sagittal to the video camera, ensuring the GRF point of application was in the middle of the foot F4 (see Figure 4). The image was recorded and uploaded to video analysis software (Kinovea 0.8.15) to enable the angle of the SVA of the AFO-FC to be measured using Owen's method.[43] This determined the static SVA angle.

AQ5 On the same day, each participant was then asked to walk 4-minute trials for three times on a 32-m walkway in the gait laboratory, allowing kinetics and kinematics to be captured using force plates and 18-camera optoelectronic motion analysis system (Vicon, Oxford, United Kingdom) for a wider study. The gait analysis protocol included the use of two high-speed video cameras, one placed in the frontal plane and the other in the sagittal plane. The cameras enabled two-dimensional analysis of gait and posture in addition to sophisticated three-dimensional analysis, which is beyond the scope of this manuscript.

Temporal mid-stance was identified, which was described by Gibson et al.[51] as occurring at 30% of the gait cycle. During TMST, the pelvis, the trunk, and the head are directly over the foot and the GRF seems to be vertical. The knee of the swing limb can just be seen anterior to the stance limb and the heel of the swing limb can be seen posterior to the stance limb.[42] The corresponding frame of video was identified and uploaded onto the 2D analysis software, so the SVA angle could be measured using Owen's method.[37,43,46]

Fig 4 4/C

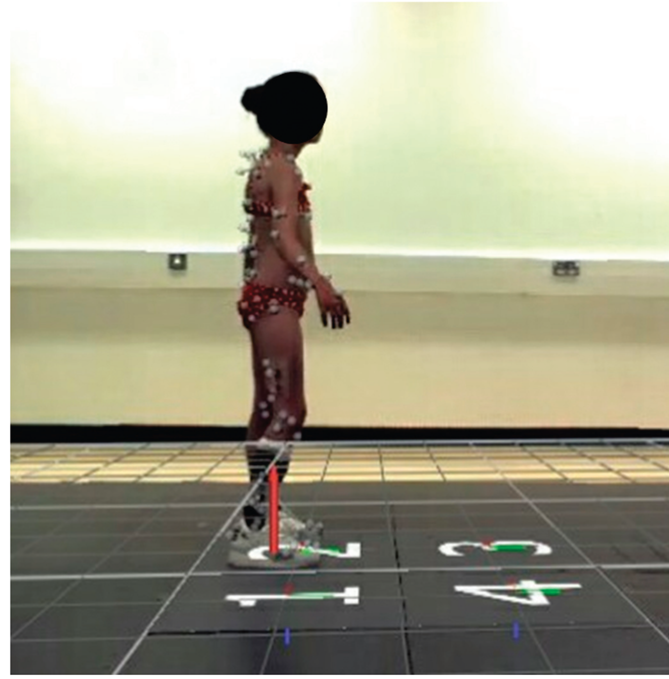

Figure 4. Illustration of measurement where a participant stood on the force plate in AFO-FC with the visible GRF.

RESULTS

The results of the SVA of the AFO-FC during quiet standing and during five walking trials were measured for each participant (see Table 3). The SVA of the AFO-FC measured while the T3 subject was static correlated with the SVA measured at TMST to within 0.25° to 0.4° (see Figure 5 for representative illustration F5

Fig 3 4/C

Figure 3. A, Over-splint footwear with temporary wedges. B, Tuned AFO-FC with permanent modifications to the sole unit.

Table 3. Static and dynamic SVA angles

Subject	Static SVA	Dynamic SVA Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean dynamic SVA	Average difference in static versus dynamic SVA
ID2	12°	12°	10°	12°	12°	12°	11.6°	0.4°
ID 4	12°	12°	12°	10°	12°	12°	11.6°	0.4°
ID5	13°	14°	13°	13°	14°	13°	13.4°	0.4°
ID8	11°	11°	14°	11°	11°	11°	11.6°	0.6°

of the static measurement and the corresponding dynamic measurement for the same participant).

DISCUSSION

The present study demonstrates that the SVA of the AFO-FC measured statically (ISO defines static alignment as "static alignment: process whereby the bench alignment is refined while the prosthesis or orthosis is being worn by the stationary patient"[52]) correlates to the SVA measured at TMST during gait (ISO defines dynamic alignment as the "process whereby the alignment of the prosthesis or orthosis is optimized by using observations of the movement pattern of the patient"[52]). While measuring the SVA of the AFO-FC in relaxed stance, each subject placed both lower limbs on the foot plate. This method was chosen as opposed to only one foot on the foot plate to reduce the risk of distorting the subject's normal relaxed stance position and to ensure that the weight was distributed evenly between both lower limbs.

All four subjects' SVA of the AFO-FC measurements statically correlated to the dynamic SVA measurement to within 0.4° to 0.6°. The results of this study support Owen's method[42,43] of measuring the SVA. The aim of this study was to measure the SVA in static and compare it with the SVA dynamically at TMST; in doing so, it is important to ensure ecological validity.

