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The Shank-to-Vertical-Angle as a parameter to evaluate tuning of Ankle-Foot Orthoses

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ABSTRACT

The effectiveness of an Ankle-Foot Orthosis footwear combination (AFO-FC) may be partly dependent on the alignment of the ground reaction force with respect to lower limb joint rotation centers, reflected by joint angles and moments. Adjusting (i.e. tuning) the AFO-FC's properties could affect this alignment, which may be guided by monitoring the Shank-to-Vertical-Angle. This study aimed to investigate whether the Shank-to-Vertical-Angle during walking responds to variations in heel height and footplate stiffness, and if this would reflect changes in joint angles and net moments in healthy adults. Ten subjects walked on an instrumented treadmill and performed six trials while walking with bilateral rigid Ankle-Foot Orthoses. The AFO-FC heel height was increased, aiming to impose a Shank-to-Vertical-Angle of 5°, 11° and 20°, and combined with a flexible or stiff footplate. For each trial, the Shank-to-Vertical-Angle, joint flexion–extension angles and net joint moments of the right leg at midstance were averaged over 25 gait cycles. The Shank-to-Vertical-Angle significantly increased with increasing heel height ($p < 0.001$), resulting in an increase in knee flexion angle and internal knee extensor moment ($p < 0.001$). The stiff footplate reduced the effect of heel height on the internal knee extensor moment ($p = 0.030$), while the internal ankle plantar flexion moment increased ($p = 0.035$). Effects of heel height and footplate stiffness on the hip joint were limited. Our results support the potential to use the Shank-to-Vertical-Angle as a parameter to evaluate AFO-FC tuning, as it is responsive to changes in heel height and reflects concomitant changes in the lower limb angles and moments.

1. Introduction

Ankle-Foot Orthoses (AFOs) are frequently applied in patients with neurological disorders, aiming to normalize joint kinematics and joint kinetics during walking [1–4]. Although it has been shown that AFOs can significantly improve sagittal joint kinematics and kinetics [2,3,5–7], inadequate alignment of ground reaction force (i.e. distant from the joint rotation centers) during walking negatively impacts the effectiveness [4,8,9].

Tuning of the AFO optimizes the alignment of the ground reaction force with respect to the joint rotation centers, enhancing normalization of the joint kinematics and kinetics [8–12]. Such tuning can be described as the process in which the properties of an AFO-Footwear Combination (AFO-FC) are manipulated. Commonly used adjustments comprise changing the footplate stiffness to affect the point of application of the ground reaction force, and altering the heel-sole differential (i.e. the difference in height between the heel and forefoot of the shoe), which affects shank orientation [8]. The combined effect of the AFO-FC's ankle angle and heel-sole differential can be described in terms of the Shank-to-Vertical-Angle (SVA). The SVA, i.e. tibia inclination, is the angle between the anterior surface of the tibia and the vertical in the global sagittal plane [8,13]. It is clinically often measured using sagittal video recordings [13]. The SVA is considered inclined, when the shank is tilted forward, or reclined, when it is tilted backward with respect to the vertical. Owen [13] suggested that an appropriate shank orientation at midstance aligns the ground reaction force to the joint rotation centers, which contributes to stability, facilitates adequate switching from flexion to extension moments at the knee and hip, and lowers vertical center of mass

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excursion. Accordingly, the SVA at midstance may be an important and relatively simple parameter to evaluate the effects of adjustments to the AFO-FC during its tuning process [8,13], also because information on the ground reaction force and calculations of joint moments are not always available in clinical practice.

Several studies in patients with neurological disorders report the SVA, and describe a normalization of gait parameters following changes of the heel-sole differential [11,12,14,15]. However, in all available studies, the SVA was measured while the patient was in a static position, whereas there is no evidence showing that the SVA in this position represents the SVA at midstance [8]. Evidence on the effects of changing the footplate stiffness on the SVA, as well as on joint kinematics and kinetics is also lacking. Yet, in clinical practice, such manipulations of footplate stiffness, in addition to changing the heel-sole differential are commonly applied. Since tuning of these AFO-FC properties is generally guided by monitoring the SVA at midstance, insight is needed in how the SVA responds to changes of the heel-sole differential and footplate stiffness, in order to assess its potential as a parameter to evaluate the effects of such manipulations.

To this end, we evaluated in healthy young adults (i) whether the SVA at midstance can be influenced during walking with an AFO-FC by applying commonly used manipulations within the process of tuning (i.e. changing AFO-FC heel-sole differential and footplate stiffness), and (ii) how changes in the SVA, as a result of the manipulations, are reflected in ankle, knee and hip flexion–extension angles and net internal joint moments at midstance. We hypothesized that the SVA would be responsive to changes in AFO-FC heel height and that this would be reflected by increased knee and hip flexion angles and net internal joint extension moments at midstance. As a stiff footplate mainly aims to shift the ground reaction force forward without affecting joint flexion–extension angles, we expected no response of the SVA to changes in footplate stiffness, while it was expected to affect internal net joint moments.