The authors are aware that not all clinicians have access to three-dimensional gait analysis equipment. The study of Eddison et al.[53] on the common clinical practice of AFO-FC tuning in the United Kingdom reported that 34% of respondents reported they do not tune the AFO-FCs of their patients because they do not have access to three-dimensional gait analysis and a further 27% reporting that the process is too time-consuming. Thus, the method used in this study of uploading an image and using video analysis software to determine the SVA angle was purposely chosen to ensure that the method is clinically applicable and accessible to all clinicians. It is also important to note that the static SVA of the AFO-FC can also be measured using a simple goniometer.

Currently, there is no other study in the literature that has measured the SVA at mid-stance and compared it with the SVA of the AFO-FC measured statically. Although we have not

Fig 5 4/C

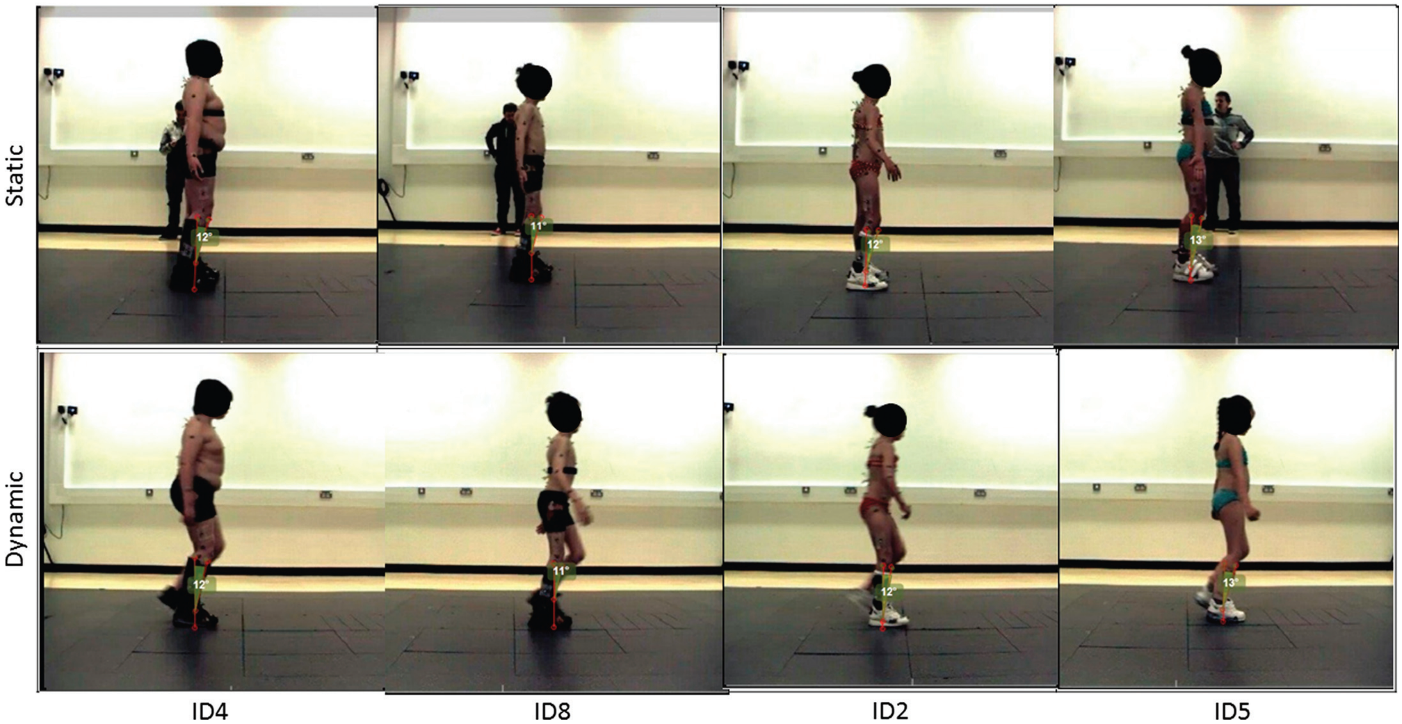

Figure 5. Representative static SVA and SVA at mid-stance for various participants.

subjected the data to any detailed statistical tests due to low participant numbers, the results pave the way to design further structured studies with accepted statistical power. In addition, reported values will also inform future studies that investigate the material properties for AFOs and the combination of AFOs and footwear.

As stated, the aim was to ensure that the method used remained clinically applicable; however, there is a limitation with using video analysis software, as most of the commercially available ones measure the angle to the nearest whole degree. Another limitation of the study was the ability to ensure that the subject was in the true sagittal plane to the camera during the static SVA of the AFO-FC measurement, but during gait, it is not possible to ensure that a child with pathological gait remains in the true sagittal plane at the point the child passes the video camera.

Although the case series analysis shows clinical applicability, the robustness of this validity has to be established with larger participant groups. It might be possible in a research setting to overcome the limitations posed by video analysis by introducing other technologies such as inertial motion sensor-based systems.

CONCLUSIONS

This study seems to indicate that measuring the SVA of the AFO-FC statically is an accurate way of determining the SVA at TMST during gait.

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