2. Methods

2.1. Participants

Ten healthy young adults (3 male; mean (SD) age: 24 (3) years; mean (SD) body mass index: 22.8 (2.2)) participated. All subjects provided written informed consent in accordance with the procedures of the Institutional Review Board of the VU University.

3. Materials

For this study, two pairs of prepeg carbon AFOs were manufactured (European shoe size: 39 and 43) (see Fig. 1A). Each participant chose the best fitting pair. The stiffness of the AFOs at the ankle and metatarsal joints was measured using BRUCE [16], which is an instrument to define AFO mechanical properties. The AFOs were rigid at the ankle (7.9 Nm deg^{-1}), aiming to immobilize the ankle joint at 0°.

According to Owen [13], important kinematic characteristics at midstance (e.g. thigh inclination) can only be preserved with an SVA ranging from 7° to 15°, while an SVA of 10–12° is suggested to be optimal. In the current study, AFO-FC heel-sole differential was varied using three heel heights by applying insole wedges, aiming to impose an SVA of 5°, 11° and 20° in static position. As such, the effects of SVA manipulations near the presumed optimum and outside the suggested optimal range were investigated. The height of the wedges was pre-defined for both AFO-FCs, using a dedicated instrument to measure heel height and heel-sole differential of an AFO-FC when doffed (Vertical Inclinometer on a Rail (VICTOR) [17]) (see Fig. 1B). Using VICTOR, low (size 39:0.6 cm; size 43:1.3 cm), medium (size 39:2.8 cm; size 43:2.8 cm) and high (size 39:4.9 cm; size 43:5.3 cm) heel heights were specified (see Fig. 1). These heel heights were combined with two different degrees of footplate stiffness, which could be changed by adding a stiff inlay footplate (0.89 Nm deg^{-1}) to the AFO's flexible footplate (0.06 Nm deg^{-1}). The provided shoes (i.e. flexible sneakers) were large enough to allow for the insole wedges.

3.1. Measurements

Subjects walked on the GRAIL system (Motek Medical BV, Amsterdam, the Netherlands), consisting of a split-belt instrumented treadmill (ForceLink©, Culemborg, the Netherlands) and a passive marker motion capture system (Vicon, Oxford, UK), collecting marker trajectories. Ground reaction forces were captured from force sensors mounted underneath both treadmill belts, and synchronized with kinematic data at 120 Hz.

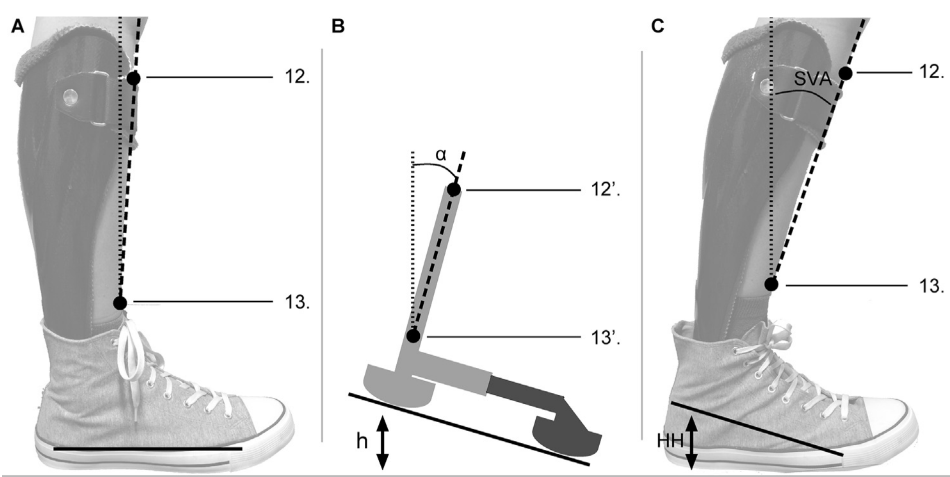

Fig. 1. (A) Picture of the Ankle-Foot Orthosis-Footwear Combination (AFO-FC) of the right leg without insole wedges. (B) Schematic representation of the Vertical Inclinometer on a Rail (VICTOR [17]), with virtual markers 12′ and 13′ as analogue reference points of the anatomical markers at the tibial tuberosity (Fig. 2, #12) and tibia (Fig. 2, #13). VICTOR was used to determine the height of the insole wedges to impose a Shank-to-Vertical-Angle of 5°, 11° and 20° during the walking trials. Wedges were added to increase the height (h) of the heel probe until the inclination angle (α) reflected the pre-defined angles of 5°, 11° and 20°. (C) Picture of the AFO-FC including insole wedges (pre-defined using VICTOR (h)), resulting in the heel height (HH). The Shank-to-Vertical-Angle (SVA) during walking was calculated as the angle between the line at the anterior surface of the tibia (dashed) (i.e. the line connecting the marker at the tibial tuberosity (#12) and tibia (#13)) and the vertical (dotted) in the global sagittal plane. This SVA was expected to represent α. Dotted: the vertical as used for SVA calculation; dashed: line at the anterior surface of the tibia, representing the long axis of the shank in the global sagittal plane; solid: estimated position of the footplate in the shoe.